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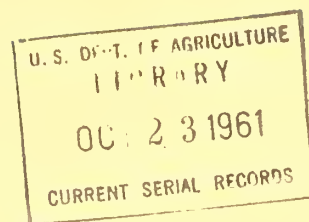
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Cooling APPLES and PEARS in Storage Rooms

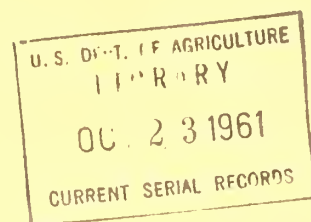
Marketing Research Report No. 474

UNITED STATES DEPARTMENT OF AGRICULTURE,
Agricultural Marketing Service,
Transportation and Facilities Research Division

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Resume
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**Cooling
APPLES
and PEARS
in Storage Rooms**

Marketing Research Report No. 474

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Marketing Service
Transportation and Facilities Research Division

Preface

This report covers work conducted under a long-range research project centered at the Wenatchee, Wash., field office of the Transportation and Facilities Research Division, Agricultural Marketing Service, to improve the operation and design of cold storage houses for apples and other tree fruits. It covers the effect on the cooling rate of fruit of containers of various types and dimensions, method of packing, and patterns in which the containers are stacked; the relation between air distribution and cooling performance; the factors influencing uniformity of temperature during storage; and the cost of various air distribution systems.

Improved efficiency in marketing farm products is the objective of a broad program of research by the Agricultural Marketing Service, and this study is a part of that program. This research was carried on under the general supervision of Joseph F. Herrick, Jr., marketing research analyst, Handling and Facilities Research Branch, Transportation and Facilities Research Division.

Since the manuscript for this report was prepared, some work has been done on the cooling rates of apples in pallet boxes. Preliminary data were published in a report titled "Handling and Storage of Apples in Pallet Boxes," AMS-236. More complete data are to be published in another report.

The author is indebted to the following organizations which cooperated by making their storages available for

test purposes and thus provided a vast commercial-scale "laboratory:" Apple Growers Association, Hood River, Oreg.; A. Z. Wells Orchards, Azwell, Wash.; Blue Ribbon Growers, Yakima, Wash.; Blue Star Growers, Cashmere, Wash.; Cascadian Fruit Shippers, Wenatchee, Wash.; Cashmere Cooperative Growers, Cashmere, Wash.; Cashmere Fruit Exchange, Cashmere, Wash.; Cashmere Pioneer Growers, Cashmere, Wash.; Cubberley Fruit and Cold Storage Co., Tieton, Wash.; Entiat-Wenoka Growers, Entiat, Wash.; Fruit Growers Service, Monitor, Wash.; J. D. Hamilton Fruit Co., Wenatchee, Wash.; Hi-Line Growers Cooperative, E. Wenatchee, Wash.; Karr Orchards, Yakima, Wash.; Lake Chelan Fruit Growers, Chelan, Wash.; Leavenworth Fruit and Cold Storage, Leavenworth, Wash.; Lloyd Garretson Co., Yakima, Wash.; Mad River Orchard Co., Entiat, Wash.; Matson Fruit Co., Selah, Wash.; Methow-Pateros Growers, Pateros, Wash.; Ninth Street Skookum Growers, Wenatchee, Wash.; Oroville Warehouse Co., Oroville, Wash.; Perham Fruit Co., Yakima, Wash.; Peshastin Fruit Growers Association, Peshastin, Wash.; Regal Fruit Co., Tonasket, Wash.; Richey and Gilbert Co., Yakima, Wash.; Small Bros., Entiat, Wash.; Southern Oregon Sales, Medford, Oreg.; Wells and Wade Fruit Co., Wenatchee, Wash.; and Wenatchee-Wenoka Growers, Wenatchee, Wash.

Contents

	Page		Page
Summary	2	Economic factors in evaluating air distribution systems	43
Background of study	3	Conclusions	46
Objectives	4	Literature cited	47
Previous investigations	4	Appendix	48
Relation of approach temperature to cooling performance	4	Methods of research	48
Factors affecting cooling performance	9	Method of observation	48
Containers	10	Analysis and evaluation of cooling performance	49
Stacking methods	15	Analysis to predict approach temperature	50
Air velocity	17	Analysis to predict effect of several variables on cooling performance	53
Air distribution pattern	17	Analysis to determine effect of starting period on cooling coefficient and half-cooling time	55
Factors affecting uniformity of air and fruit temperatures	35		

Summary

In the Pacific Northwest, apples and pears are usually received and cooled in the same rooms where they are subsequently stored; this procedure is known as "room cooling." It eliminates the necessity for special facilities and handling that are common when precooling is practiced.

A good room-cooling operation should cool the fruit as rapidly as possible with little or no special handling of the product; should maintain as nearly uniform product temperature as possible during the storage period; and should accomplish these objectives at minimum overall cost.

When the necessary refrigeration capacity is provided to handle the heat that must be removed from the fruit, then the dimensions, nature of the container, and manner of stacking are the most important factors that influence cooling performance.

Cooling performance is compared in terms of "half-cooling time," which denotes the time required to reduce the original temperature of fruit halfway to the temperature of the cooling air. The term "characteristic cooling time," as used in this report, means the same thing as half-cooling time. The influence of the factors mentioned on half-cooling time for some of the more common containers and stacking arrangements is shown by the following list of half-cooling time values that were encountered:

Unpacked pears in cannery lugs in individual rows, 6 to 10 hours.

Unpacked pears in cannery lugs in palletloads, 8.6 to 18.4 hours.

Unpacked apples in standard apple boxes in individual rows, 6.9 to 14 hours.

Unpacked apples in standard apple boxes in palletloads, 15.4 to 23.4 hours.

Packed pears in wood boxes in individual rows, 23 to 36 hours.

Packed apples in wood boxes in individual rows, 27 to 50 hours.

Packed apples in wood boxes on pallets, 45 to 66 hours.

Air passage through the packages is an important factor in the better performance shown by unpacked fruit.

Distance from the center of a pile of packages to the surface where the heat is removed is a most important factor. Half-cooling time in a package where convection is negligible varies almost with the square of this distance.

Increased air velocity past the package has some effect in reducing cooling time, but as the package exposure becomes less favorable, the effectiveness of increased air velocity falls off rapidly.

The half-cooling time and approach temperature (temperature difference that remains between fruit and air after cooling) are definitely related. The approach temperature is approximately 1° for a 30-hour half-cooling time, 2° for a 60-hour half-cooling time, etc.

Approach temperature, variation in quantity of cooling air circulated in different sections of the storage room, heat transmission into packages in contact with outside walls or ground floors, and variations due to poor operations of control systems are the major factors that produce nonuniform fruit temperature during storage.

The average difference between warmest and coldest fruit in the rooms during the storage season should not exceed 2° F. Many instances were observed where the difference was greater than 2°, and study of the effect of various factors on uniformity of storage temperature has led to the following general conclusions:

Fluctuation of temperature over a period of several days affects storage uniformity; fluctuation of air temperature over a 2-hour period caused by control operation cannot be detected in the fruit temperature.

Improper adjustment of air distribution systems is a major cause of nonuniform storage temperatures, and some of the most severe cases of nonuniformity have been traced to this cause.

Airflow pattern should conform to the stacking pattern to secure the most nearly uniform fruit temperatures.

The quantity of air circulated should be sufficient to provide an air turnover rate of at least 7.5 times per hour in the empty storage.

With packed fruit, those locations in the storage that cool more slowly stabilize at a higher temperature, and those that cool rapidly stabilize at a lower temperature.

An economic analysis of the costs of air distribution in the storages observed indicates that the multiple overhead unit system recently applied to palletized storages offers a definite saving over previous methods. Observations of such systems indicate good performance where the system is applied in accordance with the requirements for producing uniform storage conditions, as pointed out in this report.

Cooling Apples and Pears in Storage Rooms¹

BY G. F. SAINSBURY, *agricultural engineer*²
Transportation and Facilities Research Division

Background of Study

In the Pacific Northwest, apples and pears seldom require special precooling facilities. They are usually received and cooled in the same rooms where they are stored, because less handling is required. This procedure is commonly called "room cooling."

Room cooling does not strictly qualify as precooling, and it rarely is accomplished as rapidly as true precooling. Nevertheless, for most apple and pear storage operations, commercial operators feel that it represents a good compromise between costs and ideal procedure. A knowledge of factors controlling the effectiveness of room cooling is of great importance to the storage operator and to the engineer designing facilities of this type.

Work on precooling was included in the project at Wenatchee, Wash., and that work has been reported previously (11).³

The product to be room cooled may be high-piled manually or mechanically, at the time it is placed in the room or within a few days after entering the room. The fruit entering the room may be already packed, or it may be loose in picking containers and be held for some time in the containers before going to the packing line. In one method of handling, room cooling approximates true precooling; in that case, warm fruit is brought into the room and cooled before packing to remove most of the field heat, and then is removed, packed, and returned to cold storage for later sale.

In room-cooling operations, it is desirable that the cooler provide economical storage and handling facilities and also as rapid cooling as is possible, and that subsequently the commodity temperature be as uniform as possible and be near the minimum allowable temperature for the commodity.

Any discussion of room cooling as a substitute for precooling must recognize that the process has limitations in cooling speed. First, directing air

through packages uniformly on a large scale is difficult, so air velocity past the containers is rarely as great as in specially built precoolers; second, sustained room air temperatures much lower than the minimum optimum storage temperature of the commodity are not permissible. In certain types of precoolers, controlled airflow can be maintained and used to enhance the heat transfer from the commodity, and low air temperatures can be used to increase the heat flow rate. This last measure presumes that the commodity will be removed from the precooler before actually cooling any lower than the minimum allowable temperature.

This report does not deal with the problem of adequate refrigerating capacity to handle the cooling load, but is concerned with the performance of those storages having adequate capacity. It should be emphasized that adequate capacity to handle the heat load is an absolute prerequisite for a good room-cooling operation.

As the study developed, it became apparent that many factors were involved in the performance, of which some were elements of the room design and air distribution systems, some were elements of handling procedures used, and some were dependent upon the containers selected by the operators. To provide satisfactory room cooling, all of these factors must be considered. It is the intent of the report to generalize the results sufficiently that they will be of value in providing operators and engineers with reasonable guides for determining the *effect* of a proposed change in room design, handling procedure, or container selection.

The evaluation of cooling performance in terms of "characteristic cooling time" or "half-cooling time" is an important feature of this report, because this time is a performance yardstick now being used by other workers concerned with cooling performance. "Characteristic cooling time" or "half-cooling time" is the time required to cool fruit from its initial temperature halfway to the temperature of the cooling air. It is designated by the letter "Z" in formulas used later in this report.

¹ The work which is the basis of this report was done with the cooperation of the Washington State Agricultural Experiment Station.

² Resigned from the Agricultural Marketing Service.

³ Italic numbers in parenthesis refer to items in literature cited, p. 47.

The basic law of cooling, upon which the concept of half-cooling time depends, was set forth by Sir Isaac Newton over two and one-half centuries ago. Yet the earliest reports that the author could find on application of the law to evaluating the performance of various cooling arrangements for fruits go back only about 20 or 25 years. They are reports by English workers on the Food Investigation Board of the Department of Scientific and Industrial Research of Great Britain. Some of the information in those reports (14) has been cited herein. Shortly after that time, R. L. Perry, of the University of California, introduced the term "cooling coefficient" in comparing the performance of various methods of cooling asparagus. The cooling coefficient is the decrease in fruit temperature, in °F. per hour, divided by the average difference in temperature between the fruit and the surrounding air. This factor has been used

also by W. T. Pentzer in some of his publications on grape cooling, and by the author. Thevenot (16) pointed out the relation between half-cooling time and cooling coefficient, and the basic relationships of cooling performance have been well summarized by Guillou in an article (3). The emergence and adoption of a reliable quantitative measurement of cooling performance is an important development in this field of research. It is particularly interesting that many workers in widely separated areas have contributed to this development. The work of E. W. Hicks (5) of the Commonwealth Scientific and Industrial Research Organization of Australia has been put to considerable use in this report. Many others have contributed to the development of the quantitative evaluation of half-cooling time, but the work of those indicated above has been particularly helpful to the author.

Objectives

This study was designed to: (1) Determine the characteristic or half-cooling time required for apples and pears when room cooling is done; (2) evaluate the effect of various types of packaging methods, stacking methods, and air velocities through the stacks on the half-cooling time; (3) determine "approach temperatures" between cooled fruit and air, and their relation to characteristic cooling time; (4) determine the factors affecting the uniformity of fruit temperature during storage;

(5) evaluate the performance of various types of air distribution systems on the basis of uniformity; (6) investigate the economic factors associated with various types of air distribution systems.

The "approach temperature" is the difference between temperatures of the air and the fruit after stability has been reached; the fruit temperature then normally remains slightly higher than the temperature of the cooling air. It is occasionally designated as "A.T." in this report.

Previous Investigations

Reports on research aimed at some of these objectives have been published (2, 8, 9, 15); however, considering the importance of the problem and the number of possible arrangements of cooling rooms and factors affecting their performance, many problems remain for investigation. Most of the investigators have been concerned chiefly with problems of uniformity of storages and have approached the problem through two general techniques. Smock, Kayan, and Francis (15) and Grierson-Jackson and Fisher (2) based their evaluations of performance on measurement of air velocity at accessible locations in the storage and in the stacks. Hukill and Wooten (8) and

Rostos (9) based their conclusions principally on observations of fruit temperatures and the variations encountered at different locations during the storage period. Smock, Kayan, and Francis also reported some work on temperature distribution.

This report uses the latter method because it is applicable during actual storage and can be applied to both accessible and inaccessible locations. In some cases, observations of air velocities have been made, to study the relationships between air motion, rapidity of cooling, and uniformity of temperature.

Relation of Approach Temperature to Cooling Performance

Fruit in storage produces a small amount of heat due to its respiratory processes, even when held at 30° to 31° F. To dissipate this heat as it is generated requires a temperature difference between the fruit and the surrounding air. Sometimes the difference is smaller than can be measured reliably by the methods used in this study. In other cases, the temperature difference

can be determined. This temperature difference may constitute a serious problem in storage operation. It is referred to as the "approach temperature."

The net amount of heat produced by respiration of the fruit at a given temperature varies with the amount of evaporation of moisture from the fruit (9). Some of the heat generated by respiration is used

to evaporate the moisture. At storage temperatures of 31° to 32° F., the heat produced about balances the heat required for evaporation when the shrinkage rate (weight loss) is 1 percent per month.

Gerhardt's study of Golden Delicious apples in a standard wrapped pack showed a shrinkage of about 3.6 percent over a period of 6 months, or 0.6 percent per month (1). He also showed that shrinkage for Anjou pears in standard packed boxes ranged from two-thirds to 1 percent per month. When film liners are used in such packages, the weight loss is less than one-third percent per month in all cases.

Additional data have been published by Schomer (13) showing that Delicious and Winesap apples in standard wrapped-pack boxes lose moisture at the rate of approximately one-third percent per month. In fiberboard shipping containers, the shrinkage is slightly higher and, when sealed liners are used, the shrinkage is one-eighth to one-sixth percent per month.

This information shows that in most cases where the product is sufficiently protected from the cooling medium by the package or liners, the shrinkage rate remains under one-half percent per month and at least one-half of the heat of respiration will be available as net heat that must be removed from the package by conduction.

In certain cases, an analysis can be made to predict the approach temperature based upon known characteristics of fruit, packages, and thermal properties of the materials involved. This analysis is presented in the appendix. It gives some insight into what can be expected from certain modifications of airflow or package arrangement. The analysis is limited to the case where heat is dissipated from two sides of a pile. The more complex cases of heat loss from four or six sides of a package are not considered.

Table 1 has been derived from the analysis in the appendix. It shows how various factors such as stack arrangement, moisture loss from fruit, and variation in outside surface conductance affect the approach temperature.

Although moisture loss varies somewhat with the variety of apples or pears, the most significant factor is whether or not the product is packed in a sealed liner. Moisture loss therefore may be considered as a variable associated with the type of package. The approach temperatures when moisture loss is one-eighth percent per month are 1.75 times greater than those when moisture loss is one-half percent per month, so the rate of moisture loss is a very significant factor in approach temperature.

The velocity of air past the package also can be an important influence on approach temperature (see columns "Possible variation due to *U*" in table 1; "*U*" represents the heat transfer through the carton to the air). In the more easily cooled stack arrangements, this factor is almost as important as the moisture loss rate. In stacks less favorably arranged, the effect of air velocity on surface conductance becomes less important than the moisture loss characteristics of the package.

The effect of stack arrangement upon heat dissipation is the most important variable of all. As shown in table 1, the approach temperature at the center of the boxes, when only one end of the container is exposed, is five to six times greater than when the container has two sides exposed.

These calculations have been made for fiberboard containers or cartons, because only one or two faces of an individual container is exposed in the normal stacking procedures considered. Standard packed wooden boxes stacked on their sides create small chimneys between stacks by virtue of their bulged tops and bottoms, as shown in figure

TABLE 1.—Approach temperature calculated for packed cartons of apples at 31° F. room temperature using various stacking arrangements, moisture loss rates, and outside surface conductances

Stacking arrangements	Approach temperature when moisture loss rate is: ¹				Possible variation due to "U" when moisture loss is:	
	½ percent per month and when:		⅓ percent per month and when:		½ percent per month	⅓ percent per month
	U=0.33 ²	U=0.8 ³	U=0.33 ²	U=0.8 ³		
2 sides of container exposed.....	° F. 0. 46	° F. 0. 30	° F. 0. 81	° F. 0. 53	° F. 0. 16	° F. 0. 28
2 ends of container exposed.....	. 93	. 67	1. 63	1. 17	. 26	. 46
2 rows stacked together, one end of each container exposed:						
At center of either container where distance from edge of pile is 10 inches.....	2. 34	1. 81	4. 09	3. 17	. 53	. 92
At center of pile.....	2. 82	2. 29	4. 93	4. 01	. 53	. 92

¹ Based on a respiration rate for the fruit of 3 mg. of CO₂/kg. of fruit/hr.

² "*U*" is overall heat transfer through carton to air, based on heat transfer coefficient from outside surface to air=0.5 and resistance of fiberboard carton.

³ "*U*" is overall heat transfer through carton to air, based on heat transfer coefficient from outside surface to air=4 and resistance of fiberboard carton.

1. An analysis is more difficult because the heat is not all conducted from one face or two parallel faces, but instead leaves from three or four



FIGURE 1.—Typical stack of pears packed in wood boxes and stacked on sides. Note how bulged tops and bottoms create spaces so that four surfaces are exposed. Apples are packed with less crown on top but with sufficient curvature on tops and bottoms to give exposure of four surfaces when stacked in individual rows.

faces of the box. Furthermore, it is doubtful if the heat transfer from the exposed end or ends is the same as from the partially sheltered side surfaces. Because of these complications, the analytical discussion of approach temperature considers only cartons.

Furthermore, the analytical calculations consider only those packs where wraps or partitions within the package provide sufficient obstruction to air current that convection is a negligible factor in heat removal. This does not mean that convection entirely eliminates approach temperature, but convection does act to decrease approach temperature. In some cases, with unpacked fruit, convection reduces approach temperature until it is not measurable.

Several factors have a substantial influence upon approach temperatures. It appears that, regardless of airflow past a package and the improvement in heat transfer coefficient from surface to air that may be achieved by a favorable airflow characteristic, the effect of unfavorable stacking patterns and package characteristics may produce a fairly large approach temperature. Increased airflow may reduce the approach temperature if the pack-

age is sufficiently open to allow some air passage through it.

Approach temperature exists because there is some generation of heat within the packages and a thermal potential is necessary to discharge this heat from the point of generation to the cooling medium against the various thermal resistances of the commodity and the package. In cooling the package initially, it is also necessary to discharge the heat contained in the package to the cooling medium, against these same thermal resistances. An analysis of factors affecting cooling performance was made to explore the similarity between cooling performance and approach temperature.

During initial cooling, the respiratory heat from the product is usually a fairly small portion of the total heat to be removed from the product, and the more rapidly the product cools, the less important is this component. Even in situations where cooling is relatively slow, that is, a half-cooling time of 70 hours, the net respiratory heat in a package where the normal moisture loss is at the rate of one-eighth percent per month is only about one-third of the heat being removed during cooling. In the same situation, with a moisture loss of one-half percent per month, the sensible respiratory heat is about 20 percent of the heat lost from the package. A half-cooling time as slow as 70 hours is not often encountered in practice. For half-cooling time in the order of 25 hours, which is more normal, the net respiratory heat amounts to 11 percent of the total heat removed when moisture loss rate is one-eighth percent per month, and 6.5 percent of the total heat removed when moisture loss rate is one-half percent per month.

From this appraisal of the magnitude and variations that occur in respiratory heat during the cooling period, it appears that moisture loss characteristics of the package are not nearly so important during the cooling period as they are during the holding period. However, the variations produce effects that operate in the same direction as in the holding period.

Using the formulas presented by Hicks (5), an analysis was made and is presented in detail in the appendix to predict cooling performance for various stacking arrangements and outside surface conductances. These are presented in table 2.

The coefficient of outside surface conductance varies approximately as the 0.67 power of the air velocity (5). The highest heat transfer coefficient presented in table 2 would require 22 times the air velocity of the lowest. For stacking arrangement I, an increase of 22 times in air velocity past the package practically doubles the speed of cooling. For arrangement II, this same increase in air velocity produces about a 50 percent increase in the speed of cooling. And for arrangement III, the same increase in air velocity produces only a 26 percent increase in cooling speed. In general, the cooling coefficient is increased by increased air velocities, but the extent of the effect is greatly influenced by different stacking arrangements.

TABLE 2.—*Half-cooling times calculated for packed cartons of apples using various stacking arrangements and outside surface conductances*

Stacking arrangement	Outside surface conductance (II)	Half-cooling time (Z)
I. Stacked end to end, space between sides—2 sides exposed to air-----	<i>B.t.u./hr./sq. ft./° F. Td.</i>	<i>Hours</i>
	0.5	35
	1.0	25
	2.0	20
	3.0	19
	4.0	18
II. Single rows stacked side to side—2 ends exposed to air-----	.5	74
	1.0	58
	2.0	51
	3.0	48.6
	4.0	47.3
III. 2 rows stacked closely to together—1 end only of each carton exposed-----	.5	233
	1.0	206
	2.0	189
	3.0	187
	4.0	184

The approach temperature is similarly influenced by air velocity past the package, but the increase in approach temperature associated with the lower air velocity indicated above is 51 percent for arrangement I, 39 percent for arrangement II, and 23 percent for arrangement III.

Although air velocity change does not produce effects that are in exactly the same proportions for cooling performance and approach temperature, the effects are in the same direction and in the two latter arrangements are of comparable magnitude.

As is the case with approach temperature, the most significant variable in cooling performance is stack arrangement. The variation in stack arrangement with containers of a given size produces variation in stack width. Equation 8-A in the appendix indicates that the cooling coefficient varies inversely almost as the square of the width of the stack. From table 2, it can be seen that cooling under arrangement I is 7 to 10 times as fast as with arrangement III, and also that stacks in arrangement I cool 2 to 2.6 times as fast as in

arrangement II. Cooling in arrangement II is from 3 to 4 times as fast as in arrangement III.

Table 3 gives a summary comparison of the influence on approach temperature and characteristic cooling time of the various factors that have been considered. Arrangement of stacks is the most significant factor affecting either approach temperature or characteristic cooling time, and cooling time is affected a little more than is approach temperature. Air velocity past the stacks affects the heat transfer coefficient, and this in turn influences both approach temperature and characteristic cooling time. Here again cooling time is subjected to a greater influence. However, variation in moisture loss rate produces a greater effect on approach temperature than on cooling time.

Table 3 shows that each factor that produces an increase in half-cooling time also produces an increase in approach temperature. Although the percentages of increase are not the same in all cases, they are quite similar and in all cases the change is in the same direction. From this analysis of the factors involved as well as from consideration of the generalities of the case, it is reasonable to expect that slow cooling, or large values of half-cooling time, will be associated with large approach-temperature values.

Figure 2 shows some values of approach temperatures plotted against half-cooling time as obtained by test. On the same chart are plotted values obtained from table 1 to show the predicted relationship between approach temperature and cooling performance at the two moisture loss rates considered. The observed approach temperatures are generally higher than the predicted values. This may be because the calculated half-cooling time values were larger than one would expect from the observations. Part of the difference may come from the higher respiration rate of the fruit that remains at the higher temperature. At 34° F., the respiration rate is about 15 percent greater than at 32°. No allowance for this factor was made in calculating the expected approach temperatures.

The data plotted on figure 2 cover only packed wood boxes or cartons, stacked with sides only exposed to airflow, and packed cartons stacked one wide or two wide with ends exposed to airflow.

TABLE 3.—*Increase in approach temperature and half-cooling time of apples packed in cartons caused by changes in stacking arrangement, outside surface conductance, and moisture loss characteristics of package*

Factor	Ratio of increase caused by changing from stacking arrangement—			Ratio of increase caused by changing coefficient of outside surface conductance from 4.0 to 0.5 B.t.u./hr./sq. ft./° F. Td. with stacking arrangement—			Ratio of increase caused by changing moisture loss rate from ½ percent to ⅓ percent per month with stacking arrangement—		
	I to III	I to II	II to III	I	II	III	I	II	III
Approach temperature ¹ -----	1.33	1.10	1.11	1.51	1.39	1.23	1.75	1.75	1.75
Half-cooling time, Z-----	1.47	1.30	1.33	2.0	1.50	1.26	1.05	1.11	1.26

¹ Air temperature at 31° F.

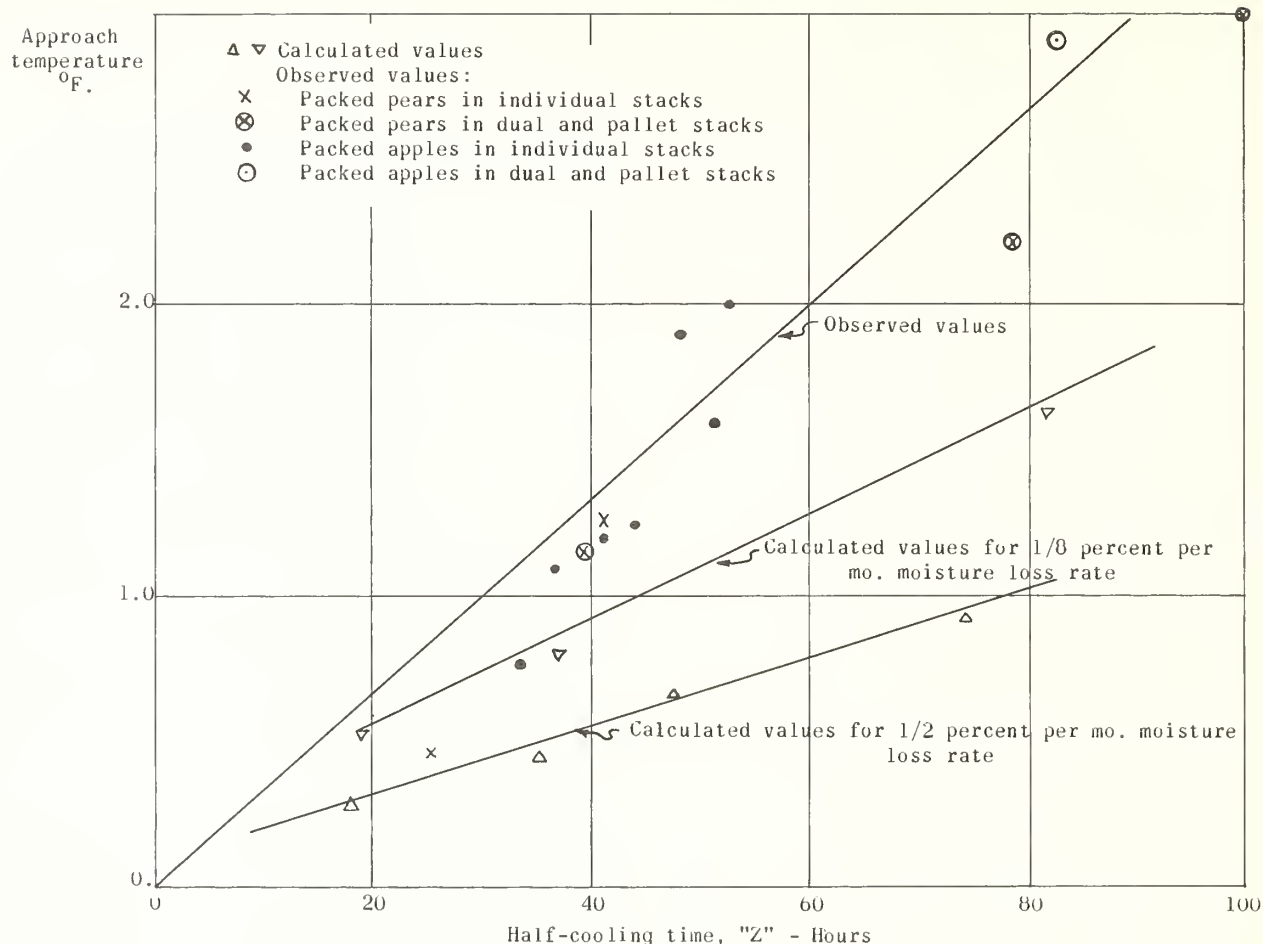


FIGURE 2.—Relationship of approach temperature and half-cooling time for apples and pears and observed values for carton without vents and for wood boxes stacked with sides exposed.

These are the cases for which theoretical values could be readily calculated and, for the most part, are cases where little of the heat is removed by convection.

Figure 3 shows additional experimental values for packed wood boxes, stacked with ends exposed to the main airflow but with some exposure of the sides (the most usual situation with packed wood boxes), and for various types of boxes filled with unpacked fruit. In the latter, convection can be a considerable factor in the cooling. The straight line drawn on figure 2 representing the actual relation between approach temperature and half-cooling time has been transposed to figure 3, where it also makes a fairly valid representation of the relationship.

From figure 3, it is apparent that there is a greater scatter of the points representing unpacked fruit than packed fruit. Part of this is due to the fact that with unpacked fruit the approach temperature is lower, and any slight error in temperature measurement has a greater effect on the approach temperature measured. Also, convection is an important mechanism in cooling in this

situation. The convection currents may be largely self-generated by the fruit heating the air, or they may be induced in part by the air circulation system used in the room. The self-induced currents tend to die out as the fruit approaches the room temperature, whereas the convection due to air circulation through the room will remain. The half-cooling time is determined from observations during the time when self-induced convection currents are of importance, whereas the approach temperature is determined after these currents have largely been eliminated. Therefore, it is reasonable to expect that the approach temperature would be higher in proportion to the half-cooling time for unpacked fruit than packed fruit. Figure 3 shows that most of the values plotted for unpacked fruit fall above the line drawn for packed fruit.

The experimental data confirm the idea that difficulty in cooling fruit due to package characteristics or surface exposure is associated with a higher final difference between fruit temperature and storage room air temperature. Some instances have been noted, with very slow cooling,

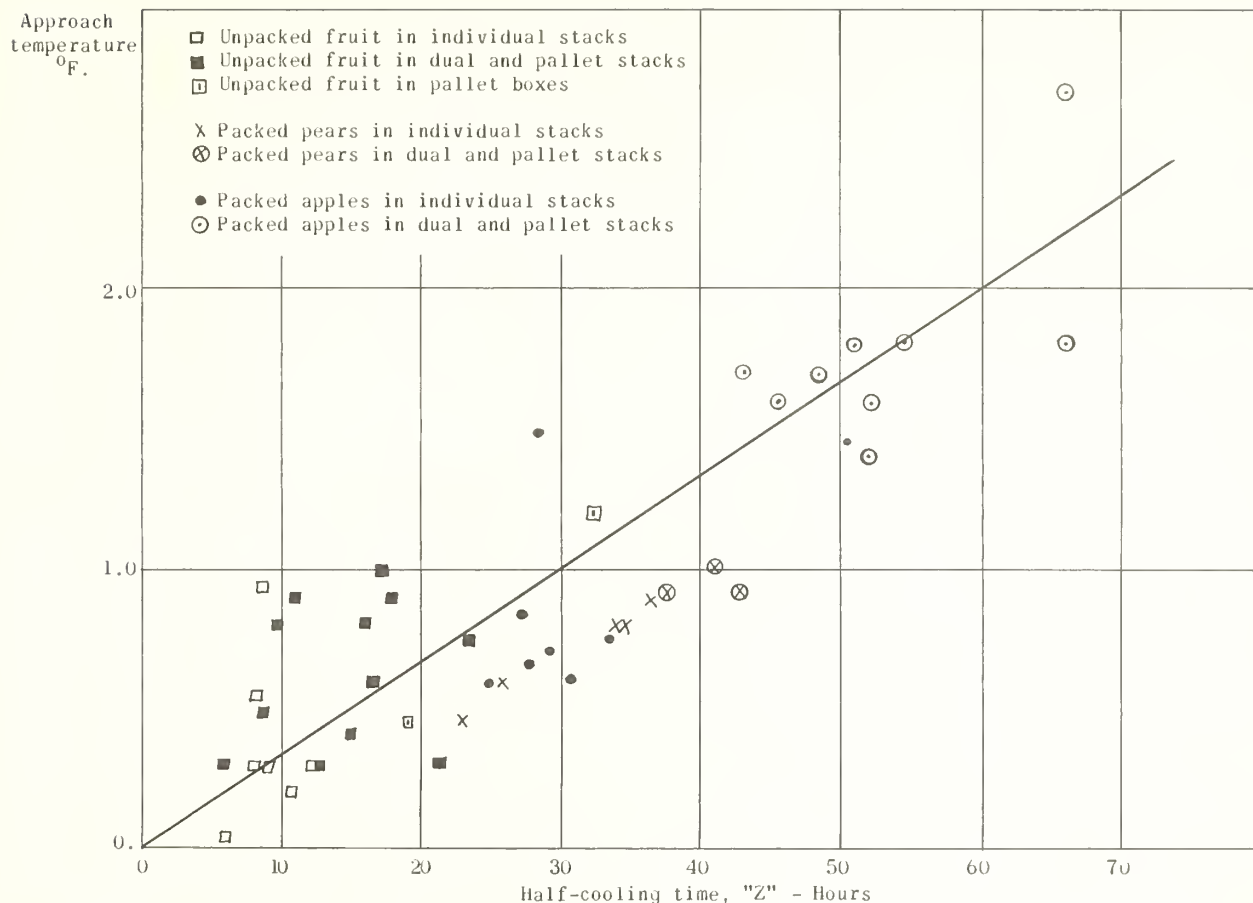


FIGURE 3.—Relationship of approach temperature and half-cooling time for unpacked fruit in boxes and pallet boxes, and for packed fruit in wood boxes stacked with ends exposed and in palletloads.

where this difference was from 2° to 3°. One test was made, that is not included in figures 2 and 3, where approach temperatures of 3° to 4° were observed. In this case, the initial temperature of the fruit entering the room was so low that it did not cool through a sufficient range for reliable determination of a cooling coefficient.

For packed fruit, the relation between approach temperature and half-cooling time approximates the following relation:

$$\text{Approach Temp.} = 0.033 \text{ Half-Cooling Time}$$

$$\text{A.T.} = 0.033 \text{ Z}$$

For unpacked fruit, the relation of approach temperature and half-cooling time is influenced by a number of factors that depend on convection currents through the fruit, and the relationship is less readily evaluated. In most cases, the approach temperature for unpacked fruit does not exceed 1° F. and in many cases it is less than 0.5° F.

Factors Affecting Cooling Performance

Analytical formulas for calculation of cooling coefficients and half-cooling time are presented in the appendix (5). Formulas and charts are available that may be used to check these calculations (4). They were used in a number of cases, and excellent agreement was found between the results of the two calculations.

The formulas and curves can be used to make some estimate of the cooling to be expected with a standard wood box of packed fruit where there is some exposure of the bulged surfaces of the box (4). Wood boxes are cooled from four sides when

the boxes are stacked in rows with both ends exposed, and they are cooled from three sides when two boxes are butted together and one end of each is exposed, as in a stack on a pallet. It seemed reasonable to expect that the heat transfer coefficient from surface to air for the less exposed sides would be less than from the ends, and therefore the calculations were made on such an assumption. Table 4 shows the condition assumed and characteristic cooling time determined for each calculation. In the case of cooling from four sides, the calculated and observed times agree

TABLE 4.—*Calculated cooling coefficients and half-cooling times for apples in standard packed wood boxes using various stacking arrangements and outside surface conductances*

Arrangement	Assumed heat transfer coefficient (h)		Calculated		Remarks
	Ends	Sides	Cooling coefficient (C)	Half-cooling time (Z)	
	<i>Btu./hr./sq. ft./° F. Td.</i>	<i>Btu./hr./sq. ft./° F. Td.</i>	<i>° F./hr./° F. Td.</i>	<i>Hours</i>	
II. Stacked in rows with 2 ends of each box exposed—some exposure of sides due to bulges.	1.0 .5 1.0	0.5 .25 .33	0.032 .024 .028	22 29 25	Either value fits observed results, but $h=1$ and 0.33 seem more likely values.
III. Stacked in double rows with 1 end of each box exposed—some exposure of sides due to bulges.	1.0 1.0	.33 .25	.0214 .0163	33 43	
					This fits observed results best.

best for the case where the heat transfer coefficient from the ends was taken as 1.00 Btu/hr./sq. ft./°F. Td. and that for the sides was 0.33. When boxes are cooled from three surfaces, the values for heat transfer coefficients of 1.00 for ends and 0.25 for sides come close to observed results.

Containers

The foregoing discussion has indicated that the cooling performance may be greatly affected by the container or packaging method, by the stacking method, and to some extent by the air veloc-

TABLE 5.—*Characteristic cooling time, air turnover rate, air velocity, and approach temperature in storages cooling Bartlett pears in cannery lugs*

Plant	Characteristic cooling time Z for stack arrangement			Air turn- over, times per hour	Average air velocity	Ap- proach temper- ature	Air distribution system	Remarks
	Single rows	Stand- ard pal- let	Dual stacks					
	Initial temperatures generally 70° F. and above							
8	Hours	Hours	Hours	Number	F.p.m.	° F.	Reversed air system	Staggered stacks. Ratio $C_R/C_A=0.59$.
7	9. 9	14. 4		10	22		do	
11		10. 8		10. 9		0. 9	High-velocity outlet system	
17	7. 3						Pipe coils and auxiliary	
20	6. 4				10	. 95	Pipe coils	
	Initial temperatures generally 60° to 70° F.							
2	10			7. 5	32		Medium-velocity outlet system	Chimney stacks. Normal pallet stack. Pallet stack covered by large polyethylene bag.
7	9			13. 3	61		Reversed air system	
8	8			7. 5	25		Medium-velocity outlet system	
8		8. 6		10			Reversed air system	
10		18. 4		7. 2			Air distributed from duct at far wall.	
15		9. 2		22. 2		0. 83	Multiple overhead unit system	
21	6				49	. 05	Air distribution from ceiling joist spaces.	
26			7. 8		36	. 5	High-velocity outlet system	
			21. 3	6	18	. 4		
12		{18. 2 35. 7}	{13 }				Medium-velocity outlet system	
	Initial temperatures generally 50° to 60° F.							
22	9. 2			7. 1	37	0. 3	High-velocity outlets, 2 levels with slotted floor between.	

ity past the containers. A great deal of experimental evidence has been gathered illustrating these points.

In tables 5 and 6, the experimental evaluation of cooling performance of unpacked fruit is summarized. These observations show the influence of variations in the container on the cooling of unpacked fruit. The most striking increase in cooling time for unpacked fruit due to the container is encountered when fruit is either picked in boxes with polyethylene liners or when pallet-load-size polyethylene bags are placed over the pallet loads when they are put in storage. The use of a cover over a palletized load of boxes doubles the cooling time (table 5). Individual

unpack boxes with poly liners, handled in dual stacks with industrial clamp trucks, required $3\frac{1}{2}$ times as long to cool as similarly stacked boxes without the liners (table 6). These individual boxes with liners required 50 percent more time to cool than the palletload with the one big cover. The large cover also has the advantage that it may be placed over the load after the load has been in storage for a day or two and most of the heat has been removed.

Only a small quantity of fruit is picked into polyethylene liners at present. The practice may increase with Golden Delicious apples to protect the fruit from shrinkage when there is a delay of

TABLE 6.—Characteristic cooling time, air turnover rate, air velocity, and approach temperature in storages cooling unpacked Anjou pears and apples in apple boxes

Plant	Characteristic cooling time Z for stack arrangement				Air turn-over, times per hour	Average air velocity	Approach temperature	Air distribution system	Remarks
	Single rows	Standard pallet	Dual stacks	Special arrangements					
12	Initial temperatures generally 70° and above.								
	Hours	Hours	Hours	Hours	Number	F.p.m.	° F.	Medium-velocity outlet system	
	-----	17. 4	-----	-----	13	-----	1. 05		
6 18	Initial temperatures generally 60° to 70° F.								
	9. 5	-----	-----	-----	8. 6	31	-----	Reversed air system	
	11. 6	-----	-----	-----	7. 5	40	-----	High-velocity outlet system	
16 27 32	Initial temperatures generally 50° to 60° F.								
	-----	15. 4	-----	-----	11. 8	30	-----	Sidewall supply and return ducts	Special 5-box-wide pallets.
	-----	17. 6	-----	-----	15	51	0. 9	High-velocity outlet system	
	-----	-----	-----	5. 9	8	67	. 3	do	
	Initial temperatures generally 40° to 50° F.								
6 8	8	-----	-----	-----	8. 6	-----	0. 55	Reversed air system	Unpacked fruit picked in polyethylene bags. Special clamptruck loads, 3 and 4 boxes wide.
9	-----	21. 5	-----	-----	10	-----	-----	do	
	-----	23. 4	-----	-----	10	25	. 75	do	
	14	-----	19. 3	-----	8. 6	65	-----	High-velocity outlet system	
13 14	-----	-----	12. 1	-----	8. 6	30	{ . 2 . 3	do	
	10. 6	-----	-----	-----	7. 5	-----	. 3	do	
7	7. 9	-----	-----	-----	5. 0	-----	-----	3-floor slotted floor storage, air supplied at sidewalls and center.	
30	6. 9	-----	-----	-----	-----	-----	-----	Medium-velocity outlet system	
	-----	20. 3	-----	-----	13	26	. 8	Reversed air system	
	-----	-----	16. 4	-----	13. 3	-----	. 6	do	
	-----	-----	54. 1	-----	13. 3	-----	2. 7	do	
22	-----	-----	-----	25	11. 5	19	. 6	do	
22	15. 4	-----	-----	-----	17. 1	73	. 43	Large overhead units without ducts, auxiliary fans in bays where there are no units.	Standard 1-bushel box. 20-bushel box, solid bottom. 20-bushel box, slotted bottom.
	12	-----	-----	32. 4	7. 1	-----	. 33	High-velocity outlet system, 2 levels with slotted floor between.	
	-----	-----	-----	19. 5	7. 1	-----	. 45	do	



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FIGURE 4.—A typical dual stack of cannery lugs handled with industrial clamp-type truck. Note the passages formed at the top of the side of each lug by the cleats.



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FIGURE 5.—A typical dual stack of unpacked apples in standard apple boxes.

2 or 3 months between harvest and packing into polyethylene-lined cartons.

It appears more desirable to use palletload or clamp-truck load cover bags and place them over the loads after the loads have been in storage 2 or 3 days than to use individual picking box liners. Although the procedure requires rehandling of the fruit in storage, the benefits from more rapid cooling are appreciable.

The cannery lug shown in figure 4 has a slight advantage in cooling performance over the apple box in figure 5 as a container for unpacked fruit. When used in single rows, the cannery lugs had a minimum half-cooling time of 6 hours in the tests, and apple boxes had a minimum of 6.9 hours. The maximum half-cooling time for single rows of cannery lugs was 10 hours and for apple boxes 14 hours. When used in palletloads, the fastest and slowest half-cooling times in cannery lugs were 8.6 and 18.4 hours, respectively; the fastest and slowest half-cooling times of unpacked fruit in apple boxes were 15.4 and 23.4 hours. The cannery lug has a cleat at the top which allows a passage about 1 inch high for air to enter the box on both sides. Furthermore, the depth of fruit in a box is less than in an apple box. These two factors may account for the more rapid cooling noted with the lug. No two tests on the two containers are absolutely comparable, but the figures indicate that cooling unpacked fruit in apple boxes

may take 15 to 30 percent longer than in cannery lugs.

Some data are presented in table 6 for plant 22 comparing the cooling of unpacked apples in the standard apple box and in 20-bushel pallet boxes. One pallet box had a slotted bottom, a slot around the sides at the bottom, and solid sides; three other pallet boxes were similar except that the bottoms were solid. All pallet boxes were 4 by 4 by 2 feet deep.

When the cooling is compared with that obtained in several standard bushel boxes placed nearby in single rows, the pallet box with the slotted bottom required over 50 percent longer to cool and the solid-bottomed pallet box required 2½ times the cooling time of the standard box. The performance of the pallet box with the slotted bottom was about the same as was generally obtained with palletloads of standard boxes, but the box with the solid bottom required about 50 percent longer to cool than the longest period required for palletloads of standard boxes. These results indicate that when container size is increased, careful design must be used to avoid excessive cooling time.

Tables 7 and 8 summarize the cooling performance of packed fruit observed in 29 different tests. Many of these observations show how variations in packaging can affect the cooling performance of packed fruit in storage rooms.

TABLE 7.—Characteristic cooling time, air turnover rate, air velocity, and approach temperature in storages cooling packed pears in wood boxes and in other packages

Plant	Characteristic cooling time Z for stack arrangement			Air turnover, times per hour	Average air velocity	Approach temperature	Air distribution system	Remarks
	Single rows	Standard pallet	Dual stacking					
	Hours	Hours	Hours	Number	F.p.m.	° F.		
2	26.9			7.5	48		Medium-velocity outlet system	
12		40.4		13		1.0	do	Airflow crosswise to stack rows.
12		37.2		13		.9	do	Do.
		39.8		13		1.13	do	Packed in single-thickness fiberboard cartons.
23	25.4			6.7		.6	Ceiling outlets and returns in joist spaces.	
				6.7		.8	do	In wood boxes with polyethylene liners.
25	27.7			12			High-velocity outlet system	
21	32.5			6.1	37	.8	Sidewall supply and return system.	
			43.2	6.1	20	.9	do	
28	25.4				10	.46	Vertical circulation down through stacks and out through floor slots.	
	41.2				9	1.24	do	Packed in multithickness fiberboard cartons.
29	25.2				6		Pipe coils in room with auxiliary fans.	
	35				8		do	Packed in single-thickness carton with veneer liner.
	37.5				7		do	Packed in multithickness carton.
8			34.0	less than		.8	Center and sidewall duct supply system.	
			39.5			.9	do	
			100.0		10	3.0	do	Wood boxes with polyethylene liners. Packed in multithickness carton.

The general run of characteristic cooling time observed for pears is slightly less than for apples. For instance, when pears are stacked in single rows the value is generally from 25 to 27 hours, whereas apples in the better locations tested took from 27 to 30 hours. The apple box is 2 inches deeper at the ends, and although it is normally packed with less crown, it averages about 1½ inches greater depth. Since the depth is the minimum dimension of each box, the cooling advantage of the pear box is understandable.

The use of polyethylene liners with packed fruit produces some lengthening of cooling time, but the effect is not nearly so drastic as that on unpacked fruit. In a location where packed pears without liners cooled fairly rapidly (table 7, plant 23), the half-cooling time of boxes with liners was 35 percent greater than that of unlined boxes. In cases where the unlined fruit cooled more slowly, the increase in half-cooling time due to polyethylene liners was only 16 to 20 percent (table 7, plant 8, and table 8, plant 7).

Comparisons of the cooling characteristics of standard wood boxes and fiberboard cartons often involve stacking factors, because stacking may have a greater effect on the exposure of the carton to the cooling medium than on the exposure of wood boxes. If a comparison is limited to instances where the exposure is identical, several tests may be cited. At plant 12, wrapped pears packed in single-thickness fiberboard cartons showed a half-cooling time only 7 percent greater

than similarly packed fruit in wood boxes (table 7). The carton was in a pallet stack arranged with one end exposed to the airflow, and the two sides had some exposure to air because each test carton was incorporated into a palletload of wood boxes. There was more exposure of these cartons than would be normal in entire palletloads of cartons.

At plants 28 and 29 (table 7), the exposure of the various types of containers was equal, and here a multilayer carton containing wrapped pears had a characteristic cooling time that was 50 to 60 percent greater than that of the packed wood box. At plant 29, similarly packed fruit in a single-thickness carton with a veneer liner required 40 percent longer to cool than wrapped pears packed in a wood box. At plants 28 and 29, sides of packages were exposed to the air, and, in this instance, the distance through the standard wood box in the direction of heat flow is about 2 inches less than for the cartons.

The distance from center to heat disposal face is important in movement of heat from a package, and accounts for a great deal of the difference observed in these instances. The rest of the difference must be attributed to the extra thermal resistance encountered as extra layers of fiberboard are added to the ends and sides of the cartons.

In table 8, several comparisons are afforded between wrapped and packed fruit in wood boxes and tray-packed fruit in cartons. This comparison is not as clean-cut as the comparison with

TABLE 8.—Characteristic cooling time, air turnover rate, air velocity, and approach temperature in storages cooling packed apples in wood boxes and in other packages

Plants	Characteristic cooling time Z for fruit stack arrangement				Air turnover, times per hour	Average air velocity	Approach temperature	Air distribution system	Remarks
	Single rows	Standard pallets	Dual stacks	Special arrangements					
1	Hours	Hours	Hours	Hours	Number	F.p.m.	° F.		
		49.6			10.8	47		Long-travel airflow through 2-floor bldg.	
				49.6	10.8	47		do.	Boxes stacked on end, 3 long x 4 wide x 2 high. Standard pallet placed with sides exposed.
				66.0	10.8	47		do.	Special pallet, 3 long x 3 wide x 5 high with sides exposed.
				82.5	10.8	47		do.	Airflow at 45° to stack rows.
5	33.5				13.3	59	0.4	Medium-velocity outlets	
6	28.2				8.6			Reversed air system	
	29.0				8.6		.7	do.	
7	30.0				13.3			do.	
8		54.2			10.0	30		do.	
		66.0			10.0	22	2.7	do.	
9	26.2				8.6	93		High-velocity outlets	
	27.3				8.6		.67	do.	
13	28.2				7.5	45	1.5	do.	
14	30.2				5.0		.6	3-floor slotted floor storage, air supplied at sidewalls and center.	
16		52.0			11.8	38	1.4	Sidewall supply and return ducts.	
19				33.5		53	.76	Pipe coils in room, auxiliary fans, slotted floor.	Boxes stacked with ends butted and slight spaces between sides.
12		82.5			13.0		2.35	Medium-velocity outlets	Most of the locations under cooling unit platform.
		42.8			13.0		1.7	do.	} Airflow crosswise to stack rows.
		45.7			13.0	29	1.6	do.	
		51.0			13.0	32	1.8	do.	Airflow parallel to stack rows.
		66.0			13.0	29	1.8	do.	Do.
		¹ 154.0			13.0	39	3.34	do.	Tray packed in double-thickness cartons.
		¹ 181.0			13.0	39	3.63	do.	Wrapped and packed in extra-heavy cartons.
24	50.6				5.8		1.45	Center supply, side return ducts.	Wood boxes stacked in carton stacks.
	51.0				5.8		1.6	do.	Tray pack in cartons, unperforated trays.
	40.8				5.8		1.2	do.	Tray pack in cartons, perforated trays.
23	47.5				6.7		1.9	Ceiling outlets and returns in joist spaces.	Tray pack—unvented carton, unperforated trays.
	52.5				6.7		2.0	do.	Tray pack—small vents in carton, unperforated trays.
	40.8				6.7		1.6	do.	Tray pack—small vents in carton, perforated trays.
	26.0				6.7		.8	do.	Tray pack—large vents in carton, perforated trays.
7	27.7				13.3		.86	Reversed air system	Wood boxes stacked in carton stacks.
	36.7				13.3		1.11	do.	Cell pack without polyethylene liner.
	44.0				13.3		1.24	do.	Cell pack with polyethylene liner.
30		43.1			17.1		² 1.6	Large overhead units without ducts, auxiliary fans.	
31			54.4		15.8	21	1.8	Multiple overhead units without ducts.	Airflow crosswise to stack rows.

¹ Cooled through a very small range.

² This approach temperature for only a part of the test locations, which had Z=52.2 hours.

the pear packs, because only the top layers of the tray-packed cartons contain wrapped fruit. The results at plant 24 may be used as an instance where wood boxes and tray packs had similar exterior surface exposure. In this case, the standard box was in a single-row stack of cartons and had very little exposure of its bulged sides, and the half-cooling time was much slower than normal for wood boxes stacked in single rows. The tray-packed carton with unperforated trays required about the same cooling time as the wood box, while cartons with perforated trays required about 20 percent less time. However, the cooling time of both cartons was considerably greater than the normal time for wood boxes in a single row.

Since there were no wraps in the lower levels of the tray-packed cartons to interfere with air movement, and because the test mentioned had shown some advantage in providing better internal passages for circulation in the package, a test was made at plant 23 wherein the cooling performances of various modifications of tray-packed cartons were compared (table 8). The cartons with small vents had two $\frac{3}{4}$ - by 2-inch slots in each end; the carton with large vents had two $\frac{3}{4}$ - by 2-inch slots in each end.

There was little difference in the cooling of unvented cartons and those with small vents when unperforated trays were used, and the half-cooling time was similar to that observed at plant 24. When perforated trays were used in cartons with small vents, the cooling time was reduced about 20 percent and was similar to that observed at plant 24 when perforated trays were used in unvented cartons. The combination of the large vents and perforated trays provided a marked improvement in cooling performance. The characteristic cooling time was about half of that required for the cartons with small vents and unperforated trays, and compared favorably with the time normally required for packed wood boxes stacked in single rows. This cooling time was about the same as had been observed for cooling packed pears in similar locations in this storage in a previous test (table 7).

From this experiment, it appears that it is possible to secure cooling performance equal to that obtained in a standard wood box if adequate exterior vents and perforations for internal circulation are provided. This equal performance has been noted under conditions where the cartons had less surface exposure than the wood boxes.

Another container that is of interest is the cell-pack carton, used principally for Golden Delicious apples. The data given in table 8 for the experiment at plant 7 do not provide a simple comparison between the cooling in cell-pack cartons and in wood boxes, because the wood boxes had side exposure as well as end exposure. Although the wood boxes were placed in carton stacks, they were enough smaller than the cartons that they had side exposure. The half-cooling time for the wood boxes is comparable to that observed at other

locations where packed wood boxes were stacked in single rows. Since much of the difference observed in this test seems attributable to difference of exposure, these comparisons will be discussed further in a later section dealing with the effect of stacking methods on cooling performance. However, it appears that the cell-pack container shares characteristics noted for the cartons used for wrapped and packed pears; namely, increase in distance from center to heat disposal face adversely affects the cooling performance, and the use of more layers of fiberboard has a similar effect. There appears to be little opportunity to vent the cell-pack carton to provide better circulation, because of the multiplicity of internal partitions of the wrapped fruit in the cells.

The studies indicate that containers affect cooling in the following ways:

1. By allowing or denying air access to the fruit for cooling by convection. The great difference between the cooling time required for packed and unpacked fruit under similar stacking conditions illustrates this point. A second illustration is the slow cooling of unpacked fruit picked in polyethylene liners.
2. By varying the distance through which heat must be conducted from the center of the container to the exposed surfaces.
3. By imposing varying amounts of thermal resistance to heat flow through the package itself.
4. By shape characteristics which determine how many exposed surfaces the container has for a given stacking procedure. This factor is inseparable from the next main point to be considered in evaluating cooling performance.

Stacking Methods

Utilization of space in a given storage usually determines stacking methods. Occasionally some thought may be given to cooling of the commodity, but generally space utilization and ease of handling are the determining factors.

Boxes

In the older storages using clamp-type two-wheel handtrucks, conveyors, and manual stacking, space was usually left between the box ends so that each box would be accessible to the stacker's hand for grasping, or to the clamps on the truck for setting down or picking up the stack. As handling has become mechanized, there is a greater tendency to handle unit loads two and occasionally three stacks wide and from two to four stacks deep. The effect of larger unit loads on cooling performance varies with the package. When unpacked fruit was cooled, palletloads of pears in cannery lugs had a half-cooling time 50 to 80 percent greater than pears in lugs in individual rows. Palletloads of unpacked apples in apple boxes had about twice the characteristic

cooling time of similar fruit stacked in individual rows. These comparisons are made by taking from tables 5 and 6 the general run of fastest and slowest values shown for characteristic cooling time in the single-row and palletload columns.

The comparison of unit loads handled with clamp-type industrial trucks without pallets versus unit loads handled with forklift trucks on pallets is not clear cut with the data at hand. In table 5, the best record for handling in dual stacks, that is, with clamp-type industrial trucks, is slightly better than any test on standard pallets, and the poorest is slower than any test on pallets. The same thing is true of the results in table 6 if the one test at plant 7 is included, as it should be, among the tests using clamp-type industrial trucks.

From a practical standpoint, the slowest cooling found with any stacking arrangement for unpacked fruit in bushel boxes, excepting those locations where polyethylene liners were used, is as good as the best cooling experienced with packed fruit. For this reason, it has been felt that the cooling performance experienced in larger unit loads of unpacked fruit was acceptable, even though it was slower than in individual rows. The data available on 20-bushel pallet boxes suggest that differences in construction of the boxes may cause considerable difference in cooling performance. Performance slower than that normally experienced in packed boxes may be associated with some types of construction.

When packed wood boxes are cooled in palletloads, the characteristic cooling time is about 60 to 100 percent greater than when they are cooled in single rows. Normal half-cooling time in single stacks appears to be in the order of 25 to 30 hours, whereas 40 to 66 hours have been required in standard pallet stacks.

Table 8 shows some observations on the cooling of special pallet stacks of wood boxes. When the boxes were stacked on end and arranged three long, four wide, and two high, the cooling was about the same as for a normal palletload (table 8, plant 1). When special palletloads were made up three wide and two and three long and placed with sides of boxes exposed to the space between palletloads, the cooling was slower than in the normal load, and in the three-long load was about 60 percent slower. With this arrangement, very little air flows through the pallet horizontally, and the center position is a considerable distance from the edge of the pile.

One test was made in a plant where packed wood boxes were stacked with ends butted together and the air circulation space consisted only of the chimneys formed by the bulged surfaces of the boxes. A slotted floor and overhead pipe coils provided a pattern of vertical circulation in this storage (table 8, plant 18). The characteristic cooling time was only about 10 to 15 percent greater in this instance than in most storages where boxes were stacked in individual

rows. The air velocity through the air spaces between boxes was higher than most of the observed velocities noted in table 8. However, the ratio of the cooling coefficient, determined with respect to air adjacent to the boxes, to the coefficient determined with respect to average room air temperature was much lower than usual. This is another way of saying that the air passing the boxes was substantially warmer than room temperature during the major part of the cooling period and that better cooling could be accomplished if this ratio were near to 1 instead of the value of 0.53 observed. Thus it appears that the box-cooling characteristics were not greatly harmed by this method of stacking, but the method of stacking did cut down the amount of air that passed the boxes.

Cartons

In many cases, the fact that cartons have flat sides and so can be stacked closer than wood boxes is an important factor in the stacking arrangement. Table 7 shows that the multithickness carton tested at plants 28 and 29 took 50 to 60 percent longer to cool when the exposure was about the same as that of the wood box, but when placed in dual stacks, at plant 8, where the tight stacking characteristics of the carton cut exposure to a minimum, the characteristic cooling time was three times as great. A report is available in greater detail on this test (12), but the essential point here is that the package characteristics are such that a very unfavorable stacking pattern may be selected, and, in turn, extremely poor cooling may result. This is substantiated by the results in table 8 for plant 12 in the tests comparing cooling of wood boxes and two types of cartons in palletloads. In this test, the fruit in the cartons cooled through a rather small range, and the characteristic cooling time values determined are open to some question, since they may be measurably influenced by the heat of respiration. However, the approach temperatures for the fruit in cartons show that the cooling coefficient is very low. In this case, palletization of cartons results in a very tight stack with only one end per box exposed, and the cooling performance is most seriously penalized. Primarily, this penalty arises from the stacking arrangement, and part of the remedy lies in modifying the stacking arrangement so that more than an end of each carton is exposed to the air.

Later in this report, it will be shown that in storage rooms where the fruit was stacked so that the rows and the spaces between rows were parallel to the normal airflow pattern, variation in holding temperatures at various points in the room was less than in rooms where airflow and stack rows were not parallel. An attempt was made to see if this relation held true during the initial cooling period, but a clear demonstration of this point could not be made. At plant 12 (table 8), the

opposite was observed. On the other hand, at plants 5 and 31 (table 8), where the fruit rows and the airflow pattern were not parallel, somewhat slower than average cooling was obtained than was normal, in one case for individual stacks, and in the other case for stacks handled in unit loads (two stacks wide and three long). In both of these instances, the amount of air circulated in the storages was greater than in most locations tested.

The principal effect of stacking arrangement on cooling performance seems to be dimensional; that is, stacking arrangements that increase the distance through which heat must be conducted from the center of the pile to an exposed surface increase the characteristic cooling time. This appears to be true even with unpacked fruit, where convection is a considerable factor in cooling.

Air Velocity

The experimental observations relating air velocity and cooling performance are quite unsatisfactory. Observations could be made only at those locations where there was enough headroom above the stacks to drop the sensing element of the air meter down to the position of the test boxes. As a result, air velocity measurements are available for only about half of the tests. In tables 5 to 8, inclusive, data have been included giving the air turnover in the storage in number of times the air circulates per hour. This figure is obtained by dividing 60 by the empty volume of the usable portion of the storage and multiplying this figure by the volume of air circulated. Although this is a convenient index to judge the air circulation capacity of one storage against another, it does not necessarily follow that air velocities past test locations are proportional to this index. Induced secondary circulation, air bypassing the stacks, and inequalities of distribution all play a part in determining the air quantities passing the test locations.

Study of the data presented in tables 5 through 8 do justify, however, the general conclusions that with unpacked fruit there are definite instances where the shortest characteristic cooling time is associated with the higher air velocities, and that the slowest cooling is associated with one of the slowest velocities. These effects are noted in table 5 for plants 21 and 26, and in table 6 for plants 7, 30, and 32. In the cooling of packed fruit, there are some instances where fairly rapid cooling is associated with the higher air velocities, but there are other instances where similar cooling performance has been observed with much lower velocities. From these observations, we may conclude that air velocity is a more significant variable in the cooling of unpacked fruit than it is in the cooling of packed fruit.

When results of individual tests are studied, it is generally true that the slowest cooling takes place in those locations where air velocity is very slow (20 f.p.m. or less) and the most rapid cooling

takes place in those locations where high velocities (in the order of 100 f.p.m.) have been measured. However, for velocities in between 20 and 100 f.p.m., the correlation of cooling performance and air velocity cannot be claimed with these data.

All air velocities were measured between stacks, and no attempt was made to measure air velocity within the containers. Probably such a test would not be justified in the case of packed fruit, because it appears reasonable that the velocity would be very low. However, it must be pointed out that, with unpacked fruit, particularly during the first several hours of cooling, the air velocity through the container may be appreciable. Where there is sufficient headroom available, it is possible to determine which fruit has recently been placed in a storage simply by walking around over the stacks. Above the stacks recently introduced into storage, a warm updraft is appreciable. After these same stacks have been in storage several days, warm air currents rising from the stacks no longer can be detected.

A further observation regarding the role of convection in cooling loose fruit is that during the cooling process the positions near the bottom of the stack cool more rapidly than those near the top, but often the point near the top of the stack will ultimately come to a lower final temperature than the bottom. Such an instance is illustrated in figure 6.

At first the warm air currents rising through the stack keep the upper part from cooling as rapidly as the bottom because the effective cooling medium is warmer. As the bottom of the stack loses heat and can no longer heat the air, cooler air passes the tops of the stacks and finally, because the tops have slightly better exposure to the cooling medium, they drop to a lower temperature. This phenomenon was not observed in any of the packed fruit cooling tests. With packed fruit, containers in locations that cool most rapidly reach a final temperature lower than those in the more slowly cooled locations.

None of the plants tested showed an average air velocity for all test locations in excess of 100 f.p.m. In certain plants, there were individual locations where air velocity exceeded 100 f.p.m., but in these plants lower velocities at other locations brought down the average. In some plants, the average was less than 10 f.p.m. It must be remembered that there is more difficulty in making a reliable measurement of low air velocity than in measuring higher speeds. The low-velocity measurements should be regarded only as approximations.

Air Distribution Pattern

Most of the foregoing discussion has been based on the average characteristic cooling time determined at a given test location. To explore the relation between cooling performance and air distribution, data are presented showing the varia-

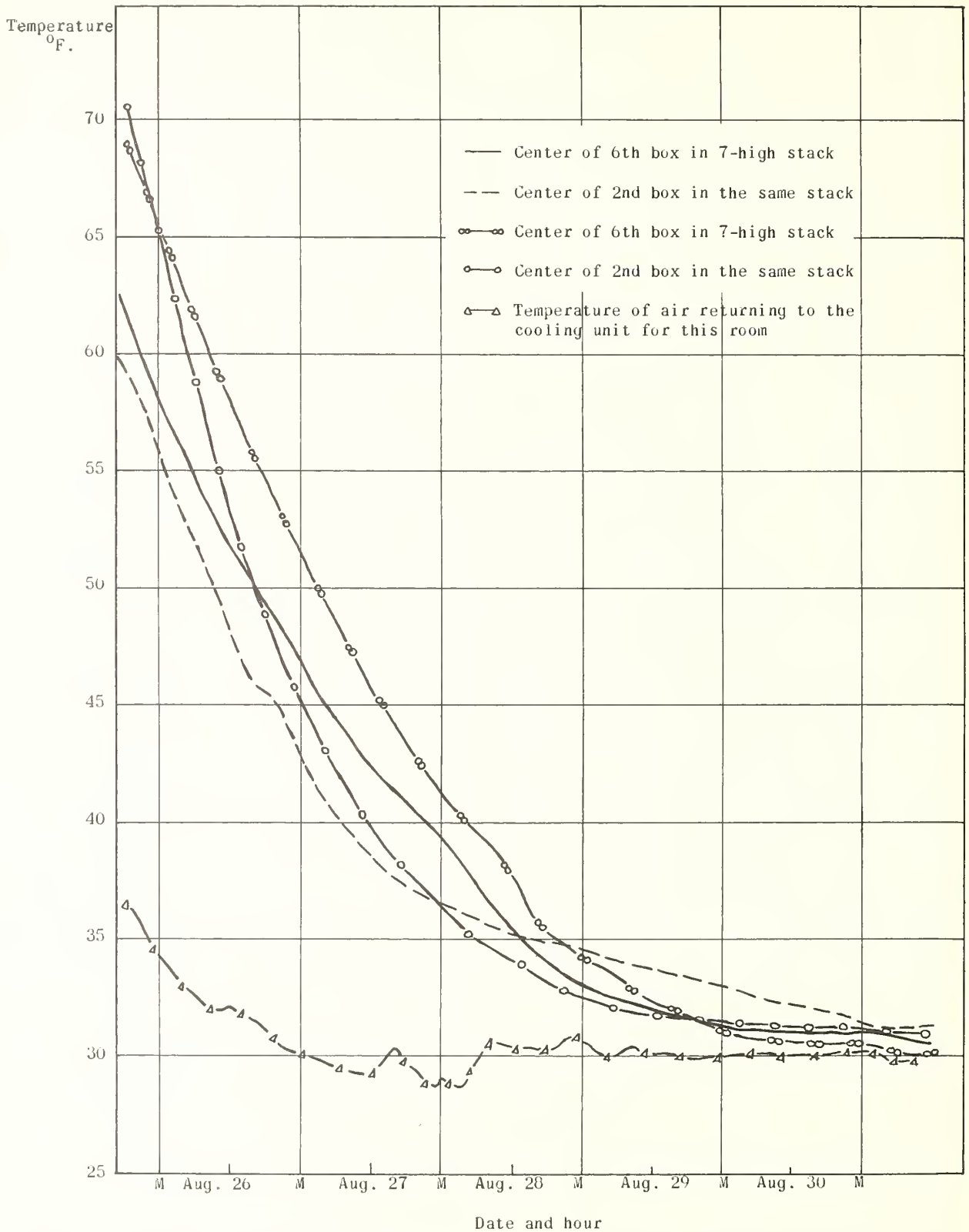
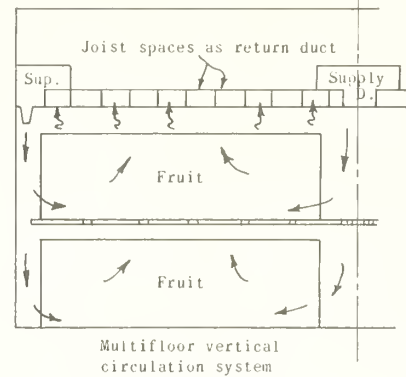
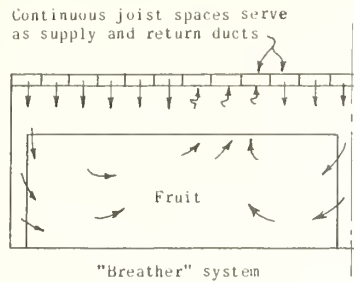
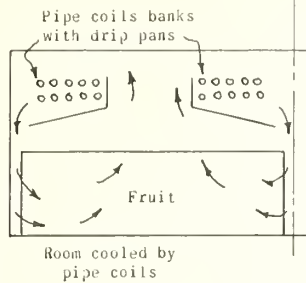


FIGURE 6.—Temperature of unpacked pears in cannery lugs at plant 26, showing how pears in top positions cooled slower but came to a final temperature lower than those in bottom positions.

VERTICAL CIRCULATION SYSTEMS



HORIZONTAL CIRCULATION SYSTEMS

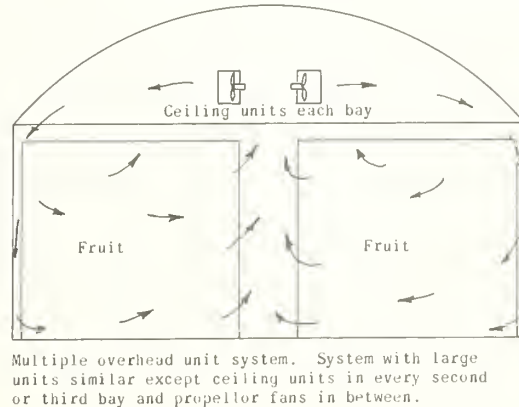
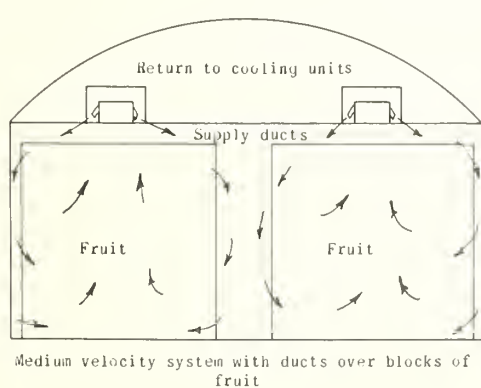
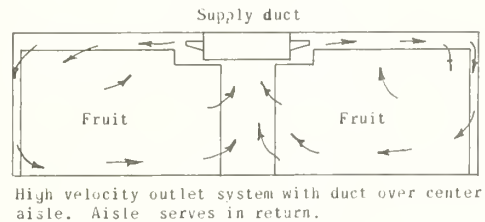
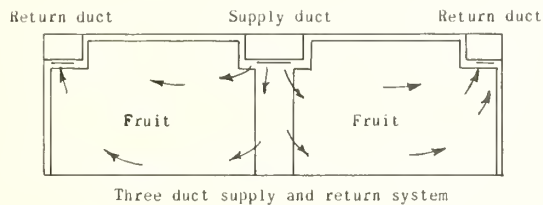
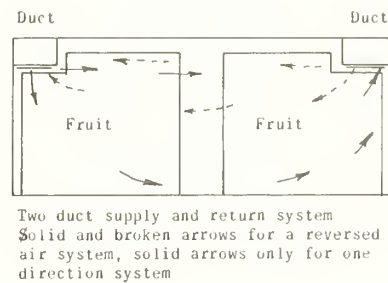
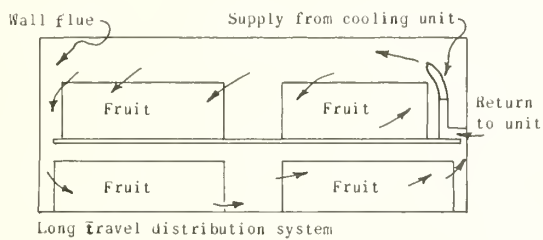


FIGURE 7.—Sketches of various types of air distribution systems.

tion in cooling performance at different test locations in a given plant.

Since it has been shown that both containers and stacking methods have great influence on the cooling performance, it follows that valid comparison of performance of different air distribution systems must be made on the basis of similar containers and stacking methods.

Air Circulation Systems

Before presenting observations, some discussion of the types of air circulation systems encountered and the general pattern of distribution from them is needed. Circulation systems may be classified in several ways. For instance, there are forced circulation systems and natural circulation systems and mixtures of the two. The first type is represented by any system using fans to force air through cooling surfaces of various types where there is some measurable resistance to flow. The same circulating device may also distribute the air through the storage from a system of ductwork. The second type of system is represented by pipe coils or plate evaporators placed in the room to set up a natural air circulation. Often this circulation is augmented by auxiliary fans, which exemplify the third type of system mentioned.

Air circulation systems also may be classified by the direction of movement of primary air circulated by the system; the direction may be basically a vertical or a horizontal movement across the room (fig. 7).

Natural convection systems produce basically vertical circulation. This is true even though some horizontal movement can be obtained by proper baffling and coil location (fig. 8).

Certain forced circulation systems also are basically vertical systems. The so-called "breather" system, which has been installed in a number of

plants in the Pacific Northwest, conducts air from a main supply duct through small ducts created by sealing the bottom of joists and using the spaces between joists as ducts (fig. 9). Outlets from these spaces are placed at various intervals. Adjoining joist spaces are used as returns. There is no general circulation across the room, but only a vertical circulation down from the outlets and back up to the adjacent group of returns. In reality, the circulation is not much different from that obtained with a pipe coil system.

A modification of this system is sometimes used in multifloor storages where the floors between are slotted and the several levels comprise one circulation area (fig. 10). In such a case, air may be discharged down the side walls and down the center aisle and return up through the stacks of fruit. This system requires more horizontal movement of air than the other vertical circulation systems, but the horizontal travel is rarely more than 25 feet. The system may be provided with high-velocity outlets and aspirate a substantial secondary circulation into the primary air supply.

Forced draft systems where the air movement is basically horizontal through the room fall into two general types: First, where outlet velocities from the ducts are fairly low, secondary aspiration is not great, the supply openings do not primarily determine the direction of airflow, but instead the arrangement and adjustment of return duct openings is important in determining the airflow pattern; second, where outlet velocities are medium, 800 to 1,200 f.p.m., or high, 1,500 to 3,000 f.p.m., and secondary circulation is a great factor in the performance of the system. These



BN-11794-X

FIGURE 8.—Storage room cooled by banks of pipe coils with drip pans beneath to catch moisture during defrosting.



BN-11795-X

FIGURE 9.—Storage room with "breather" circulation system. Supply outlets from ducts formed by joist spaces shown in foreground with baffle covers. Return openings to ducts formed by joist spaces in background without covers.



BN-11796-X

FIGURE 10.—Multifloor storage equipped with a vertical circulation system, showing openings from ducts above top floor. Supply openings with outlet nozzles along wall. Center supply openings are the large shuttered openings beside nearest electric light service conduit. Shuttered return opening in middle area. Grilled floor over aisle in foreground. Diagonal slotted floor in stacking area.

latter systems usually direct the supply of air in such a manner as to achieve the desired pattern of distribution and use the aisles in the room as return passages.

Several forms of low-velocity outlet systems with return ducts are found where air travel is principally horizontal. In one type, air is discharged into a center aisle and travels to each sidewall, where it is picked up in return ducts (fig. 11). Occasionally such systems supply air at the sidewalls and return it at the center, but such a system was not among those tested.



BN-11797-X

FIGURE 11.—Storage room equipped with a three-duct supply and return system, showing center supply duct with small openings at ceiling and large openings in bottom of duct. Return duct along one wall, with openings similar to those in the supply duct. Similar return duct on other sidewall not shown.



BN-11798-X

FIGURE 12.—A storage room with a two-duct supply and return system. Supply duct shown over aisle, with large opening in bottom of duct for discharging air into aisle. Return duct on opposite wall is not shown.

Another type has the supply duct along one side of the room and the return duct along the other side of the room (fig. 12). A modification of this is the reversed air system, wherein a set of dampers is automatically positioned so that air is supplied from the left side of the room and returned from the right for a set period (usually 1 hour) and then is supplied from the right side and returned from the left. Occasionally this type of operation is achieved by reversing fans rather than by damper manipulation. Hukill and Wooten (8) described this system in considerable detail. Tables 5 through 8 indicate that a large number of the plants tested had a reversed air distribution system.

Medium- and high-velocity outlet systems, where return ducts are either very short or nonexistent, take several forms. The most distinguishing features of the different forms are the outlet construction and the location of the supply duct with respect to aisles and sidewalls. Usually the duct is above a center aisle and the air discharges across the ceiling to the sidewalls, passes down the walls, and comes back to the aisle through the stacks of fruit (fig. 13). Occasionally, in very wide rooms, two ducts may be used, discharging to the sidewalls and to the center, where either a diverter on the ceiling or the action of the two airstreams colliding forces the air down and back through the fruit. Some systems of this general type are installed with the ducts above a block of fruit rather than above the aisles. The return circulation in such cases is somewhat hampered.

The medium-velocity systems may be provided with special duct outlets or with openings or slots in the ducts (fig. 14). The high-velocity



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FIGURE 13.—A high-velocity outlet distribution system with duct over center aisle. Outlet nozzles shown blow air to sidewall and back through fruit.

systems are always provided with some type of discharge nozzle for efficient conversion of the pressure energy in the duct to velocity energy in the emergent airstream.

Another system which distributes air in the same manner as the medium- and high-velocity outlet systems with horizontal travel is the multiple overhead unit system (fig. 15). Here, separate cooling units may be placed in the overhead space above the aisle and arranged to blow to the side walls, creating a pattern of circulation and aspirating a quantity of secondary air in the same manner as the high-velocity outlet system. Sometimes one or two pairs of units are used in each 20-foot section of the building; in other cases, units of larger capacity are used in every second or third section of the building, and air is



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FIGURE 15. A storage room equipped with a system of multiple overhead units in each bay.

diverted slightly sideways to cover the sections where no cooling units are located (fig. 16).

In some of these systems, auxiliary fans are placed above the aisle in the sections without cool-



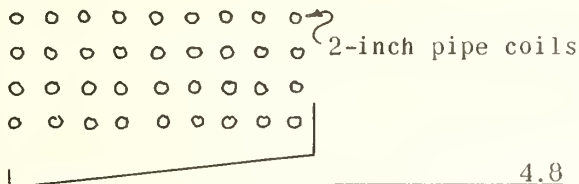
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FIGURE 14.—A medium-velocity outlet distribution system in a palletized storage, with supply duct located above a block of fruit.



BN-11802-X

FIGURE 16.—Rooms equipped with these large-capacity overhead refrigeration units have booster fans in bays between units to provide adequate air circulation.



CL of building

						4.8	5.9				8.4		6.0
	14.4		11.7			X	X				X		X
	X		X			13.4	14.5				8.4		10.4
	17.5		23.3										
	7.3		11.4			7.1	11.3				8.6		5.1
	X		X			X	X				X		X
	8.5		13.7			14	21				14.4		7.6

Z for test boxes at location X

Upper figure "Z" in hours determined with respect to adjacent air temperature.

Lower figure "Z" in hours determined with respect to room air temperature.

FIGURE 17.—Cooling Bartlett pears in cannery lugs in individual stacks in storage room with pipe coils, plant 20.

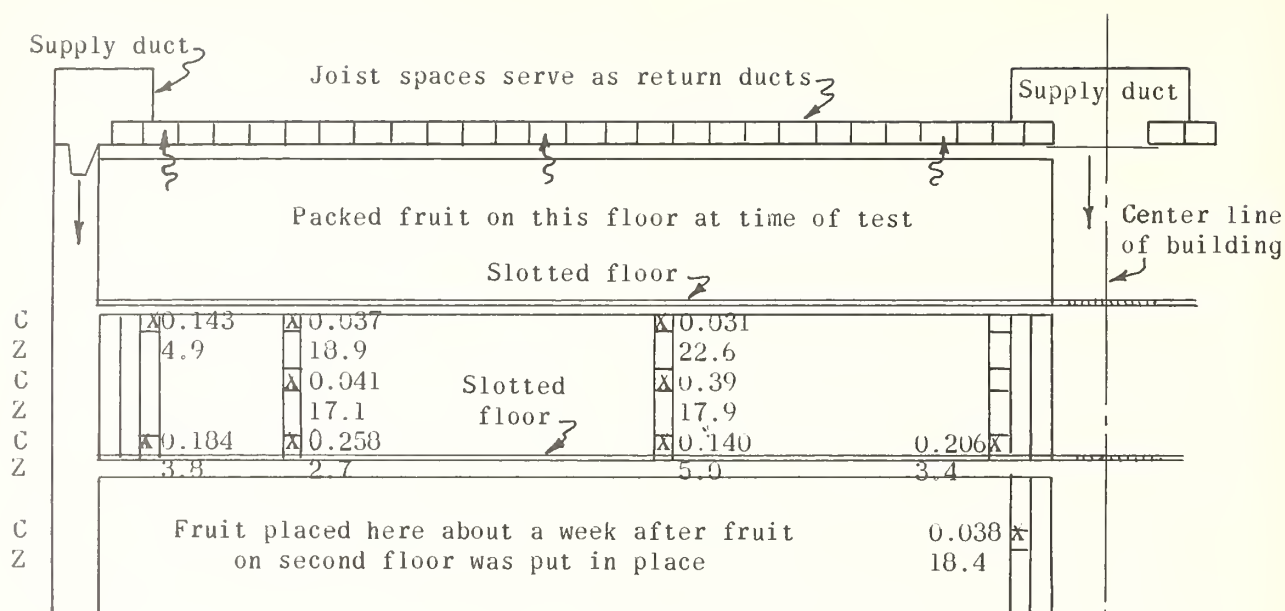
ing units, to circulate air to the sidewalls and maintain the same general pattern of circulation as in those sections where cooling units are installed. Figure 7 is a diagram of each of the systems of air distribution discussed, and figures 8 through 16 are photographs of typical installations of these various types.

The cooling pattern and performance of the various types of air distribution systems are best illustrated by a series of sketches. The first of these portrays the cooling of unpacked fruit in storages representing the various systems, and the second illustrates the cooling of packed fruit with various systems. Wherever air velocity measurements are available, they are indicated on the drawings. Also noted are the warmest and coldest fruit locations indicated by observations during the storage period.

Figure 17 shows the pattern of cooling pears in cannery lugs for the various test locations at plant 20 (table 5), which is cooled by pipe coils. In addition to the characteristic cooling time determined with respect to the air adjacent to the test box location, a value is shown for the characteristic cooling time determined with respect to room tem-

perature. The two sets of values are shown here because there is considerable difference between the two. This difference indicates that the air among the stacks is considerably warmer than the room air during the cooling period. The extent of the difference may be gaged by the ratio of the two values at a given location. The cooling time observed at the various locations is quite variable, and there does not appear to be any systematic variation. Air velocities between stacks were measured after the fruit was cooled, and were quite low; they have been omitted from the chart because it was felt that, in view of the rapid cooling experienced, convection current must have been much stronger when the fruit was warm.

Figure 18 shows a storage room using a forced vertical circulation system. In this system also, there is a great variation in the cooling performance at different locations, but the variation is fairly systematic. In all cases, the bottom boxes on the second floor in test stacks cooled rapidly, but most of the middle and top boxes cooled rather slowly. When these stacks on the second floor were placed, the floor below was unoccupied and there was a good source of cold air below the



Z in hours and cooling coefficient, C, for locations marked X. Z was determined from conversion of the average of the cooling coefficients

Average cooling coefficients, C, for:

Top boxes	0.070
5th boxes	0.040
Bottom boxes	0.197
2nd floor	0.102

Corresponding half-cooling time, "Z," for second floor location = 6.9 hr.

FIGURE 18.—Cooling unpacked apples in standard apple boxes in individual stacks in storage room using forced vertical circulation, plant 14.

bottom boxes to come up through them and cool them rapidly. As this air moved up through the boxes, it became warm and was not a very effective heat removal agent. Since the cooling performance is calculated with respect to the air outside the boxes rather than the air passing through the boxes, the cooling performance for the upper boxes is penalized considerably. The results for the stack on the bottom floor indicated that the opportunity for air to enter the bottom box on this floor was not as good as on the second floor.

Figure 19 shows the cooling performance pattern for a storage where the airflow is horizontal from a supply duct on one side of the room to a return duct on the opposite side. Fruit is handled in 36-box palletloads stacked 2 palletloads high. Here the lower palletload tends to cool more rapidly than the upper loads, and most rapid cooling in the lower pallets is near the aisle, which also serves as a supply air plenum. Less variation of cooling performance is apparent here than in the previously illustrated storage.

Figure 20 shows the performance pattern obtained in a large reversed-air palletized storage.

For the most part, the lower boxes cooled more rapidly and the upper pallet positions near the center aisle cooled most slowly. Generally, air velocity at the lower pallet level was greater than at the upper pallet level.

Figure 21 illustrates the results of two tests in the same palletized storage using a medium-velocity outlet system with ducts above the block of fruit. In one case, unpacked Anjou pears were cooled in standard apple boxes and were stacked only two palletloads high. In the other test, unpacked apples were stacked three palletloads high. In all cases in the first test, the boxes in the bottom palletload cooled faster than those in the top palletload. The initial fruit temperature for this test was above 70° F., and the effect of convection up through the stacks would explain this situation. The apple cooling test was performed later in the season when initial fruit temperatures were between 40° and 50° F. Here the results were more variable and certain top locations that received a direct blast of air from the outlets cooled quite rapidly, whereas other top locations near and under the ducts cooled

Supply duct										Return duct
↗ ↘										↗ ↘
27th row	from E. end	15.5	18.8			23.			17.3	
18th row	from E. end					21.1		15.3		17.3
27th row	from E. end	9.3	12.1			13.3			15.2	
18th row	from E. end					14.2		17.3		17.1

Z in hours for center boxes in upper and lower pallet load in stack and row locations in room as indicated.

Average cooling coefficient for above locations = 0.0454
Corresponding half-cooling time, "Z" = 15.4 hr.

FIGURE 19.—Cooling unpacked apples in palletloads of standard boxes, plant 16.

Duct								Duct							
							Z (hr)	39.5	29			26.2	30	18.3	24.5
							Air velocity (fpm)	20	8			27	7	16	22
						Position in storage with respect to E. end of building		5th row	15th row			15th row	23rd row	5th row	23rd row
							Z (hr)	20.2	23.8			19.9	19.9	22	17.9
							Air velocity (fpm)	50	15			24	20	25	48

Z and air velocities for center boxes in upper and lower pallet loads in stack and row position in room as indicated.

Average cooling coefficient for above locations = 0.0299
Corresponding half-cooling time, "Z" = 23.4 hr.

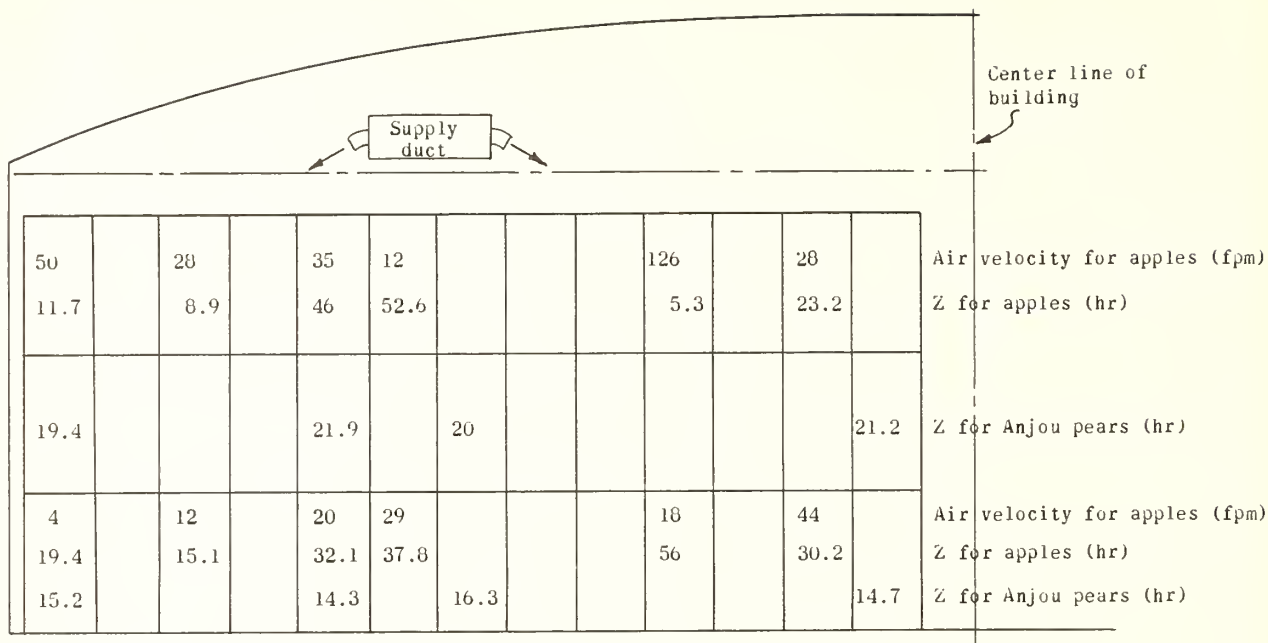
FIGURE 20.—Cooling unpacked apples in palletloads of standard apple boxes in storage room using a reversed-air system, plant 8.

very slowly. Bottom locations in the area beneath or near the ducts cooled more slowly than locations at the front or rear of the row. The air velocity measurements may be correlated with cooling performance in some locations, but not in all instances.

Figure 22 illustrates the performance of a high-velocity outlet system at plant 18, where the ducts are located above the aisles, but more than one duct and aisle are required because of

the room width. Here the lower boxes tend to cool more rapidly than the upper boxes, and the slowest cooling position is the upper position near the aisle. This situation is characteristic of this circulation pattern.

Figure 23 shows the pattern observed in plant 15, where unpacked pears were cooled in cannery lugs arranged in chimney stacks on pallets. Cooling was supplied by multiple overhead units located in each bay. Except for two top pallet

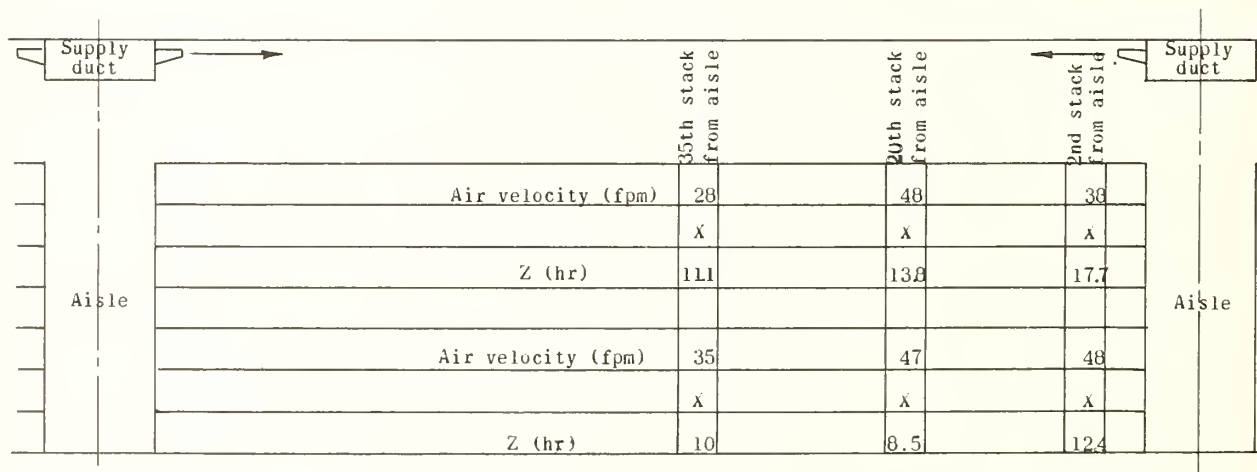


Z for test cooling of unpacked Anjou pears in apple boxes stacked only two pallet loads high, and Z and air velocity for later test cooling of unpacked apples in apple boxes stacked three pallets high.

Average cooling coefficient for test on unpacked Anjou pears = 0.0402
Corresponding half-cooling time, "Z" = 17.4 hr.

Average cooling coefficient for test on unpacked apples = 0.0345
Corresponding half-cooling time, "Z" = 20.3 hr.

FIGURE 21.—Cooling unpacked fruit stacked in palletloads of standard apple boxes with stack rows parallel to direction of airflow, plant 12.



Air velocity and Z at test locations marked X

Average cooling coefficient for these locations = 0.0602
Corresponding half-cooling time, "Z" = 11.6 hr.

FIGURE 22.—Cooling unpacked apples in standard apple boxes in individual stacks in storage room using high-velocity forced horizontal circulation of air, plant 18.

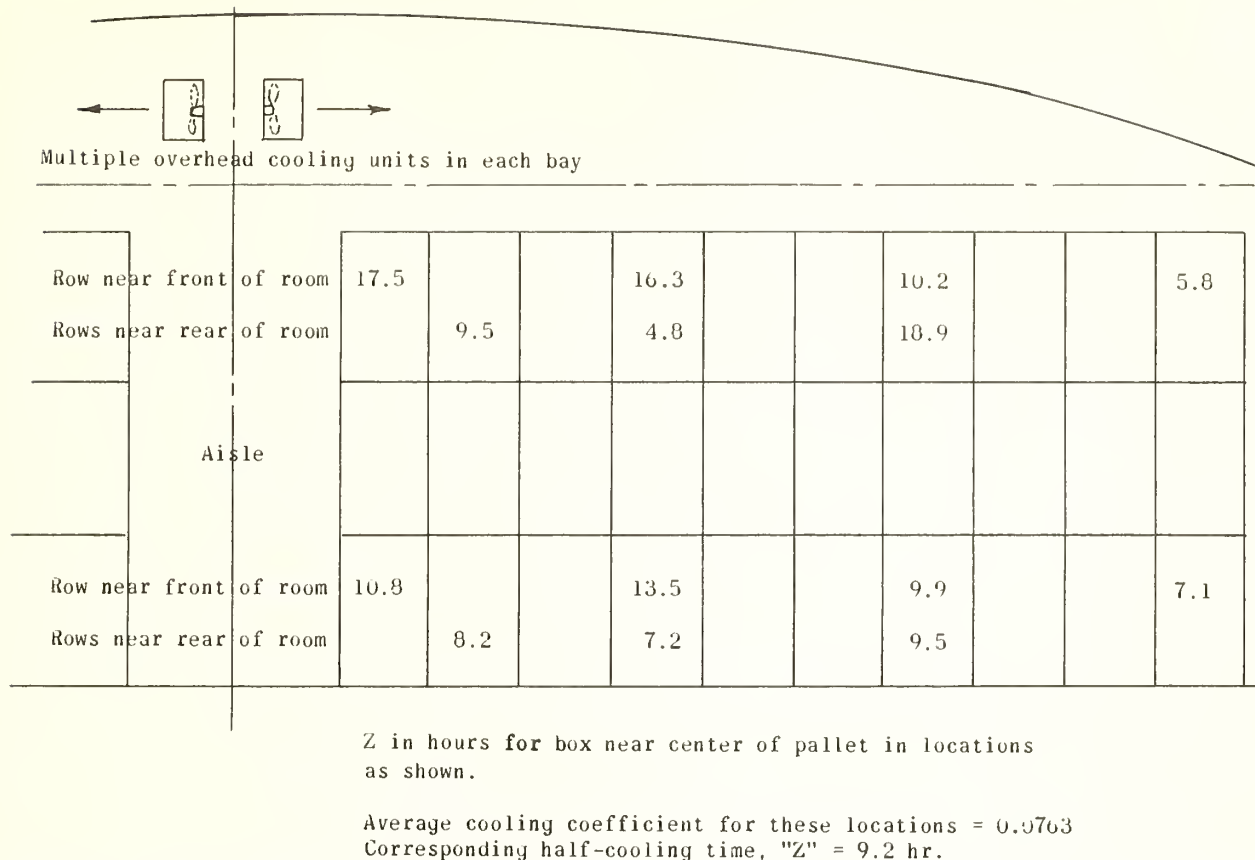


FIGURE 23.—Cooling unpacked Bartlett pears in palletloads of cannery lugs in storage room using multiple overhead cooling units, plant 15.

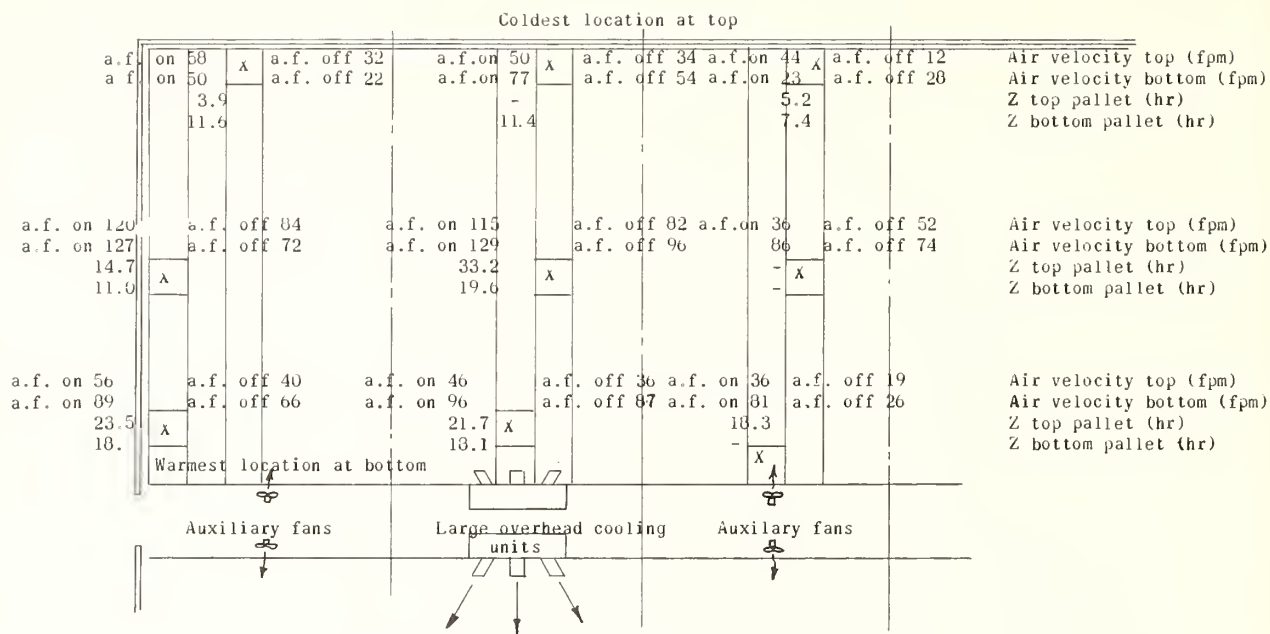
positions, where supply air blew directly on the load, the bottom positions cooled more rapidly and the upper positions on the aisle were slow-cooling positions. The values for the stacks in the row near the rear of the room show some deviation from this pattern. At this point, the roof cuts down, the cooling units are mounted lower in the overhead space, and there is some constriction in the airflow to the back of the row. The top pallet that was four stacks back from the aisle appeared to have received a direct blast of air. The top pallet seven stacks back was located in a row under a truss and seemed to be somewhat blocked off from the air supply.

Figure 24 shows the cooling pattern observed at plant 30 when palletloads of unpacked apples were cooled with a system of large overhead cooling units and auxiliary fans to maintain circulation in bays not provided with cooling units. Here the top pallet position at the rear of the row received a direct air blast and cooled most rapidly. In other locations, the bottom pallet positions cooled more rapidly.

Two sets of air velocities are shown for each test position; one, when the cooling unit fans and auxiliary fans were operating, and the other, when only the cooling unit fans were operating. When this test was conducted, the cooling was performed with the auxiliary fans in operation.

At the end of 9 days, the warmest test location was less than 2° F. higher than the coldest location. The auxiliary fans were then stopped for 4 days, and during this time the warmest fruit was from 3 to 3½° warmer than that in the coldest test location. Based upon this experience, it is recommended that in this type of system the auxiliary fans should operate continuously.

In most of the storages, when unpacked fruit was cooled, the bottom containers cooled more rapidly than the top ones and this is attributed to convection through the stacks. In a few cases, top containers receiving a direct air blast cooled quite rapidly, but these were not representative of a majority of the locations in the room. Great variations of cooling performance were observed at different locations in the same room with unpacked fruit. Usually this was because certain positions were exposed to abnormally high rates of airflow through the containers. Other experimental work (11) has established that, if individual fruits can be exposed to sufficient flow of air to take the heat away nearly as fast as it can be conducted from the interior to the surface of the fruit, the half-cooling time is something less than an hour rather than 6 to 25 hours as observed in these tests. Individual boxes may be favorably exposed and tend toward the performance experienced with freely exposed fruit.



Plan of test locations showing air velocities at top and bottom of stacks with auxiliary fans (a.f.) on and off, Z for top and bottom position (auxiliary fans on during cooling period), and warmest and coldest positions at end of test period.

Average cooling coefficient for these locations = 0.0455
Corresponding half-cooling time, "Z" = 15.4 hr.

FIGURE 24.—Cooling unpacked apples in standard wood boxes stacked in palletloads in storage room using large overhead cooling units and auxiliary fans, plant 30.

Illustrations of cooling patterns for packed fruit in storages using various types of air distribution systems show less variation in cooling performance, and in many cases the pattern of cooling is somewhat different because there is no convection effect through the stack.

Figure 25 shows the pattern observed when cooling packed apples in plant 19, cooled by pipe coils, where a vertical circulation pattern existed. Cooling performances with respect to adjacent air temperature and with respect to room air temperature are shown in this instance because there was such a large difference between the two values. The characteristic cooling time calculated with respect to room temperature was less for the bottom locations than for the top. When performance was calculated with respect to adjacent air temperature, top or bottom location was not associated with rapidity of cooling; however, the position near the back wall seemed to cool faster by either index, and it is notable that air velocity through the stacks was much greater here than in the other locations. In this storage, a slotted floor was provided and cold air dropped from the coils to the floor, entered this space, and then passed up through the stacks. Better access to the space beneath the floor at the sidewalls than at the aisle explains the superior performance near the sidewall.

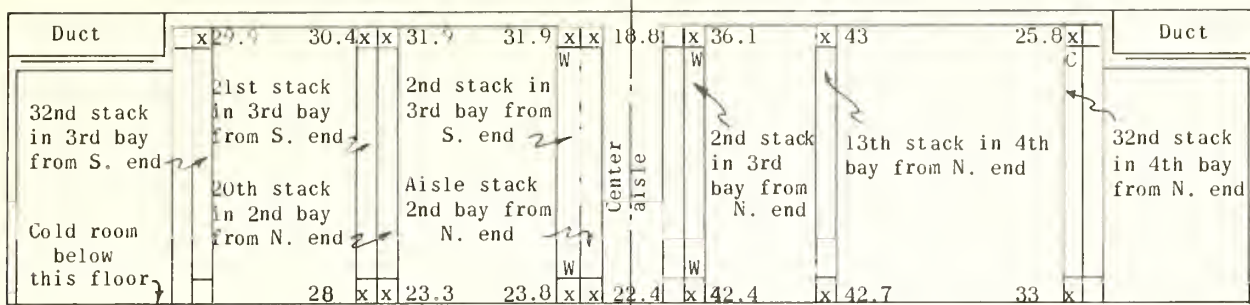
Figure 26 shows the performance pattern at plant 14, where a vertical forced-air circulation pattern was used in a multiple-floor storage. On the second floor, the lower boxes in the stack cooled more rapidly than the upper boxes, but this was not true on the bottom floor. Boxes near the sidewalls on the second floor cooled more rapidly than those near the aisle.

Figure 27 shows a three-duct supply and return system used at plant 24. Three types of packages were used on this test, but the same general cooling pattern at the various stack locations resulted with each package.

Figure 28 shows the performance obtained at plant 16 with packed fruit stacked on pallets in a two-duct supply and return system. In most locations, the upper pallets cooled slightly faster than the lower. Generally, the cooling performance was quite uniform. Near the return duct, both the cooling and the air velocity were slower.

Figure 29 represents performance at plant 6 of a large reversed-air installation where packed fruit was stacked in individual rows. Cooling performance did not appear to be systematically associated with room location in this test.

Figure 30 shows the performance at plant 9 of a high-velocity distribution system with the duct located above a center aisle. The uniformity of performance is noteworthy, as is the fact that



Z in hours for locations marked x. W indicates the warmest locations during the holding period, C is the coldest. The aisle stack in the 2nd bay from the north end was next to a conveyor opening to the upper floor and was subjected to an unusual draft.

Average cooling coefficient for these locations = 0.0241
Corresponding half-cooling time, "Z" = 29 hr.

FIGURE 29.—Cooling packed apples in standard wood boxes stacked in individual rows in storage room using reverse air circulation cooling system, plant 6.

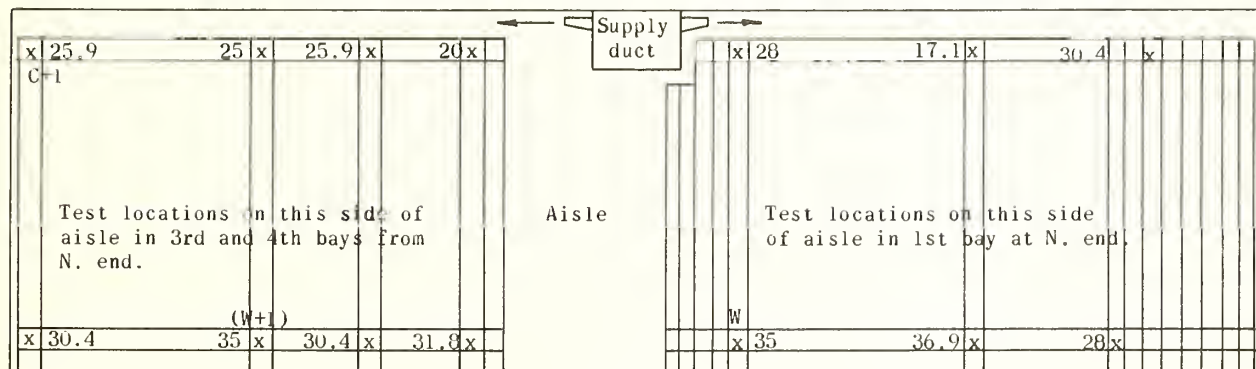
fruit in top locations generally cooled slightly faster.

Figure 31 shows a high-velocity outlet system in a wide room at plant 13, where two ducts located above the aisles were used. Here again the upper containers cooled more rapidly than the lower.

Figure 32 shows the results obtained with the medium-velocity outlet system at plant 12, where the ducts were located above the block of fruit. In the test illustrated, the left-hand section of the room had fruit stacked in rows running crosswise to the normal airflow, and the right-hand section of the room had the fruit stacked parallel to the airflow. The average cooling performance in the crosswise rows on the left was slightly better than

in the parallel rows on the right, but this was due principally to the influence of the one high value of a location that was subjected to a direct airflow from a duct outlet. The amount of variability observed in the crosswise rows was much greater than in the parallel rows, and this was reflected by greater differences in warmest and coldest positions during the holding period.

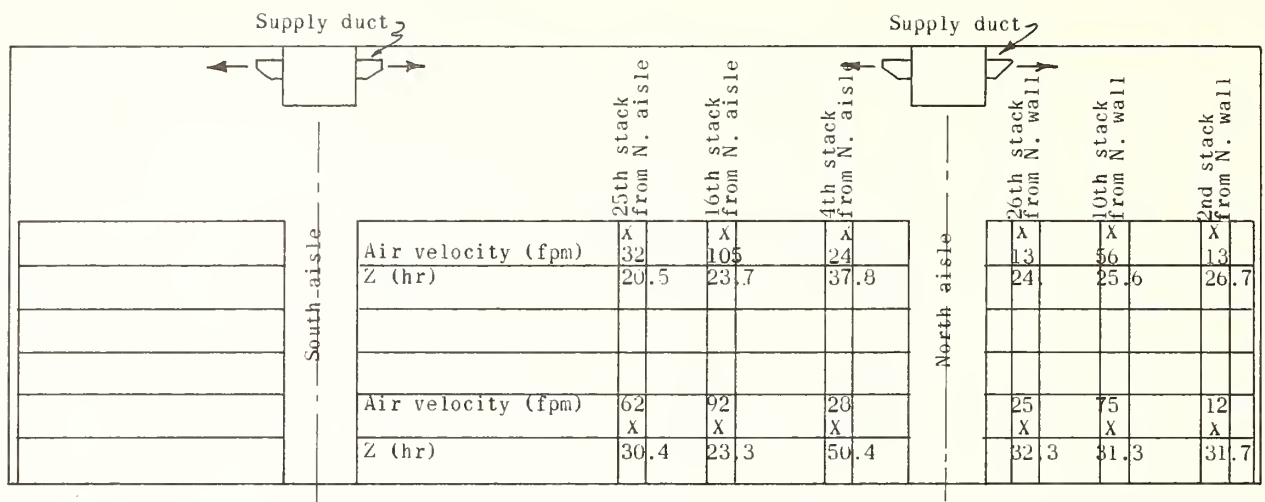
Figure 33 shows the pattern of cooling of pallet-loads of packed Anjou pears in this same storage. In this case, all rows were crosswise to the airflow. Results of two different tests are presented, and the noteworthy feature is the general agreement of these results.



Z in hours at test locations marked x. W indicates warmest location during holding period, W+1 is the next warmest, C is the coldest, and C+1 is the next coldest.

Average cooling coefficient for these locations = 0.0256
Corresponding half-cooling time, "Z" = 27.3 hr.

FIGURE 30.—Cooling packed apples in standard wood boxes stacked in individual rows in storage room using a high-velocity air distribution system, plant 9.



Z and air velocity at locations marked x

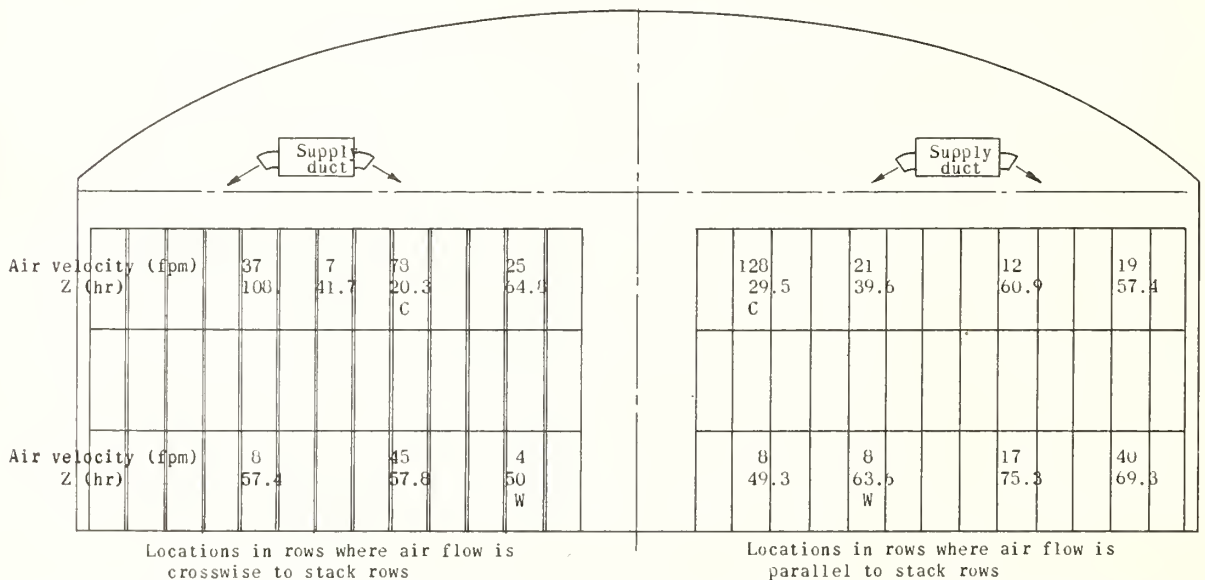
Average cooling coefficient for these locations = 0.0243

Corresponding half-cooling time, "Z" = 28.2

FIGURE 31.—Cooling packed apples in standard wood boxes stacked in individual rows in wide storage room using a two-duct high-velocity air distribution system, plant 13.

Figure 34 illustrates the pattern of cooling of loads placed in storage position with a clamp-type industrial truck in rows stacked crosswise to the normal airflow. Multiple overhead cooling units were located in each 20-foot bay of the structure. Not all loads at the test locations entered the room

warm enough to determine their cooling performance, and therefore velocities are given for some locations where characteristic cooling times are not indicated. Generally, the locations near the sidewalls cooled the best, and those locations near the center line of the building cooled quite slowly.

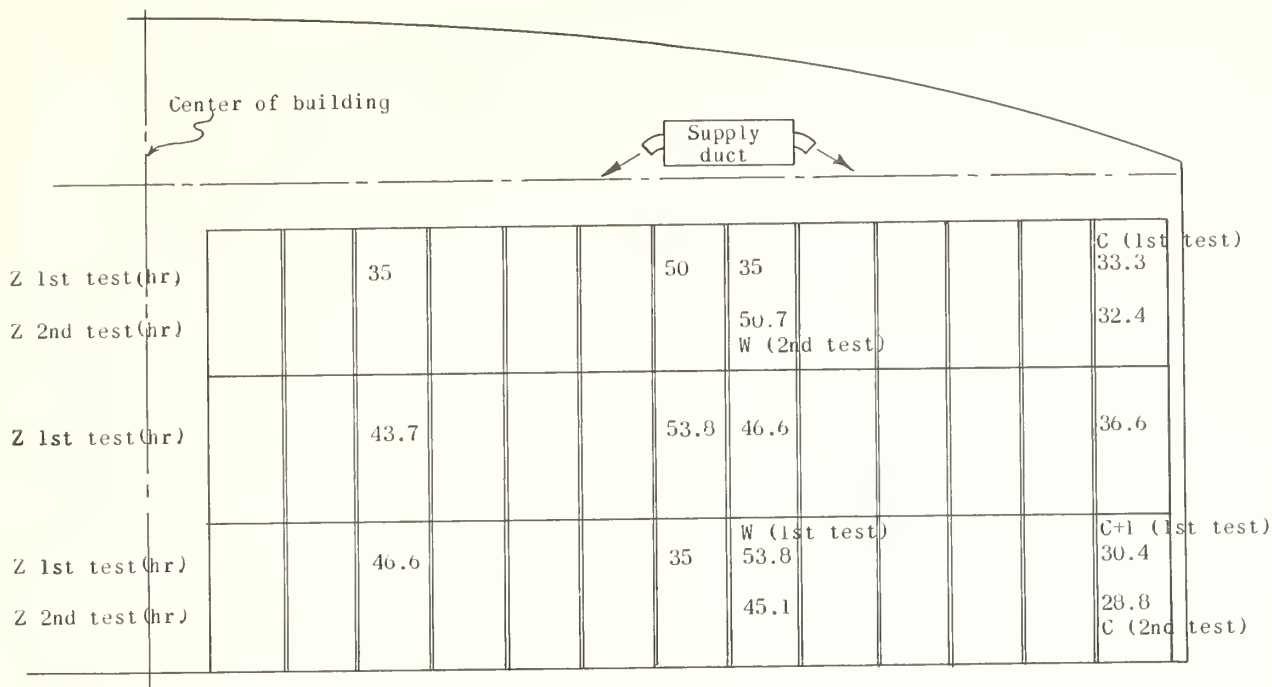


Average cooling coefficient for these locations = 0.0153
Corresponding half-cooling time, "Z" = 45.7 hr.

Average cooling coefficient for these locations = 0.0137
Corresponding half-cooling time, "Z" = 51. hr.

Locations marked C are coldest during storage period and those marked W are warmest.

FIGURE 32.—Cooling packed apples in standard wood boxes stacked in palletloads in storage room using a medium-velocity cooling system and supply ducts located over blocks of fruit, plant 12. One side of room arranged with rows parallel to airflow and the other side with rows crosswise.



Z for two tests cooling packed Anjou pears. W denotes warmest position during holding period following cooling, C denotes coldest position, and C+1 is the next to coldest position.

Average cooling coefficient for these locations on 1st test = 0.0173
Corresponding half-cooling time, "Z" = 40.4 hr.

Average cooling coefficient for these locations on 2nd test = 0.0188
Corresponding half-cooling time, "Z" = 37.2 hr.

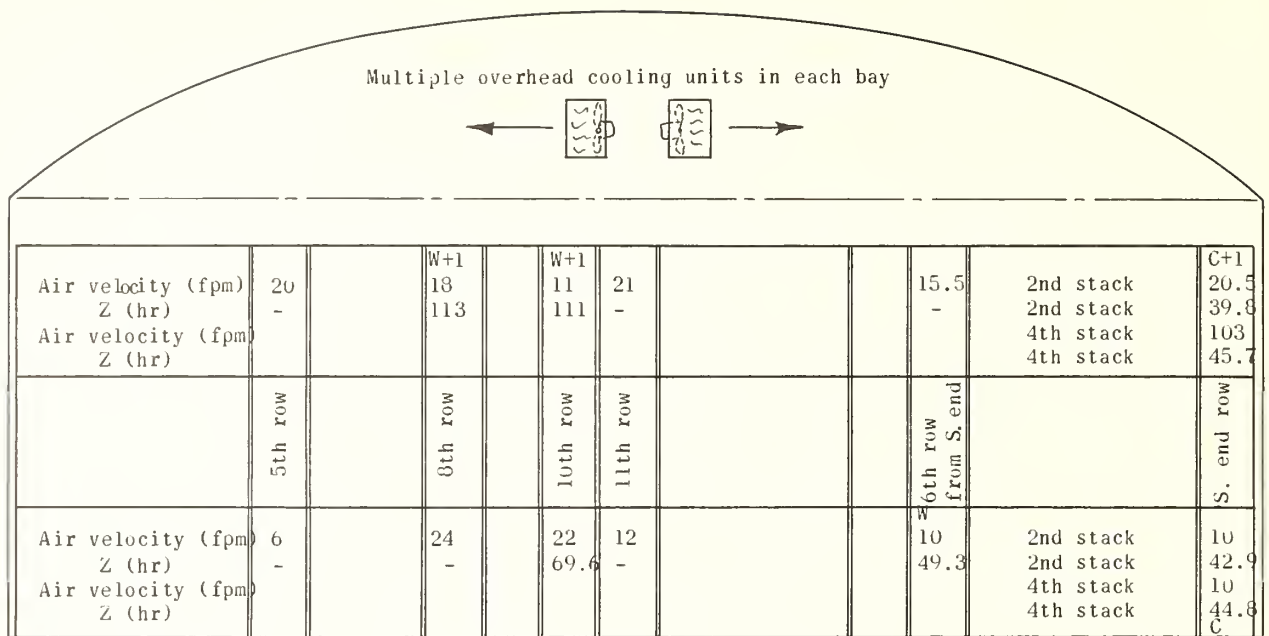
FIGURE 33.—Cooling packed Anjou pears in standard wood boxes stacked in palletloads in storage room using medium-velocity cooling system with supply ducts located over blocks of fruit and with stack rows running crosswise to airflow, plant 12.

The velocities shown in this test are averages of velocities recorded for 10 minutes on both sides of the stack at each location.

Figure 35 shows the pattern obtained in a special cooling room of rather unusual construction. Air was introduced at the ceiling at one end of the room and passed down through stacks of fruit which were carefully placed, with clearance between sides of adjacent stacks maintained by lathing the stacks. Strips on the floor kept the stacks about 2 inches above the floor, and beneath each stack row was an adjustable slot that opened into the joist spaces below the floor. These slots served as air outlets from the room, and the joist spaces provided leaving air ducts which opened into a corridor at the center of the building. This corridor served as a main return duct to a central aircooling apparatus. Each room of this type was rather small (about 10-carload capacity). As each row was filled, the floor slot was opened and air was passed through the stacks. The cooling performance and air velocities shown on figure 35 indicate that proper adjustment of so many

openings is difficult, and, although excellent results were obtained in the rows near the ends of the room, the overall performance was quite similar to that of other installations where packed fruit was cooled in individual stacks.

When all of these results are considered, it appears that container and stacking arrangement are much more important factors in cooling performance than is the air distribution arrangement. However, the importance of air distribution becomes more apparent when considering the variation of cooling performance and the pattern that the variation takes. This variation has an effect upon temperature uniformity in the room during the storage period, and this is an important item in overall storage performance. Although cooling is the more dramatic aspect of storage performance—being in some respects a display of brute strength—the ability of the storage to keep the fruit at the same temperature throughout the room is an equally important aspect, and will be considered next.



Z and air velocity near test boxes in dual stacks placed by industrial clamp trucks in rows indicated. W denotes warmest location after cooling period, W+1 is the next to warmest, C is the coldest, and C+1 is the next coldest. Dashes for Z indicate that fruit at that location did not cool sufficient to determine a cooling coefficient.

Average cooling coefficient for locations indicated = 0.0129
Corresponding half-cooling time, "Z" = 54.4 hr.

FIGURE 34.—Cooling packed apples in standard wood boxes stacked in dual stacks by clamp-type industrial truck in storage room using multiple overhead cooling units in each bay and with stacks running crosswise to airflow, plant 31.

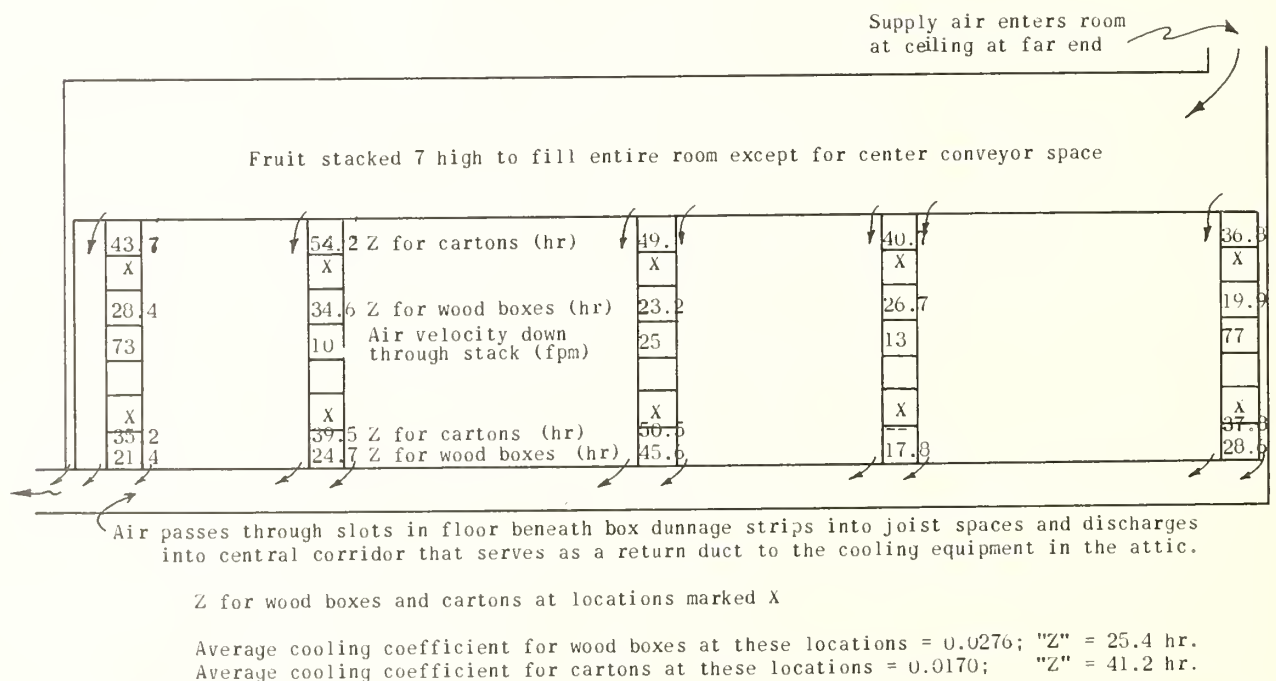


FIGURE 35.—Cooling Anjou pears in standard wood boxes and in fiberboard cartons, stacked in individual rows, plant 28.

Factors Affecting Uniformity of Air and Fruit Temperatures

An ideal storage should hold all the fruit in the storage uniformly at a pre-set temperature. Actual practice departs from the ideal in that there is some fluctuation in the temperature at the thermostat, or control point, and there is some variation in fruit temperature from any given control-point temperature at various points within the room. In discussion of the problem of uniformity of temperature, the first factor will be designated as control fluctuation and the second as fruit temperature variation. Although the first factor contributes somewhat to the second, there are other causes involved in the second that are fundamentally associated with the storage room design.

Control fluctuation may be associated with one or more of the following factors: The control instrument may be rather insensitive and may require a change of several degrees in temperature to actuate the control; the controller may be poorly located and may not be sensing the most severe temperature fluctuations; and the controller sensing element may contain sufficient mass that it lags behind the fluctuations of the actuating temperature. To assure more sensitive control, the instrument may be actuated by some intermediate medium, such as supply air, brine temperature, or refrigerant pressure, that influences room temperature. As the load changes, the relation between room temperature and these intermediate agents may change and the controller deviate from the original control point. Occasionally, some instruments seem to show a slow change or wandering of the control point, and they require periodic resetting to the desired point.

In manually operated storages, the control point is inclined to wander, since the control point is a matter of the operator's judgment and skill.

Although fluctuation caused by controls may be troublesome, it is more readily detected and remedied than some of the other factors that influence the uniformity of temperature of the stored product. Some observations have been made regarding the effect of fluctuations due to the controls, and these will be presented when observations of storage uniformity are discussed.

Variations in fruit temperature also may be due to one or more of the following factors; (1) Warm areas caused by excessive heat transmission into the room; (2) inequalities in the quantity of air passing through similar sections of the storage room, and (3) differences in approach temperature.

Quite often small sections of storage rooms placed over offices, packing areas, or machine rooms remain slightly warmer than other parts of the storage, and the fruit in such areas remains slightly warmer. Stacking of fruit directly against

outside walls, or on ground floors, results in special instances of fruit temperature variations induced by transmission. Inadequate spacing for ventilation, as well as direct contact, may result in higher temperatures at these points. Occasionally, near outside walls during very cold weather, inadequate space may result in lower than normal fruit temperatures.

Variations in fruit temperature caused by unequal quantities of air passing through similar sections of a given storage room may arise from several factors. Unusually large amounts of heat entering a section of the building may not have been properly considered when the air quantity was selected. For instance, outside walls lying parallel to the normal airflow pattern constitute an additional heat source to the air flowing near them, and this additional source of heat produces a slightly higher air temperature in such a location. A somewhat greater amount of air should be supplied at such points.

Although the air quantities intended to be distributed through the various paths of air travel may be correct, the actual distribution often departs widely from design, resulting in oversupply to certain paths and deficient air quantities in other sections of the room. If the load is constant along all paths and the air starts through each path at the same temperature, it is obvious that air temperature at the end of a path where a deficiency exists will be much higher than at the end of a path that is oversupplied. For this reason, adjustment of an air distribution system after installation is of paramount importance if temperature is to be uniform in the storage.

Previous discussion has shown how approach temperature may be affected by container, stacking method, or air velocity past the package. Generally, the same stacking method prevails throughout a given room, but different containers often are encountered in the same room. The variation in air velocity past the container is related to the uniformity of air distribution through the room. An air travel path that is oversupplied has higher velocity past the packages than an undersupplied path in the same room. Consequently, near the end of the undersupplied path, the air is warmer than normal, the air velocity lower than normal, and the approach temperature greater than normal. The normal is the value that would be obtained near the end of an airflow path through which the intended quantity of air passed.

The lowest fruit temperature may be expected at the start of an oversupplied path where higher than normal velocity reduces the approach temperature to a minimum for the container and stacking procedure used. Therefore, nonuniform air distribution and approach temperature work together in producing variation in fruit temper-

ature in a storage room. The effects of fluctuating control temperatures and of warm locations due to transmission through certain surfaces may be isolated from a measurement of fruit temperature variation; but the last two factors, air quantity variation and approach temperature variation, with a given type of package and stacking arrangement, are interrelated and, for the most part, are not broken into their two components when fruit temperature variation is measured.

The ideal in most fruit storage is to hold the fruit as close to a certain low temperature as possible. This low point may be either the freezing point of the fruit tissue or a point where low-temperature injury begins with certain fruits that are susceptible to this disorder.

A high degree of uniformity in attaining the desired temperature is important, because going below the specified temperature causes destruction due to freezing or low-temperature injury; going above the desired point hastens deterioration of the product, because it lives faster at the higher temperature. For instance, Hukill and Smith (7) showed that if Delicious apples are cooled in 7 days to storage temperatures of 36°, 32°, and 30° F., the normal storage life at 36° is about 4½ months, at 32° it is about 7½ months, and at 30° it is about 9 months. In other words, storage at 30° F. results in 20 percent longer life than at 32° F., and double the storage life experienced at 36° F. From this it appears that a continuous variation through the storage period of more than 2° will produce an appreciable difference in storage life of the fruit.

A factor which is often thought to have some bearing on the uniformity of the temperature of the stored fruit is the length of travel of the air in passing through the room. At first glance, it would seem that the shorter the path, the smaller would be the rise in temperature through that path. However, if one makes the comparison on the basis of a given total air quantity and a certain amount of heat to be absorbed, then it becomes apparent that as the air travel path is lengthened, the quantity of air moving along the path at any one time also increases, and the temperature rise from beginning to end is the same as for a shorter travel when the total air quantity and load in the room are the same. Length of travel along a given path is unimportant so long as part of the path is not bypassed by the air.

Generally, it is easier to adjust a few large air supply openings evenly than to adjust a large number of small openings. When there is some conversion of static pressure in the ducts to velocity at each outlet, a certain degree of self regulation is introduced, and such systems are usually easier to adjust than systems where velocity from each outlet depends entirely on duct velocity.

Control temperature fluctuation was noticed in a large number of instances during the observation of storage temperatures at various locations. For the most part, these fluctuations may be re-

lated to the causes previously discussed; however, there are two aspects of control fluctuation that have special interest and are worthy of special mention.

Figure 36 shows a record where unpacked Anjou pears were being cooled at plant 12. This storage was equipped with a forced circulation system with finned coils for cooling the air. Defrosting of the coils occurred automatically every 4 hours during the receiving season. At these times, the cooling unit fans stopped and warm water flowed over the coils for about 10 to 15 minutes. The continuous record of return air temperature to the cooling unit, air temperature at the test location, exposed fruit temperature at the top of the pallet, and temperature of the fruit in the center of the pallet illustrate the effect of this defrosting period on these temperatures. During the initial period of cooling, the air temperature adjacent to the test location was noticeably affected, but as cooling proceeded, the effect died out. By the 5th or 6th day, the record shows there was little variation in adjacent air temperature that can be related to the defrosting operation. For fruit in the exposed position on the top of a pallet, the same relation was observed, although the change in fruit temperature at time of defrosting was never so great as the change in adjacent air temperature. For the position in the center of the palletload, no fluctuation of fruit temperature related to the defrosting cycle could be detected.

Other tests in this same storage, and in other storages using a similar defrosting system, showed that, after the initial cooling period, little fluctuation of air temperature within the stack rows could be related to the defrosting cycle, and temperature of fruit near the center of the boxes did not fluctuate with the defrosting cycle.

Temperature fluctuation caused by controls may or may not produce a measurable fluctuation in fruit temperatures, depending on the duration of each cycle of temperature fluctuation. One particular storage was observed where the return air thermostat required a change of between 3° and 3½° in air temperature for operation. During average winter weather, the compressor would operate for about 1½ hours and be shut down for 2½ hours, making a 4-hour cycle. Even with this long a cycle, the various test locations showed little fluctuation of fruit temperature related to this rather severe variation of return air temperature. However, during one part of this record, when outside temperatures were lower than normal, off cycles of 5 to 7 hours were noted. In these cases, some fluctuation in fruit temperature was noted, amounting to 0.3° to 0.5° F. at the various test locations. From this observation, it appears that normal air temperature fluctuations caused by the control system that are confined to a period of 2 hours will not produce a measurable variation in the temperature of the fruit, but as the cycle becomes longer, there is more tendency for the fruit to follow the fluctuation in

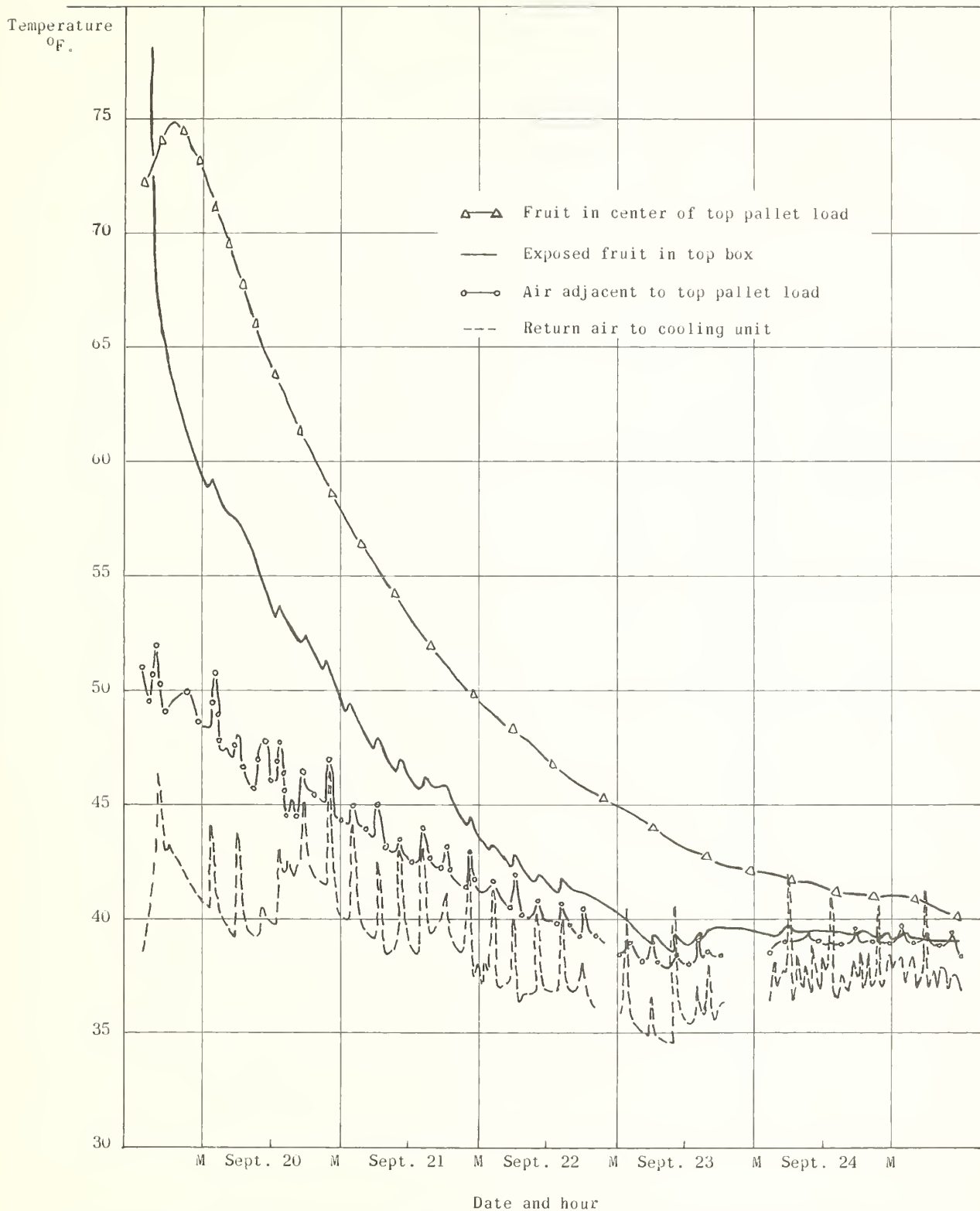


FIGURE 36.—Temperature of fruit in center of palletload, exposed fruit in top box, air adjacent to pallet, and return air, showing fluctuation produced by defrosting operation during cooling and subsequent storage, plant 12.

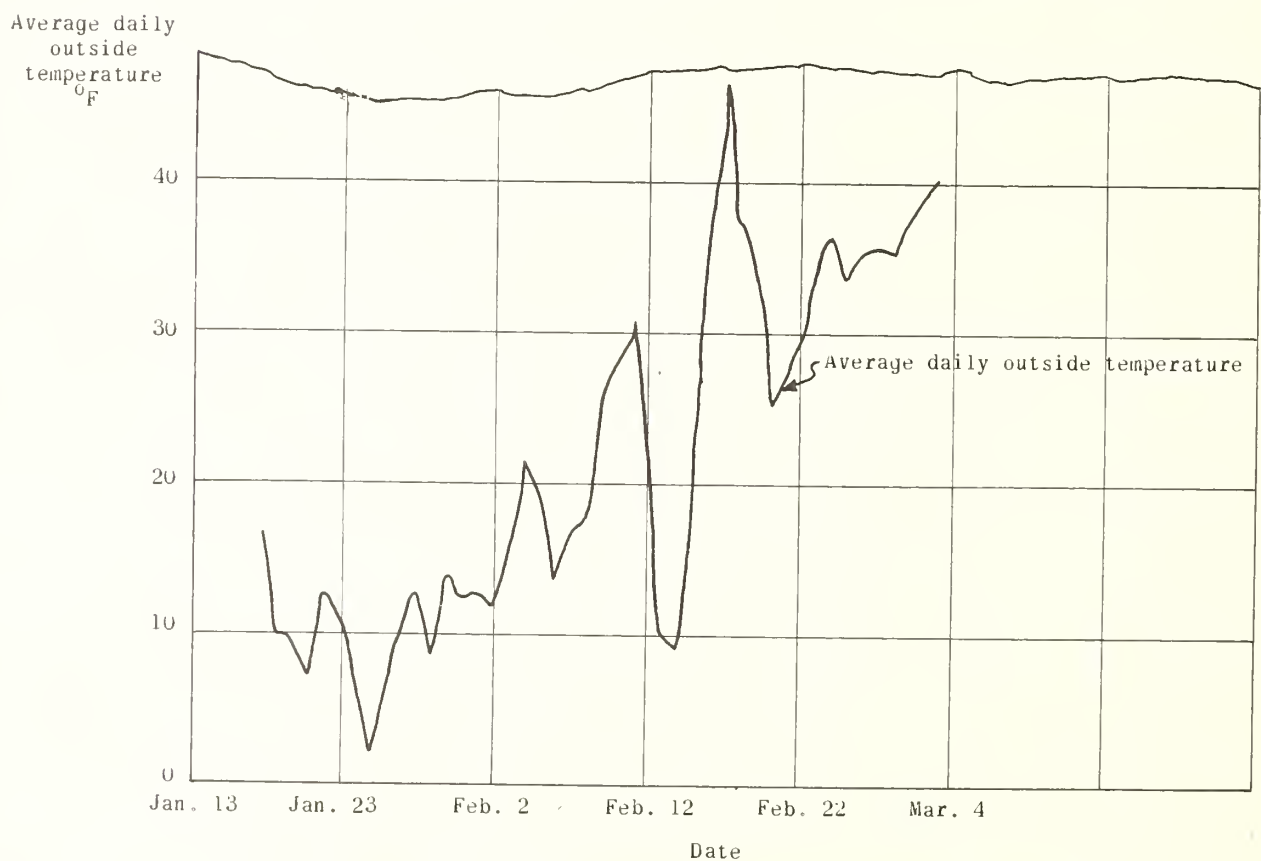
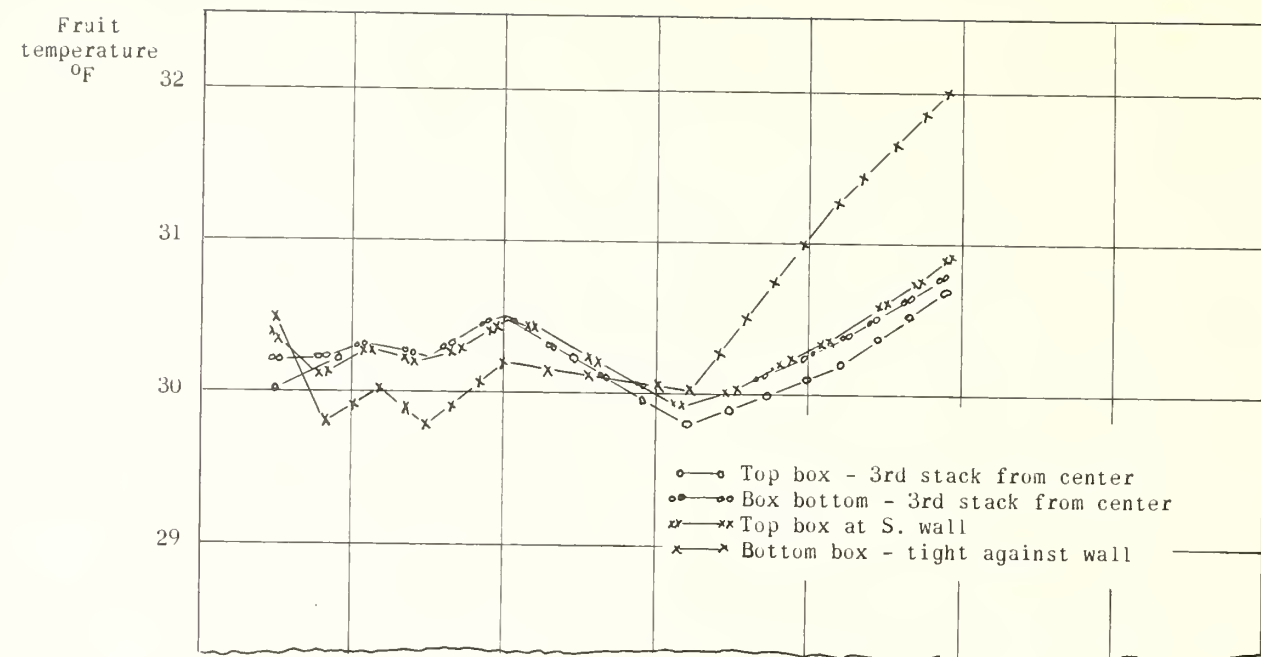


FIGURE 37.—Relation of holding temperatures and outside temperatures at plant 9.

air temperature. Some other records have shown that the fruit follows the air temperature more closely on the upswing than on the downswing. With rising air temperature, the respiratory heat of the fruit works in the same direction as the change in air temperature, whereas on the downswing, respiratory heat is in opposition to the change that conduction seeks to accomplish.

Changes of control point that take place over several days affect fruit temperature and are of greater concern than either of the control fluctuations previously discussed. Industrial-grade temperature recorders with 7-day charts assist in detecting such changes, because they provide a visual record over a sufficient time to make changes noticeable.

Instances of temperature variation due to floor transmission of heat have been reported in detail elsewhere (8, 10). Instances have also been found during these tests where fruit stacked directly against an outside wall received sufficient heating, or cooling, depending on the outside conditions, to make its temperature deviate considerably from the general temperature in the room. Figure 37 shows one such instance, and is of interest because the first part of the record shows a condition when the box was being cooled by heat transmission to the outside, and later the fruit was being heated by heat transmission from the outside.

Observations of uniformity during the storage period after 10 days had been allowed for cooling are summarized in tables 9, 10, and 11. Table 9 assembles the data in storages where the air circulation pattern was of the vertical type, table 10 gives the data for storages having supply and return duct systems and horizontal patterns of

circulation, and table 11 covers storages having supply systems without return ducts and with horizontal circulation patterns. These tables indicate the rate of air turnover in the rooms for forced circulation plants, the stacking details, length of the observation period, the number of observations where intermittent readings were used, and the average temperature differences between the warmest and coldest locations during the period of observations.

On figures 24 through 30 and 32 through 34, the coldest and warmest locations observed during the holding period are indicated. In most cases, the coldest locations are those which have cooled rapidly and the warmest locations are those which have cooled more slowly. Although the most rapidly cooled location is not necessarily the coldest, it is usually among the colder locations, and the most slowly cooled location is among the warmer locations. Occasionally some distortion of the pattern occurs due to proximity to a door or other heat source that keeps a location a little warmer than one would expect from the observed cooling performance, but in general the association of the lower holding temperatures with the more rapidly cooled locations, and higher temperatures with more slowly cooled locations, is valid.

Data in tables 9, 10, and 11 show there are a great many instances where the warmest fruit is consistently more than 2° F. higher than the coldest fruit. Only a few storages exceeded a 3° F. difference, and most of these cases could be remedied.

The comparison between the two pipe-coil storages shown in table 9 indicates that probably the tight stacking at plant 19 is hindering circu-

TABLE 9.—Average temperature variation in packed fruit during storage period and details of arrangement for storages with vertical-type air circulation pattern

Plant number and test	Air turnovers per hour	Stacking arrangements	Stacking height	Test duration	Observations	Average of maximum fruit temperature variations	Remarks
Pipe coil storages							
19—Test 1	Number	Solid stacks	Number boxes 12	Number days 46	Number 12	° F. 2. 7	Boxes stacked with ends butted and slight space between sides.
29—Test 1		Individual ¹	9	4	(²)	1. 5	Boxes stacked with ends butted and and 3-inch space between sides.
Forced circulation storages							
14—Test 1	5	Individual ³	7 and 8	51	23	2. 4	3-level room.
23—Test 1	6. 7	do ³	8	6	(²)	7. 8	1 end of room warm due to poor adjustment of air outlets.
23—Test 2	6. 7	do ³	8	20	5	1. 5	Different room from the above.
23—Test 3	6. 7	do ³	8	60	6	1. 2	Do.

¹ Stacked in individual rows with 2 sides exposed.

² Taken from a continuous recording of temperatures.

³ Stacked in individual rows with 2 ends exposed.

TABLE 10.—Average temperature variation in packed and unpacked fruit during storage period and details of arrangement for storages having supply and return systems with horizontal airflow patterns

Plant and test	Direction of airflow ¹	Air turn-overs per hour	Type of stack ²	Stacking height	Packed or unpacked fruit ³	Test duration	Observations	Average of maximum fruit temperature variation	Remarks
3-duct system									
24—test 1 -----	Par-----	Number 5. 8	Ind-----	Number boxes 8	P	Number days 2	Number (⁴)	° F. 2. 4	
Long-travel system—air passes through 2 rooms, 1 above the other									
1—test 1 -----	Par-----	10. 8	Pall-----	15	P	56	16	2. 4	Main floor.
1—test 2 -----	do-----	10. 8	do-----	10	P	130	24	3. 0	Basement.
1—test 3 -----	do-----	10. 8	do-----	10	P	13	(⁴)	3. 4	Do.
2-duct system									
3—test 1 -----	Par-----	13. 3	Ind-----	9	P	56	12	2. 0	Does not include corner location which would bring variation to 3.2°.
16—test 1 -----	do-----	11. 8	Pall-----	12	P	150	8	1. 0	
21—test 1 -----	do-----	6. 1	Dual-----	12	P	60	16	2. 1	
Reversed-air 2-duct system									
5—test 1 -----	Cross--	9. 2	Ind-----	5 ⁵	P	42	11	1. 7	Air range through room 0.75°.
5—test 2 -----	Par-----	9. 2	do-----	5	P	48	11	1. 2	Air range through room 2.0°. Proportionally more air supplied to room with crosswise stacks.
6—test 1 -----	do-----	8. 6	do-----	9	P	53	9	2. 2	Distribution system needs adjustment.
6—test 2 -----	do-----	8. 6	do-----	9	P	30	3	1. 8	Do.
6—test 3 -----	do-----	8. 6	do-----	9	P	116	13	. 8	After adjusting system.
7—test 1 -----	do-----	13. 3	do-----	11	P	70	10	2. 6	Variation in row across far end is 1.4°.
7—test 2 -----	do-----	13. 3	Dual-----	12	U	14	5	1. 7	Fruit in bags varied 3° through 50-day period.
7—test 1 ⁶ -----	do-----	11. 5	do-----	18	U	10	(⁴)	4. 3	Needs adjustment—fruit in bags varied 7.5°.
7—test 2 -----	do-----	11. 5	do-----	18	U	50	9	1. 5	After adjustment.
8—test 1 -----	do-----	10	Pall-----	15	P	53	8	1. 6	Air range through room 0.7° to 1.1°.
8—test 2 -----	do-----	10	do-----	15	P	9	(⁴)	1. 5	

¹ "Par." indicates airflow parallel to stack rows and "Cross" indicates airflow is crosswise or at right angles to the stack rows.

² "Ind." indicates that boxes are stacked in individual rows with 2 ends exposed, "Pall." indicates that boxes are stacked on pallets with 1 end exposed, and "Dual" indicates dual stacks with 1 end exposed and handled by clamp-type industrial trucks.

³ P indicates packed fruit and U indicates unpacked fruit.

⁴ Taken from a continuous recording of temperatures.

⁵ New building.

lation of air to some extent. The locations of cold and warm points in the stack as shown in figure 25 also indicate that this may be the case.

The fact that plant 14 exceeds a 2° F. variation between warm and cold locations is probably accounted for by the relatively slow air turnover in this plant. The same comment may apply to plants 21 and 24, for which data are shown in table 10.

Plant 1 in table 10 has a unique circulation system; however, there is some lack of uniformity, particularly on the lower floor. In addition, the

storage is cooled by five large cooling units located along one wall of the main-floor room. During test 2, defrosting trouble was periodically experienced during the storage season. At such times, the temperature in the air travel path from the unit that was iced up would rise 3° or 4° F. Test locations covered areas served by two different units, and some portion of the fruit temperature variation reflects the results of this malfunction.

The data in table 11 show that the medium-velocity outlet systems with ducts located above

TABLE 11.—Average temperature variation in packed and unpacked fruit during storage period and details of arrangement for storages having supply systems without return ducts and with horizontal airflow patterns

Plant and test	Direction of airflow ¹	Air turn-overs per hour	Type of stack ²	Stacking height	Packed or unpacked fruit ³	Test duration	Average of maximum fruit temperature variation	Observations	Remarks
High-velocity outlets—duct over center aisle									
		Number		Number boxes		Number days	° F.	Number	
9—test 1-----	Par-----	8.6	Ind-----	9	P	100	0.8	20	
9—test 2-----	Par-----	8.6	Ind-----	8	P	100	.7	16	
9—test 3-----	Par-----	8.6	Ind-----	8	P	10	.5	(⁴)	Air range through room 0.3°. Test made during very cold weather.
9—test 4-----	Par-----	8.6	Ind-----	10	P	130	.9	14	
2—test 1-----	Par-----	7.5	Ind-----	9	P	101	.6	22	Second floor room.
2—test 2-----	Cross-----	7.5	Ind-----	10	P	101	1.6	22	Basement room.
4—test 1-----	Cross-----	5.2	Ind-----	7	P	122	1.8	21	
25—test 1-----	Par-----	12	Ind-----	9	P	60	1.1	6	
13—test 1-----	Par-----	7.5	Ind-----	10	P	20	.9	4	
Medium-velocity outlets—ducts over the block of fruit									
5—test 1-----	(⁵)	13.3	Ind-----	7	P	80	1.8	16	
5—test 2-----	(⁵)	13.3	Ind-----	7	P	12	2.5	(⁴)	
5—test 3-----	(⁵)	13.3	Ind-----	7	P	7	2.1	(⁴)	After placing baffle curtain.
5—test 4-----	(⁵)	12	Pall-----	15	P	50	2.0	8	Ceiling was raised, operation palletized, and a cooling unit added.
12—test 1-----	Cross-----	13	Pall-----	15	P	59	2.6	9	
12—test 2-----	Par-----	13	Pall-----	18	P	90	1.9	14	
12—test 3-----	Cross-----	13	Pall-----	18	P	90	2.2	14	
12—test 4-----	Cross-----	13	Pall-----	15	P	7	2.1	(⁴)	
Multiple overhead cooling units									
31—test 1-----	Cross-----	15.8	Dual-----	18	P	4	1.9	(⁴)	
Large overhead cooling units above aisle with auxiliary fans									
30—test 1-----	Par-----	17.1	Pall-----	18	U	2	1.5 to 2	(⁴)	Auxiliary fans on.
30—test 2-----	Par-----	11.0	Pall-----	18	U	4	3 to 3.5	(⁴)	Auxiliary fans off.
30—test 3-----	Par-----	17.1	Pall-----	18	P	3	1.5	(⁴)	Auxiliary fans on. ⁶

¹ "Par." indicates airflow parallel to stack rows and "Cross" indicates airflow is crosswise or at right angles to the stack rows.

² "Ind." indicates that boxes are stacked in individual rows with 2 ends exposed. "Pall." indicates that boxes are stacked in individual rows with 1 end exposed on pallets, and "Dual" indicates stacks with 1 end exposed and handled by clamp-type industrial trucks.

³ P indicates packed fruit and U indicates unpacked fruit.

⁴ Taken from a continuous recording of temperatures.

⁵ Flow of air at 45° angle to stack rows.

⁶ Separate sections of room have individual temperature control; center section of room is 1.2° warmer than end section. If variations of 2 sections were lumped together, variation would be 2.7°.

the stacks did not produce as uniform conditions as the high-velocity systems with ducts over the aisle. These latter systems were generally able to produce the most uniform storage conditions observed, although, when the reversed-air system at plant 6 was placed in proper adjustment, it also attained a uniformity of temperature in the room that was within 1° F.

The systems at plants 30 and 31, table 11, have the same pattern of circulation as the high-velocity outlet systems. The system at plant 30 had the units located above the aisle, and produced a condition where the variation was about 1.5° F. In this plant, six large units were located overhead and controlled in pairs. On the test with packed fruit, it was noted that the control

for the center pair of units was set slightly higher than for the north end pair. As a result, temperatures in the center zone averaged 1.2° F. higher than in the end zone. The data for the end zone only have been presented in the table because it was the intention to present in these tables data on temperature variation that is related to the inherent characteristics of the circulation system. Basically, the higher temperature experienced in the center is a control problem.

Tables 9, 10, and 11 contain instances that illustrate the importance of proper adjustment of the air distribution systems. The variable results obtained at plant 23 (table 9) indicate that in that one case poor adjustment was creating a very unsatisfactory condition in the room during test 1. Fruit stored in the warm end of this room was shipped soon after completion of the test.

At plant 21 (table 10) an enclosed stairway protruded into the room and the return duct cut across a corner, leaving a small dead area beyond the return duct. Fruit in this area was consistently more than a degree warmer than any other fruit near the return ducts in this room. This location was not included in the tabulated figure for the plant because the area where this situation prevailed was very small.

The several tests at plant 6 are a good illustration of what can be done by proper adjustment of outlets with a reversed-air system. The new building at plant 7 had a most serious unbalance of distribution initially. After several adjustments, the variation was brought to less than 1½° F. It should be noted that in two of the tests at plant 7 some of the unpacked fruit had been picked in boxes with polyethylene liners to prevent shrinkage while awaiting packing. In both instances, the observed difference between warmest and coldest locations in the boxes with liners was about 75 percent greater than that observed for the ordinary field boxes located immediately adjacent to the lined boxes.

At plant 5 (table 11), an attempt was made in test 3 to divert more air through the stacks of fruit and secure more uniform temperatures thereby. The baffle curtain used produced a slight improvement, but the system of distribution in this plant has some characteristics that do not respond to a simple adjustment of this type.

The comparison of uniformity at plant 30 with auxiliary fans on and off has already been mentioned, but this may also be considered an instance of air distribution adjustment.

The tables showing temperature variation contain a number of instances that compare the uniformity obtained when air circulation is parallel to fruit rows and when it is not. The portion of plant 5 that has a reversed-air system showed more nearly uniform temperature in the room with parallel stacking, even though, in the room

with crosswise stacking, air passing through the room had a smaller rise in temperature; that is, it was supplied proportionally more air. With the high-velocity systems, those rooms where airflow was crosswise to stack rows had much greater variation than rooms where airflow was parallel to the rows, as shown in plant 2 (table 11). In plant 12, the tests 1, 2, and 3, comparing parallel and crosswise stacking, show greater uniformity in the parallel stacks. In a given zone at plant 30, the variation is less than in plant 31, where crosswise stacking is used.

There is some question whether a high-stacked palletized storage can attain as uniform a condition as a plant where fruit is stacked in individual rows. Only one record has been obtained where variation in a palletized house is less than 1½° F., and this plant stacked fruit two pallets high rather than three. On the other hand, the performance at plant 5 (table 11) was about the same after it was altered for pallet operation as when it was used with fruit stacked in individual rows.

The observations on uniformity of storage temperature may be summarized as follows:

1. Poor control may adversely affect uniformity of fruit temperature. Continuous recordings of storage air temperature will assist in detecting trouble from this source.

2. Direct transmission of heat into containers stacked against outside walls and on ground floors is a source of fruit temperature variation and should be prevented by wall spacers and floor racks or pallets.

3. Proper adjustment of the distribution system is imperative, and instances have been obtained illustrating very substantial differences in fruit temperature uniformity that are related to this factor.

4. The airflow pattern should conform to the stacking pattern in the room so that airflow is parallel with stack rows.

5. The systems distributing air from a source above the center aisle to the sidewalls and back through the fruit all showed a high degree of uniformity. Possibly this generally good performance is due in part to the fact that most of these systems are inherently well balanced from a distribution standpoint and require little adjustment. When properly adjusted, the reversed-air systems produced results equally as good.

6. Those systems where the quantity of air circulated is such that the air turnover is less than 7.5 times an hour often have greater variation than storages with a greater circulating capacity.

7. With packed fruit, those locations in a storage that cool more slowly remain at the higher temperatures and those that cool more rapidly remain at the lower temperatures during the storage season.

Economic Factors in Evaluating Air Distribution Systems

To compare the cost of various distribution systems, several factors must be taken into account. These include the power to operate the fans, the investment necessary to house the air-cooling equipment, the investment for extra space occupied by the ducts, and the fixed charges on the ductwork. The evaporators themselves should cost approximately the same per unit of capacity, assuming an equivalent quantity of surface is furnished per unit of capacity for the various types of evaporators. Although this assumption may be questioned, the result of variation of evaporator cost will not seriously affect the figures that will be presented in this section. The power cost for the refrigeration compressors has not been included in this comparison.

Table 12 compares the costs mentioned for the different air distribution systems for which performance data were presented in tables 9, 10, and 11. The box storage capacity and air turnover per hour are noted to give a general idea of the size and circulation activity of each storage. Fan power per 1,000 boxes and approximate area of duct material per 1,000-box storage capacity have been calculated from the layouts of these plants. The percentage of space occupied by the evaporators and the ducts has also been calculated. Where ducts are located above aisles, no charge has been made for the space occupied, as it would have been lost space in any event. Where ducts or evaporators are located in an overhead truss space created by the use of bowstring-type trusses, no charge was made for this space, as it is inherently waste space in such a structure. Other studies have indicated that, although such a structure contains considerable waste space, the overall economy of construction justifies its use.

The seasonal costs have been computed as follows: For fan operation, power at \$0.015 per kilowatt-hour amounts to \$76 per horsepower per 8-month season. Fixed costs on space occupied were calculated on the basis of a total of fixed costs equal to 9.5 percent of the investment cost, which was estimated at \$1,500 per 1,000 boxes; therefore, the cost of space consumed would be \$1.425 per season per 1 percent space consumed. Fixed costs for ductwork were based on an average investment of \$0.40 per square foot of duct and 15 percent annual total fixed charges on this type of equipment, making an annual charge of \$0.06 per square foot of duct surface. In the pipe-coil storage, drip pans under the coils were figured on the same basis as ductwork. In some storages,

ceilings and walls have served as a side of the duct, and where this was the case, no charge was made for that surface.

The total annual costs of the distribution systems varied from \$12.20 to \$53.90 per 1,000 boxes. Study of this variation of costs shows that much of it is related to the air turnover factor; the more air circulated, the more power cost, the more space occupied, and the larger the ducts required. If the annual cost is divided by the air turnover factor, a cost index is obtained that decreases as the turnover factor increases. In other words, if the storage is designed for twice as rapid circulation, the cost of the air distribution system does not double.

In figure 38, these index values are plotted against air turnover values and this downward trend of the index with increasing turnover is shown.

No particular duct system seems to have an overall seasonal cost advantage over the other systems, although there is one reversing system whose cost is out of line. This is chiefly due to unusual space occupancy of the system that was installed in an existing building.

The systems that have been installed overhead in pallet storages in otherwise unusable space created by bowstring trusses are free from space occupancy charges, giving them an advantage. When this advantage is coupled with the lower power requirements of the multiple-unit installations, the result is a system that gives plentiful circulation with low overall seasonal cost. The figures indicate that these overhead unit systems have a true advantage and present the lowest seasonal operating cost while giving good circulation characteristics. It is probable that the several evaporators required cost somewhat more than an installation where one large evaporator is furnished to operate with ductwork. The cost of complete evaporators and connections installed, at the time of this study, was usually about \$400 per ton of refrigeration (T.R.) capacity and usually there was about 1 T.R. installed for each 2,500 boxes of storage capacity in plants of the size considered in these studies. If an extra cost of 10 percent is allowed for the overhead unit system, and annual fixed charges are taken at 15 percent, the effect of the 10 percent greater price amounts to about \$2.40 per 1,000 boxes per year of additional charge. This extra cost will not change the economic position of the multiple overhead unit system in this comparison.

TABLE 12.—Comparison of various air distribution systems for annual operating costs, annual fixed costs due to duct work and space occupied, total annual cost per 1,000 boxes, and cost index to air distribution

Plant	Storage capacity	Air turn-overs per hour	Fan power per 1,000 boxes	Space occupied		Area of ducts or fans per 1,000 boxes	Annual cost per 1,000 boxes					
				Evap-orators	Ducts		Fan operation	Fixed charges on—			Total	Per air turnover per hour
								Equip-ment space	Duct space	Ducts		
19-----	Pipe coil storages with auxiliary fans											
	Number boxes 138, 300	Number -----	Horse-power 0. 05	Percent 8. 0	Percent 0	Square feet 70	Dollars 3. 80	Dollars 11. 40	Dollars 0	Dollars 4. 20	Dollars 19. 40	Dollars -----
	Forced circulation—vertical airflow pattern											
	135, 000	5	0. 17	1. 2	0. 5	100	12. 90	1. 70	0. 70	6. 00	21. 30	4. 26
	152, 240	6. 7	. 13	4. 0	3. 0	48	9. 90	5. 70	4. 30	2. 90	22. 80	3. 41
	3-duct system—horizontal airflow pattern											
	175, 500	5. 8	0. 11	2. 5	4. 0	80	8. 40	3. 60	5. 70	4. 80	22. 50	3. 88
	Long-travel system											
	105, 000	10. 8	0. 21	2. 6	1. 9	25	16. 00	4. 10	2. 70	1. 50	24. 30	2. 25
	2-duct system											
	¹ 19, 300	13. 3	0. 23	3. 6	6. 5	75	17. 50	5. 10	9. 30	4. 50	36. 40	2. 73
	26, 000	11. 8	. 19	. 7	4. 1	100	14. 50	1. 00	5. 80	6. 00	27. 30	2. 31
	587, 700	6. 1	. 09	1. 5	4. 5	65	6. 80	2. 10	6. 40	3. 90	19. 20	3. 15
Reversed air—2-duct system												
32, 000	9. 2	0. 16	3. 4	² 1. 5	80	12. 20	4. 80	2. 10	4. 80	23. 90	2. 60	
192, 000	8. 6	. 095	5. 8	6. 1	50	7. 20	8. 30	8. 70	3. 00	27. 20	3. 16	
227, 000	13. 3	. 19	9	14	110	14. 50	12. 80	20. 00	6. 60	53. 90	4. 05	
³ 85, 600	11. 5	. 23	-----	⁴ 7. 1	75	17. 30	-----	10. 10	4. 50	32. 10	2. 79	
285, 000	10	. 22	4. 4	3. 8	55	16. 70	6. 30	4. 90	3. 30	31. 20	3. 12	
High-velocity outlets—center duct												
110, 000	8. 6	0. 19	2. 1	2. 5	50	14. 50	3. 00	3. 60	3. 00	24. 10	2. 80	
200, 000	7. 5	. 15	1. 1	3. 1	30	11. 40	1. 60	4. 40	1. 80	19. 20	2. 56	
145, 000	5. 2	. 15	1. 6	1. 2	30	11. 40	2. 30	1. 70	1. 80	17. 20	3. 31	
¹ 16, 200	12	. 31	5	0	40	23. 60	7. 10	-----	2. 40	33. 10	2. 76	
333, 300	7. 5	0. 15	4	3	40	11. 40	5. 70	4. 30	2. 40	23. 80	3. 17	
Medium-velocity outlets—ducts over the block of fruit												
34, 000	13. 3	0. 25	3. 3	4	88	19. 00	4. 70	5. 70	5. 30	34. 70	2. 61	
¹ 100, 000	13	. 3	0	0	40	22. 50	-----	-----	2. 40	25. 20	1. 94	
Multiple overhead cooling units												
63, 900	15. 8	0. 16	0	0	0	12. 20	-----	-----	-----	12. 20	0. 78	
Large overhead cooling units with auxiliary fans												
125, 000	17. 1	0. 26	0	0	0	19. 80	-----	-----	-----	19. 80	1. 16	

¹ Capacity of test room only.

² Most of ducts over aisles in this storage.

³ New building.

⁴ Ducts not in storage space, but building was constructed with extra overhead space to accommodate ducts.

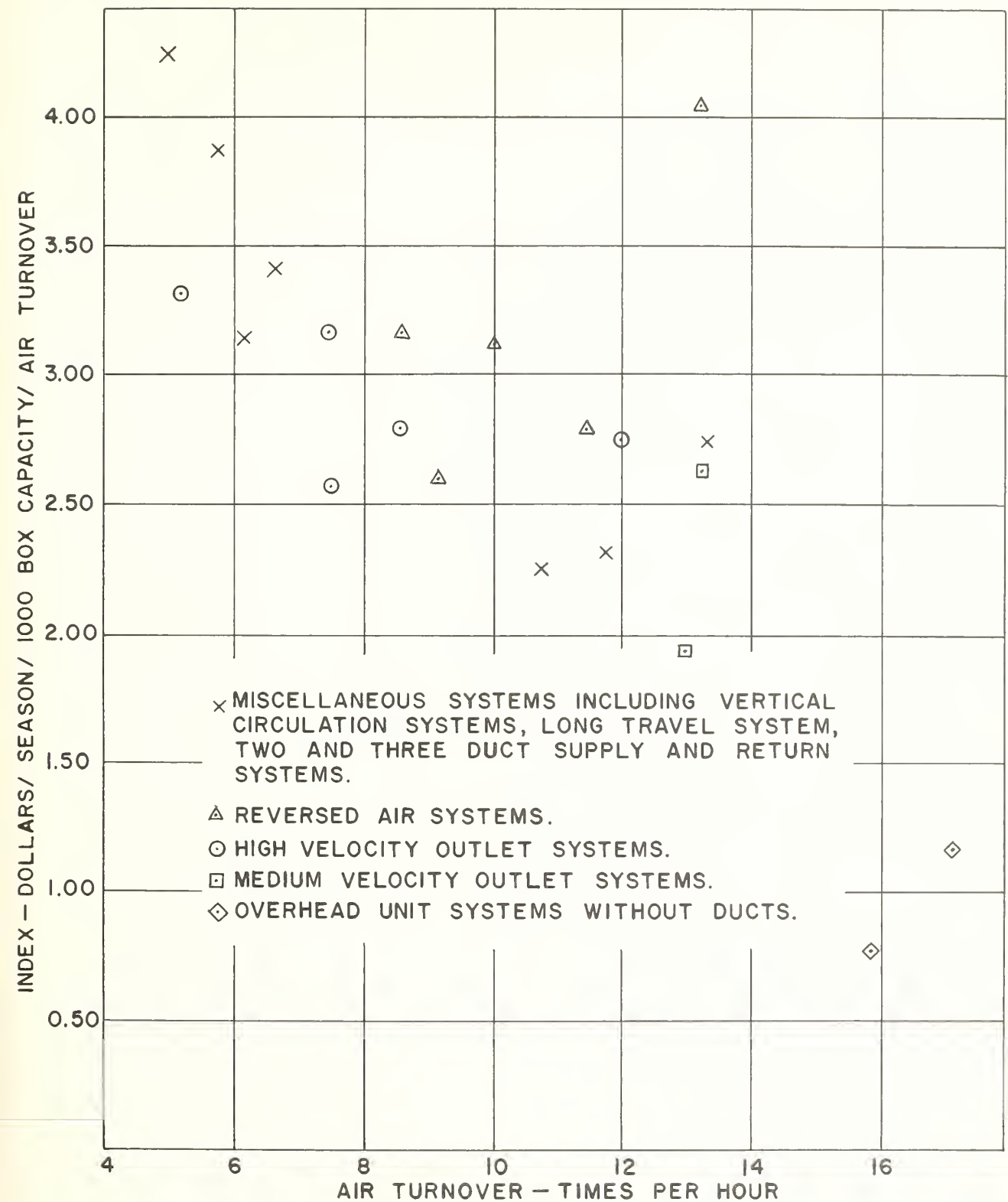


FIGURE 38.—Air distribution cost index plotted against air turnover for various air distribution systems.

Conclusions

An overall consideration of the various aspects of room cooling of fruit covers a large number of factors. Desirable practice dictates that cooling should be as rapid as possible with very little special handling of the product; once the room has been filled, the products within the room should attain as nearly a uniform temperature as possible; and finally, this performance should be attained at minimum overall cost.

The study of cooling performance has indicated that, if the room has sufficient refrigeration capacity to cope with the heat that must be removed, then the dimensions, nature of the container, and manner of stacking are the most important factors that influence cooling performance.

Boxes of unpacked fruit, through which some air can pass and take away part of the heat by convection, cool much faster than packed boxes that allow little air passage. The more provision made for air passage, the greater is the effect of convection. This is shown by the fact that unpacked fruit generally cooled somewhat faster in cannery lugs than in standard apple boxes. The restriction of convection imposed by picking into polyethylene liners in the boxes produced more than a threefold increase in time required for cooling.

In those packages where the effect of convection is small and most heat is removed by conduction, the distance from center of the package, or of the pile, to the surface where the heat is transferred to the air is probably the most important single factor. The characteristic cooling time varies almost as the square of this distance if heat is being transferred from only two sides of a pile. It follows that if a package can be arranged so that heat transfers from more than two sides, its cooling performance will be improved. Even in packages where convection can play a part in cooling, some increase in cooling time is noted as the distance from the center of the package to the heat disposal face increases.

Evidence of these principles was noted in the fact that packed boxes of pears generally cooled slightly more rapidly than did similarly exposed packed boxes of apples. The minimum dimensions from center to outside surfaces of the pear box are somewhat less than those of the apple box. Pallet stacks of packed wood boxes generally had a characteristic cooling time about 60 percent greater than similar boxes stacked with two ends exposed. Individual stacks of unventilated cartons arranged with two ends exposed took 50 to 100 percent longer to cool than similarly stacked wood boxes, because the latter had some side exposure as well as end exposure. When cartons were placed in palletloads or dual stacks with only one end exposed, three to four times longer was required for cooling.

Where fruit is tray packed and placed in cartons without liners, proper venting can assist in improving the cooling performance of the packages. Tests indicate that with two $\frac{3}{4}$ -by 2-inch holes in each end, cartons with perforated trays stacked with two ends exposed cool in the same time as standard packed wood apple boxes.

A clear-cut relation between air velocity past the package and cooling performance has not been obtained, but there is evidence that better performance is associated with increased air velocities. In individual tests, the faster cooling locations were usually in the places in the room where higher velocities were obtained, and slower cooling in a given test was usually associated with slower air velocity. Consideration of the factors involved shows that, with stacks and packages that are more difficult to cool because of greater dimensions and less exposure, increased air velocity has less effect than it has with more favorable arrangement of packages and stacks.

A definite relation has been shown, both analytically and experimentally, between cooling performance and the final temperature difference between the fruit and the air, a difference designated as "approach temperature." The experimental data fit the relation:

Approach temperature = $0.033 Z$, where Z is the characteristic cooling time in hours.

Approach temperature is influenced by the same factors that influence cooling performance, although the degree of change produced by increased air velocity past the package or by stack arrangement is somewhat less than the change these factors produce in cooling performance. Reducing the moisture loss rate produces a greater change in the approach temperature than in the cooling performance.

With packed fruit, the approach temperature is often 1.5° to 2° F., and a few instances have been observed where it is from 3° to 4° F. With unpacked fruit, approach temperature does not generally exceed 1° F. and is often less than 0.5° F.

This factor is of importance because, where containers that cool very rapidly are held in the same room with those that have a slow cooling characteristic, the minimum air temperature will be close to the freezing point of the rapidly cooled item, and the slowly cooled item must necessarily remain at this temperature plus its approach temperature.

The approach temperature is one of the factors involved in storage uniformity. Others are variations in air quantity in different sections of the storage room, heat transmission into packages placed directly against outside walls or ground floors, and variations due to control operation.

Long-time control fluctuations affect storage uniformity, but the fruit will not follow short-time

variations. The normal automatic defrosting operation does not produce variation in fruit temperature after the fruit is down to holding temperature.

Proper adjustment of air distribution systems is required, particularly for low-velocity outlet systems with return ducts. Some of the most severe cases of nonuniform storage temperatures were related to this cause.

The airflow pattern should conform to the stacking pattern to obtain the most uniform fruit temperatures. Systems that distributed air from above a center aisle and returned it to the aisle generally obtained good uniform storage temperatures.

Direct transmission of heat into containers in contact with outside walls and ground floors should be avoided through use of proper spacing devices.

Air quantities should be selected so that the air passes through the empty house at least 7½ times per hour to achieve the desired degree of uniformity.

The season average temperature of the warmest fruit location should not exceed the coldest by more than 2° F.

With packed fruit, those locations in the storage that cool more slowly remain at the higher tem-

peratures and those that cool more rapidly remain at the lower temperatures during the storage season. Convection up through the stacks during the cooling period may produce some distortion of this relation with unpacked fruit.

An economic analysis of the costs of various air distribution systems indicates that the seasonal cost of distributing the air per 1,000 boxes varies from approximately \$12.20 to \$53.90, and that for most systems this cost is related to the air turnover in the storage. A cost index to compare seasonal cost per 1,000 boxes per air turnover indicates that as the air turnover rate increases, the index decreases—in other words, cost of air distribution does not go up in direct proportion with the air turnover rate.

The cost studies indicate that the recently introduced system for palletized storages using multiple overhead ceiling units offers a distribution cost about 50 percent as great as comparable duct systems, and also a high air turnover rate. A system with several large overhead units without ducts and with auxiliary fans also shares many of these advantages. Throughout the study, high rate of air turnover has generally been associated with the better results, and it can be regarded as one of the factors in good performance.

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Appendix

Methods of Research

Method of Observation

Temperature.—Fruit temperatures were measured with copper-constantan thermocouples inserted into the center fruit in the containers selected for study. Air temperatures adjacent to fruit locations were measured with thermocouples suspended in the air spaces between rows of containers. When either supply or return air temperatures were observed, a thermocouple was inserted into the appropriate duct opening. In storages employing return ducts, the last opening of the duct before it left the room was used, and the thermocouple positioned in the duct to get a good average temperature of all of the air leaving the room.

During periods when fruit was being cooled and temperature changes were rather rapid, temperatures, as sensed by the thermocouples, were measured and recorded with a multipoint, strip-chart, electronic balancing potentiometer. This equipment was arranged to record temperatures from either 16 or 32 locations, as the test required, at the rate of 1 observation per minute. Thus the temperature of each location was measured and recorded either once every 16 minutes or once every 32 minutes, depending upon the number of stations used. Continuous recording of air temperatures during the cooling period is necessary because air temperatures may fluctuate quite rapidly over a substantial range. Consequently, occasional measurements of air temperature might be misleading regarding the average temperature during any test.

When the fruit had cooled to within a few degrees of the room temperature, and knowledge of variation of fruit temperature at different locations in the room was the prime objective, intermittent readings with a hand-balanced potentiometer of the semiprecision type were made and were highly satisfactory. A reference junction in a thermos bottle of melting ice was used with this apparatus to eliminate the difficulties encountered in carrying a compensated junction instrument in and out of cold rooms.

The recording potentiometer was checked at the beginning or end of most tests by placing a thermocouple in a thermos bottle filled with melting ice and checking the recorded temperature for this station against 32° F. In most instances, the recorded temperature did not devi-

ate from the true temperature by more than 0.5° F., although in a few extreme cases the deviation was 1.5° F. Since the main objective of the tests was determination of temperature differences, no corrections in plotting results were made to correct errors of this magnitude. In general, when several thermocouples were checked at one time, the deviation for all would be substantially the same. From this experience, it was concluded that the error observed was attributable to conditions within the instrument at the time of the test. Later, after more use, or after replacement of tubes in the electronic balancing system, the error might be greater or less, but within the limits stated.

Air Velocity.—Air velocity measuring devices were much less satisfactory than the temperature measuring systems used. Consequently, wherever the conclusions to be drawn from these two types of measurements were conflicting, the author was inclined to discount the evidence based on air velocity measurements.

The problems of air velocity measurement were many and vexing. Often the point where an observation should be made was inaccessible. Sometimes the velocity at a given point was not steady, but fluctuated widely. In systems using reversing airflow, the velocity past a given point for the flow in one direction was very different from that when the airflow was in the opposite direction.

Measurements were made with vane-type velometers and with three types of hot-wire anemometers. Duplicate readings were made in certain tests with two or more of the instruments and the agreement obtained was very poor.

Two of the hot-wire anemometers were commercial instruments of the same make; one had a directional probe and the other a nondirectional probe. Both probes were mounted at the end of 15 to 20 feet of extension lead wire and were used for obtaining air velocities between stacks. Whenever there was enough room above the stacks, air velocities were read at different levels between the stacks by lowering the probe to the desired position and reading the meter of the instrument. When the directional probe was used, considerable dexterity was required to keep the probe at the end of 10 or 15 feet of cable lined up with the direction of airflow. For this reason, the non-directional probe was used for most tests. Fluctu-

ating velocities observed with these indicating instruments were averaged by estimating the average at the time of reading.

The other hot-wire anemometer was one developed and described by Hukill (6). This instrument was arranged with long leads and was connected to the recording potentiometer for recording the potential set up in the thermocouples of the anemometer. The heating current to the hot junction was controlled by a resistance box. With this arrangement, velocities could be recorded over a period of time at a given location, and an average value determined.

In many of the tests, air velocities at test locations could not be obtained because there was insufficient space between the top of the stack and the ceiling for a man to crawl through to get to the various test locations.

Test Locations.—Test locations within a given room were selected so that both the warmest and coldest places in the room were represented, along with some intermediate locations. Some knowledge of the general performance characteristics of the rooms was required in making these selections. When conducting cooling performance tests, some compromises on test locations often were necessary because thermocouples had to be placed in fruit that was being received, and the experimental procedure had to be modified to conform with the warehousing operation.

Generally, locations were sought in the lower and upper portions of the same or adjacent stacks and at the back, front, and intermediate positions in given rows of fruit. If there was reason to believe that different rows in the room were subjected to widely differing air quantities, then different rows in the room were included. If the tests were primarily concerned with comparing the performance of different packages, then sample packages of the various types were placed at a number of representative locations in a given row. If sufficient stations were available on the recording instrument, positions in a number of rows were selected.

Various storages in the area were included in the tests because these storages represented certain types of air distribution, or cooling systems that were in general use, or systems that were being tried as a substitute for accepted forms. In all, tests were conducted in 32 refrigerated storage plants, and in some of these, a number of rooms were included that represented different refrigeration systems. Eleven different systems of air distribution are covered by the tests, and are described in the sections where their characteristics are discussed.

Analysis and Evaluation of Cooling Performance

The test records for cooling performance were evaluated by methods previously discussed by the author (11) and others (3, 16), to determine a cooling coefficient for each location. The cool-

ing coefficient for variable temperature surroundings, which is the normal state with room cooling, was calculated as follows:

$$C = \frac{\text{Fruit temperature reduction}}{(\text{Average } ^\circ\text{F. Td.}) (\text{Time})} \quad (1-A)$$

The fruit temperature reduction in each case was measured from the time when an appreciable reduction in temperature was first noted to the point when reduction in temperature stopped or tended to follow variations in room air temperature. Average $^\circ\text{F. Td.}$ (temperature difference) between fruit and air for the test period was determined by graphically obtaining average fruit temperature and average air temperature from a plot of the temperatures observed, and subtracting one from the other.

When the air temperature is reasonably constant, the logarithmic mean temperature difference between fruit and air for the test period may be substituted for average $^\circ\text{F. Td.}$ in equation (1-A). Where a constant cooling medium is used, another performance factor may be derived from the relationship described that is more readily comprehended than is the term cooling coefficient. This factor is the half-cooling time, denoted by the factor Z , which is

$$Z = \frac{\log_e 2}{C} = \frac{0.7}{C} \quad (2-A)$$

The factor Z may be calculated from cooling coefficients C determined for variable temperature surroundings, for purposes of comparison; however, Z has physical meaning only when the surrounding temperature is constant.

Later in this appendix, more detailed consideration is given to this matter and to the effect of the starting period on cooling coefficients and half-cooling time. From this analysis, it appears that characteristic cooling time might be a more appropriate term than half-cooling time. However, the use of the term half-cooling time has become quite well accepted, so it is used in this report interchangeably with characteristic cooling time.

Cooling coefficients were determined with respect to the temperature of the air adjacent to the test package (C_A) and also with respect to the average return air or average room air temperature (C_R) during the test periods. The values for C_A are the ones that were converted to Z and are shown in the various tables of experimental results. In some instances, the ratio C_R/C_A indicates that during the cooling period the adjacent air temperature was consistently higher than room air temperature or return air temperature from the room. This is an indication that a great deal of air is bypassing the fruit and that better performance could be obtained with better circulation past the stacks. However, the ratio cannot be

used as a reliable comparison between plants, because the total load coming into the room also influences return air temperature. If all tests had been conducted while plants were operating at full load, the ratio would have general significance. A great many tests, particularly on packed apples, were conducted under very light load conditions, and in these cases the ratio tends to approach 1, which would be the ideal figure indicating that all air circulation through the room is picking up as much heat as at the test location. In a few cases, the C_A/C_R ratio appears to be significant, and for these cases it is given in the tables under "Remarks," but in most cases, there are too many variables contributing to the ratio for it to be accepted as a significant gage of plant performance in these tests.

Z , the half-cooling time, is a convenient measure because it approximates the time required to remove one-half the heat that is to be taken from the commodity; in a period of $2Z$, three-quarters of the heat will be removed; and in a period of $3Z$, seven-eighths of the heat will be removed. With a 32° F. air temperature, a cooling period of $2Z$ will reduce the commodity temperature to 40° F. if the initial temperature does not exceed 64° F. For higher initial temperatures, a period of $3Z$ will generally be adequate to bring the commodity to 40° F.

All values for C and Z presented in this report were obtained by calculating the individual C values for each location in a test, averaging those pertaining to similar packages in a given test, and converting the average value obtained to Z by equation 2-A.

In the normal determination of cooling coefficients, the period of time analyzed was usually $2Z$ to $3Z$. Initially some time was required for the temperature difference to be fully established from outside to the point of measurement inside. Often a period of temperature equalization between individual fruits occurred in a package. If the thermocouple was located in a fruit that was colder than the average, it might warm up for a while before it started to cool. Such periods have been eliminated from the calculations by starting the cooling period at the first point where a consistent drop in temperature began. This procedure also eliminated the so-called "flat

portion" at the start of the cooling curve during which a temperature difference was being established. The procedure did not eliminate the period when the cooling coefficient was increasing to its full value. The period of changing cooling coefficient started when a sufficient temperature difference from outside to inside of a package had been established to start some heat flow, and ended when the full temperature difference had been established.

The cooling coefficient, or half-cooling time, calculated in this manner, included a certain penalty for this starting period which is discussed in greater detail later in this appendix.

Most of the continuous records of cooling performance ran for a week to 10 days. In the latter parts of these periods, there were opportunities to observe the final difference between the fruit temperature in the package and the adjacent air temperature. When the chart plotted from the record showed a period of a stabilized difference of temperature between fruit and air, this difference was measured and designated as the approach temperature.

Observations of uniformity of storage temperatures generally were made from intermittent temperature readings. In all cases, temperature equalization for 10 days after the fruit entered the room was allowed before any readings were included in the calculation of differences between warmest and coldest locations in the room. With intermittent readings, the difference between warmest and coldest location was noted for each time a reading was made, and the average was used as an index of variation in the room. This index, therefore, eliminated fluctuation of temperature that might occur over a period of time due to control variation or operational procedures.

These latter considerations also are important, but are best studied from examination of continuous records.

In several tests, the uniformity of storage temperature was observed from continuous records as well as from intermittent records. In such cases, the average temperatures of warmest and coldest fruit locations were measured graphically and compared. In general, the results obtained by the continuous records checked closely with the results of the intermittent records.

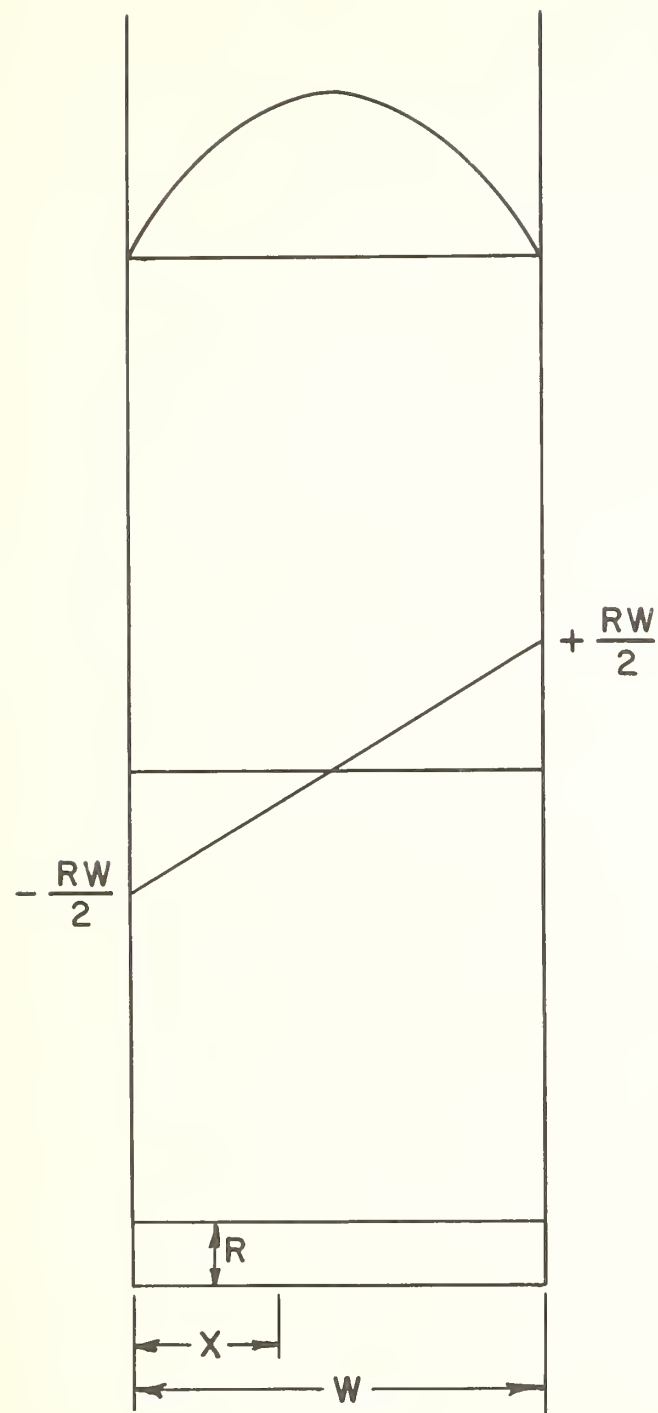
Analysis To Predict Approach Temperature

The analysis presented here to predict approach temperature is limited to the case where heat is lost from two sides of a pile of packages. The more complex cases of heat loss from four or six sides of a package are not considered. To make this analysis, the approach temperature is considered to be composed of two parts: (1) The temperature difference at the boundary, that is, the thermal potential necessary to move the heat through the package material itself and from the outer surface of the package into the air that serves

as a cooling medium; and (2) the interior temperature difference from the center of the mass of fruit to the inside surface of the package.

The boundary temperature difference is dependent upon the quantity of heat coming from the package, the area exposed for heat transfer, the thermal resistance of the package material, and the heat transfer coefficient from the surface to the air.

The interior temperature difference is more complex, since the quantity of heat passing a given cross section of the interior varies with the



TEMPERATURE DIFFERENCE

$$= \frac{R(WX - X^2)}{2AK}$$

HEAT QUANTITY MOVING
TOWARD PILE BOUNDARY

$$= \frac{-RW}{2} + RX$$

HEAT PRODUCED IN UNIT
WIDTH OF PILE = R

FIGURE 39.—Relation of heat produced, heat quantity flowing, and temperature difference at various positions in a pile of containers filled with fruit and exposed on two sides only.

distance from the center of the mass of fruit. The interior temperature difference may be determined from a formula developed below.

In figure 39, the width of the stack is represented on the horizontal axis as W and any point from zero to W is designated as X . The bottom curve, of the family of derived curves, shows the quantity

of heat produced per hour in a unit width of the stack as a constant R . The second derived curve represents the quantity of heat per box moving toward the pile boundary. Positive values represent movement toward the right, negative values represent movement toward the left boundary. At each boundary, half of the heat generated in

the pile must be dissipated. This is represented at each boundary by the quantity $\pm \frac{RW}{2}$, the sign denoting direction of flow. The quantity of heat flowing at any point X in the width of the pile is

$$q = -\frac{RW}{2} + RX \quad (3-A)$$

The temperature difference at any point is represented by the third derived curve and is calculated from the formula

$$q = -KA \frac{dT}{dX} \quad (4-A)$$

where T is temperature, A is the cross-sectional area in the direction of heat flow and K is the conductivity of the material through which the heat flows. The sign is minus to conform with the normal conventions of graphic presentation.

The expression for q , given by equation 3-A, is placed in equation 4-A and the terms transposed to give an expression for dT . When this expression is integrated, the formula for temperature difference between the boundary and any point X becomes:

$$T_x - T_B = \frac{R(WX - X^2)}{2AK} \quad (5-A)$$

where T_x indicates the temperature at point X and T_B indicates the boundary temperature.

From formula 5-A, the interior temperature difference may be calculated. Formula 3-A establishes the amount of heat which must be dissipated at the boundary. An overall transmittance value at the boundary may be calculated for package material and for the surface-to-air conductance and denoted by U .

The difference in temperature of the air (T_A) and of the boundary (T_B) may be written:

$$T_B - T_A = \frac{RW}{2AU} \quad (6-A)$$

The approach temperature is the sum of $T_B - T_A$ and $T_x - T_B$ and equals

$$\text{Approach } T = \frac{RW}{2AU} + \frac{R}{2AK}(WX - X^2) \quad (7-A)$$

For given values of R , A , U , K , and W , the maximum value occurs at $X = \frac{W}{2}$.

From these formulas, approach temperatures that may be expected under various conditions may be predicted. Reasonable values of R may

be established as follows: Assume the usual respiration value for apples at 31° F., 3 mg. of CO₂ per kg. of fruit per hour; the heat produced per day is 660 B.t.u. per ton of fruit and this reduces to 0.6 B.t.u. per box per hour with 44 pounds of fruit per box. If moisture loss from the fruit is one-half percent per month with standard packs, and one-eighth percent per month for packs with sealed liners, then the net sensible heat to be conducted from each container ranges from 0.3 to 0.52 B.t.u. per hour.

The value of R depends on the arrangement of the containers in the pile and the number wide. For simplicity, this discussion is limited to containers with flat surfaces, such as cartons that will stack closely together so regularly that the only exposed surfaces are the two sides of the pile, and the pile is considered to extend far enough in the other two dimensions that heat flow in those directions is of no consequence.

If the pile is one box wide with sides exposed to the air passages, then $W=12$ inches and R ranges from 0.025 to 0.044 B.t.u./hr./inch width/box.

If the pile is one box wide with ends exposed to the air passage, then $W=20$ inches and R ranges from 0.015 to 0.028 B.t.u./hr./inch width/box. The same values of R prevail if the pile is two boxes wide with only one end of each box exposed.

An apparent thermal conductivity (K value) of 1.56 B.t.u./hr./sq. ft./°F. Td./inch of thickness for packs of apples where convection currents are negligible has been determined by Smith, Gane, and Dreosti (14).

The cross-sectional area of the box in the direction of heat flow is approximately 1 square foot when boxes are stacked with ends exposed and 1.6 square feet when stacked with sides exposed.

The values of U for the boundary temperature difference may be approximated as follows: The conductivity of fiberboard is approximately 0.5 B.t.u./hr./sq. ft./°F. Td./inch of thickness. For an average thickness of one-half inch, the conductance would be 1. The conductance from the surface to the air varies, however; when the analytical work published by Hicks (5) is compared with some experimental values reported herein, it appears that this conductance may vary from 0.5 to 4 B.t.u./hr./sq. ft./°F. Td. Combining this with the conductance of the container, it appears that U may vary from 0.33 to 0.8 B.t.u./hr./sq. ft./°F. Td.

Those values are used with equation 7-A to calculate approach temperatures for different stack arrangements, for different rates of moisture loss from fruit, and for different outside surface conductances. The results of the calculations are given in table 13, which shows the portion of the approach temperature attributable to the internal temperature difference and to the boundary difference.

TABLE 13.—Approach temperatures calculated for packed cartons of apples at 31° F. using various stacking arrangements, moisture loss rates, and outside surface conductances

Stacking arrangement	Moisture loss rate ½ percent per month					Moisture loss rate ¼ percent per month				
	Internal Td.	Boundary Td.		Approach temperature ¹		Internal Td.	Boundary Td.		Approach temperature ¹	
		U=0.333	U=0.8	U=0.33 ²	U=0.8 ³		U=0.333	U=0.8	U=0.33 ²	U=0.8 ³
I. 2 sides exposed to air-----	° F. 0. 18	° F. 0. 28	° F. 0. 12	° F. 0. 46	° F. 0. 30	° F. 0. 32	° F. 0. 49	° F. 0. 21	° F. 0. 81	° F. 0. 53
II. 2 ends exposed to air-----	. 48	. 45	. 19	. 93	. 67	. 84	. 79	. 33	1. 63	1. 17
III. 2 rows stacked together, 1 end of each carton exposed										
Condition at center of either box where distance from edge of pile=10 inches-----	1. 44	. 9	. 37	2. 34	1. 81	2. 52	1. 57	. 65	4. 09	3. 17
Condition at center of pile-----	1. 92	. 9	. 37	2. 82	2. 29	3. 36	1. 57	. 65	4. 93	4. 01

¹ Based on a respiration rate for the fruit of 3 mg. of CO₂/kg. of fruit/hr.
² U is overall heat transfer through carton to air based on heat transfer coefficient from outside surface to air=0.5 and resistance of fiberboard carton.
³ U is overall heat transfer through carton to air based on heat transfer coefficient from outside surface to air=4 and resistance of fiberboard carton.

Analysis To Predict Effect of Several Variables on Cooling Performance

The formulas and tables presented by Hicks (5) for the cooling of a pile of packages from two sides with air temperature constant can be used to investigate the effect of air velocity past the package or stack. The formulas given for temperature at the center and the average temperature are as follows:

at center

$$\frac{t_c - t_o}{t_i - t_o} = \sum_{n=1}^{\infty} \frac{2 \sin B_n}{B_n + \sin B_n \cos B_n} e^{-\frac{B_n^2 a \theta}{\left(\frac{W}{2}\right)^2}} \quad (8-A)$$

and average temperature

$$\frac{t_a - t_o}{t_i - t_o} = \sum_{n=1}^{\infty} \frac{2 \sin^2 B_n}{B_n (B_n + \sin B_n \cos B_n)} e^{-\frac{B_n^2 a \theta}{\left(\frac{W}{2}\right)^2}} \quad (9-A)$$

where $\pm B_n$; $n=1, 2$, etc., are the roots of

$$B \tan B = \frac{hW}{2K} \quad (10-A)$$

In these equations, the symbols have the following meaning:

- t_i =initial temperature
- t_c =temperature of center at time θ
- t_a =average temperature at time θ
- t_o =air temperature
- a =thermal diffusivity of a packed box of apples=0.00445 sq. ft./hr.
- K =thermal conductivity of a packed box of apples=1.56 B.t.u./hr./sq. ft./°F. Td./inches of thickness

- θ =time in hours
- W =width of the stack=ft.
- h =heat transfer coefficient from box surface to air=B.t.u./hr./sq. ft./°F. Td.
- e =base of natural logarithms=2.7183

Except for the very early stages of cooling, it is necessary to evaluate only the first term of each series, and equations 8-A and 9-A take the simplified form where the terms A_c and A_a are substituted for the series factors:

$$\frac{t_c - t_o}{t_i - t_o} = A_c e^{-c\theta} \quad \text{for the center temperature} \quad (11-A)$$

and

$$\frac{t_a - t_o}{t_i - t_o} = A_a e^{-c\theta} \quad \text{for the average temperature} \quad (12-A)$$

In the above equations $C = \frac{B^2 a}{\left(\frac{W}{2}\right)^2}$ and is the

same as the cooling coefficient defined in equation 1-A.

Table 14 presents values for factor A_c , factor A_a , cooling coefficient C , and half-cooling time Z , taken from Hicks (5) for a stack 12 inches wide (that is, boxes or cartons stacked with ends butted and both sides presented to the air) for various values of h ranging from 0.5 to 4. A similar calculation has been made for the case where cartons are stacked in piles 20 inches wide with two ends of each carton exposed and in piles 40 inches wide with only one end of each carton exposed.

TABLE 14.—Cooling coefficients, half-cooling time, and factors A_c and A_a , calculated for packed cartons of apples using various stacking arrangements and outside surface conductances

Stacking arrangement	Heat transfer coefficient h <i>B.t.u./hr./sq. ft./° F. Td.</i>	A_c	A_a	Cooling coefficient C <i>° F./hr./° F. Td.</i>	Half-cooling time Z <i>Hours</i>
I. 2 sides exposed to air-----	0.5 1.0 2.0 3.0 4.0	1.18 1.24 1.26 1.26 1.27	0.97 .94 .89 .87 .86	0.020 .028 .035 .037 .039	35 25 20 19 18
II. 2 ends exposed to air-----	.5 1.0 2.0 3.0 4.0	1.215 1.25 1.266 1.27 1.27	.94 .90 .865 .85 .84	.0095 .0120 .0137 .0144 .0148	74 58 51 48.6 47.3
III. 2 rows stacked together, 1 end only of each carton exposed.	.5 1.0 2.0 3.0 4.0	1.25 1.266 1.27 1.27 1.27	.90 .865 .84 .83 .824	.0030 .0034 .0037 .00375 .0038	233 206 189 187 184

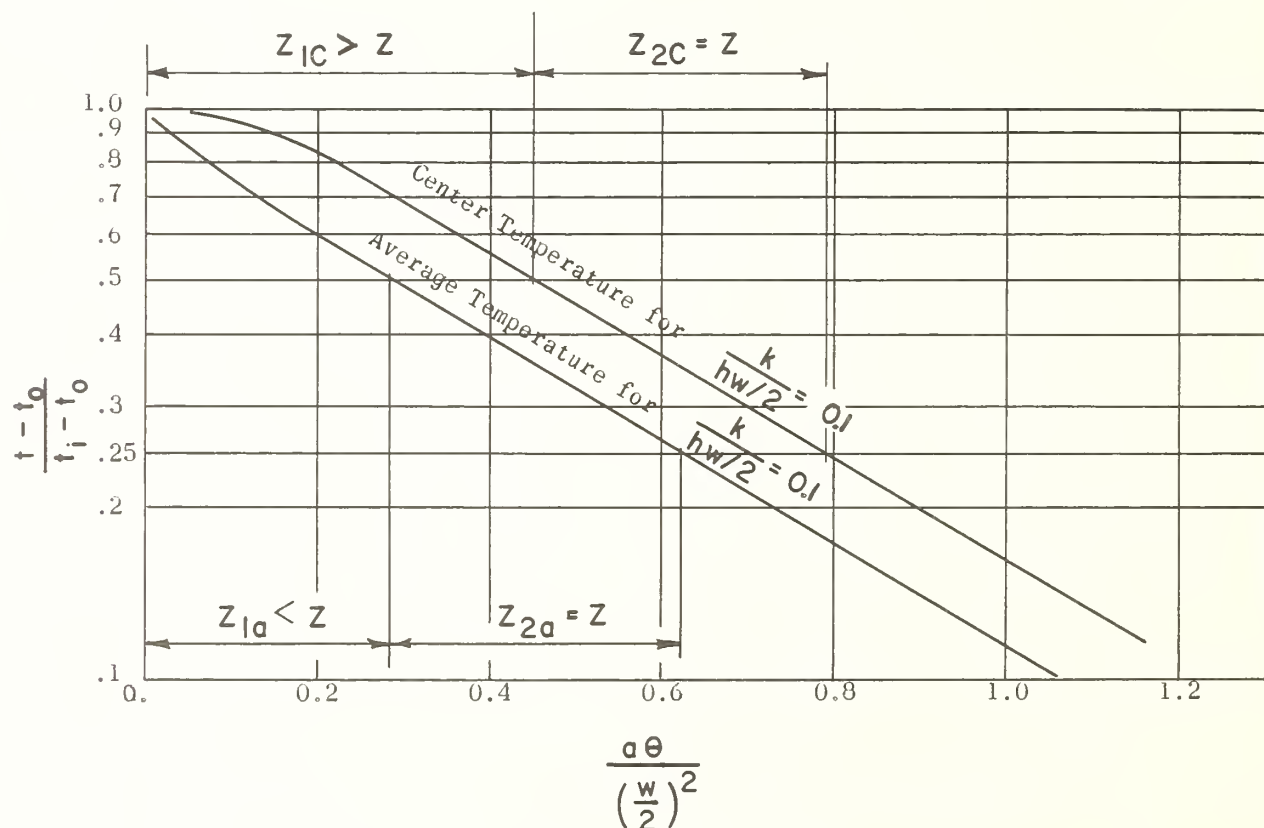


FIGURE 40.—Effect of starting period on average and center temperatures of a rectangular slab cooled from two sides only.

Analysis To Determine Effect of Starting Period on Cooling Coefficient and Half-Cooling Time

Study of the charts presented by Henderson and Perry (4) gives a better insight into the meaning of some of the factors in the Hicks equations (11-A and 12-A).

In the equation $\frac{t_c - t_o}{t_i - t_o} = A_c e^{-c\theta}$ for the center

temperature, A_c is the ratio of the apparent initial temperature difference to the actual initial temperature difference and accounts for the time taken to establish the temperature difference between the outside and the center of the package. In the equation for the average temperature, the factor A_a also relates to this starting condition. The effect of these factors can best be seen by the illustration in figure 40, where a typical center temperature and average temperature line from the chart for the cooling of rectangular slabs (4) is plotted.

For the center position, there is a period at the start where the slope of the line is less than is the case for most of the cooling process; for the average position, there is an initial period where the slope is greater than during most of the cooling period. After these periods of initial varying slope, the slope of the lines for both cases is constant and the two lines are parallel; that is, they have the same slope. Since the cooling coefficient is proportional to the slope of the line, in their straight portions, both the center and the average position have the same cooling coefficient. The time required for the initial temperature to be reduced 50 percent at the center is greater than the time for reduction from 50 percent to 25 percent, or from 25 percent to 12.5 percent of initial value. The time required for average temperature to be reduced 50 percent is less than the time required for the reduction from 50 percent to 25 percent, or from 25 percent to 12.5 percent of initial value. However, the time for reduction of temperature from 50 percent to 25 percent, or from 25 percent to 12.5 percent of initial value, is the same for either the center or the average. If we represent the time of cooling to 50 percent of initial value as Z_1 , the time to cool from 50 percent to 25 percent as Z_2 and the time to cool from 25 percent to 12.5 percent of initial temperature as Z_3 , then we may say $Z_{2c} = Z_{3c} = Z_{2a} = Z_{3a}$ and any of these may be called the characteristic cooling time, Z . However, it is also true that $Z_{1c} > Z$ and $Z_{1a} < Z$. This observation is in agreement with the fact that the factor A_c calculated in table 14 is greater than 1 in all cases and the factor A_a is less than 1.

The foregoing illustrates that the time required to reach 50 percent temperature reduction is not exactly the same as half-cooling time (which term has been used interchangeably with characteristic cooling time in this discussion). However, the

time to reduce the temperature from 50 percent to 25 percent of its initial value usually is the true characteristic cooling time. Examination of Henderson and Perry's curves shows that only in a few extreme cases for the average temperature will there be any curvature in the cooling line by the time it has passed the 50 percent reduction mark. Once the cooling curve has become a straight line on the semilogarithmic plots, then the true characteristic cooling time and true cooling coefficient may be obtained.

The method of analysis used to determine half-cooling time from the experimental data has included performance during the period designated as Z_1 . The arbitrary starting point for analysis has cut off the initial "flat area" at the start, but has not eliminated that portion where the cooling coefficient for the center position is increasing to its full value. Therefore, the experimental determinations give values that are somewhat slower than the true characteristic cooling time. When the experimental determinations were rechecked to eliminate the period Z_1 , it was found that in cases where adjacent air temperature was nearly constant during the test period, the value of Z was about 10 percent better. Where air temperature dropped during the test period (and this was the usual case), the value of Z did not change appreciably.

The factors A_a and A_c in equations 11-A and 12-A are related to the establishment of the temperature difference between the center of the package and the outside in an instance where a constant-temperature cooling medium is used. It is understandable that in such a situation, this factor would no longer be operative after the first unit of characteristic cooling time Z_1 . However, when cooling takes place in a medium whose temperature is changing, there may be a certain amount of this effect throughout the cooling process.

Therefore, we may expect that cooling coefficients determined experimentally under changing air temperature conditions will contain some influence of the factor A_c and may possibly be 10 percent lower than those determined for the same commodity, similarly packaged and stacked, where cooled in a constant-temperature medium. Fortunately most of the differences in half-cooling time that have been considered important are greater than 10 percent. Where comparisons are drawn between different packages on the same test, the penalty due to the time required to establish full temperature difference is included in the half-cooling time for all of the types of packages, and a legitimate comparison may be made, even though the determination has been made under conditions where the cooling air temperature varied.

