BENNETT 63

Thermal Characteristics of Peaches
as Related to
Hydrocooling

Technical Bulletin No. 1292

BENNETT

UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Marketing Service
in cooperation with
UNIVERSITY OF GEORGIA
College of Agriculture Experiment Stations

Preface

This study of the heat transfer characteristics of peaches and the design, operation, and performance of conventional hydrocoolers is part of a broad program of research aimed at developing improved methods and equipment for maintaining quality in fruits and vegetables.

The research was conducted cooperatively by the Transportation and Facilities Research Division, Agricultural Marketing Service, U.S. Department of Agriculture, under the general supervision of Joseph F. Herrick, Jr., marketing research analyst of the Handling and Facilities Research Branch; and by the University of Georgia, College of Agriculture Experiment Stations, under the general supervision of R. H. Brown, agricultural engineer, College Experiment Station.

Ralph E. Smith, assistant agricultural engineer, of the College Experiment Station, contributed to the planning, design, and conduct of the work. J. L. Carmon, head of the Department of Experimental Statistics, and J. C. Fortson, assistant statistician, advised and assisted in the data analysis.

Fruit used in this research was provided by the Department of Horticulture of the university.

Contents

Washington, D.C.

October 1963

Summary

This report presents data on the fundamental and applied heat transfer characteristics of peaches being cooled with water. The "effective" thermal diffusivity of six varieties of peaches was determined in laboratory tests. An average of the values of the six varieties provides a reasonable prediction of the "effective" thermal diffusivity for all firm ripe peaches. This heat transfer characteristic can be used to predict the cooling rate of peaches, based on their size and initial temperature, and the amount of hydrocooling needed to cool peaches to any desired temperature within any given period of time.

The "effective" thermal diffusivity was found to vary statistically among the varieties tested. The principal sources of variation are assumed to be attributable to such varietal factors as shape of fruit and ratio of volume of flesh to stone. The differences are too small to have practical significance under present conditions.

Under ideal cooling, the mean film coefficient of heat transfer from the surface of peaches to water was estimated to range from 125 to 165 British thermal units per hour per square foot of surface area per degree Fahrenheit. This value is approached in conventional flood-type hydrocoolers with water circulating at the rate of 15 gallons per minute (gpm) per square foot of cross-sectional area.

A flow rate of 15 gpm per square foot of cross-sectional area is recommended where depth of the fruit to be cooled is equivalent to the depth of a bushel basket. If the fruit depth is 8 inches or less, as might be the case in bulk hydrocooling, 5 gpm per square foot is effective. Should the water be dispersed into fine particles and uniformly distributed over the surface of the fruit, with spray nozzles, for example, 10 gpm is as effective as 15 gpm.

A wetting agent introduced into the cooling water at a concentration of 250 parts per million did not increase the cooling rate under the conditions studied.

Water temperature studies indicated that improved efficiencies might be gained, without seriously jeopardizing cooling rate, by forming "zones" or "stages" in the cooling tunnel at progressively lower cooling water temperatures from entrance to exit.

Use was made of the concept of mass-average temperature location in peaches during hydrocooling. By taking into account the final mass-average temperature, hydrocooling system efficiency, and cooling coefficient, a method for computing an overall performance index for a hydrocooling machine in operation is introduced.

Hydrocooler performance studies in six typical packinghouses in Georgia and South Carolina indicated that performance could be improved in most cases.

Thermal Characteristics of Peaches as Related to Hydrocooling

By A. H. Bennett, *Agricultural Engineer, Transportation and Facilities Research Division, Agricultural Marketing Service*

Introduction

Most of the peaches shipped from principal eastern producing areas to distant markets are hydrocooled. Hydrocooling simply means cooling a substance with water; ice water (33°–36° F.) is usually used for rapid heat removal.

The process of hydrocooling peaches in the packinghouse can be described as the rapid removal of heat, as soon as possible after harvest and before shipment, to reduce the fruit temperature to a level that will retard softening and inhibit growth of decay-producing fungi—principally brown rot and rhizopus rot. Hardenburg (*6*)[1] states that a desirable goal in hydrocooling is to lower the fruit temperature to 55° F. or below, but a temperature of 40° F. is required to prevent well-matured peaches from softening. If the fruit is to be cooled to an average temperature of 40° to 45° F., the grower may delay harvest until the fruit reaches a more mature stage on the tree. Fully developed, firm ripe peaches that reach the market in a sound, disease-free condition are always in demand and bring a better price than fruit that is packed green on the assumption that it will ripen in transit.

Most existing commercial hydrocoolers are of the same basic design, and are commonly referred to as flood-type hydrocoolers. This term is derived from the principle employed. Fruit, in water-resistant containers or in bulk, is conveyed through a tunnel. In this tunnel, a deluge of cold water issues, under gravity flow, through a series of orifices and is then dispersed by a wire screen for uniform coverage. Immediately, the cooling water comes in contact with all the fruit. Thus, as heat moves from inside the fruit to the surface, it is promptly removed from the surface and rapid cooling is accomplished.

With standard units, conveyor speed is variable, and cooling tunnels are available in any variety of lengths, permitting considerable operating flexibility.

Water flow rates are constant for any given length of cooler, whether a single unit or combinations of units of various lengths are used. While ice is the most prevalent means of chilling the cooling water, in

---

[1] Italic numbers in parenthesis refer to items in Literature Cited, p. 29.

some larger and medium-sized packinghouses, the water is cooled with mechanical refrigeration.

Hydrocoolers are almost always at the end of the packing line, where cooling is accomplished after the fruit has been packed in shipping containers. Where bulk cooling is practiced, the unit is usually located between the washer, or defuzzer, and the packing line.

After publication of results of a few early trials of packinghouse hydrocooling (*1*), the benefits attained quickly received widespread recognition. Subsequently, buyers began to pay a premium for hydrocooled fruit, for which demand had grown. The amount of the premium was clearly adequate to justify the purchase of hydrocooling equipment, even by the smallest packers. As a result, the peach industry called upon manufacturers of food machinery for equipment to do the job. Machinery companies then began producing hydrocoolers, although only limited information was available concerning the fundamental heat transfer characteristics of the products to be cooled. The essentials of the hydrocooling process and of operating procedures have changed little since the early models were sold.

Most commercial hydrocoolers are fully capable of doing an effective job of product cooling. Often, however, the machines are not used to their full capability. Improvement in the design of conventional machines, as well as improved operating practices, can lead to more efficient hydrocooler performance. The logical question, then, is: Can they be improved, and if so, how?

The principal factors that influence the cooling performance and operating efficiency of a conventional hydrocooler are: (1) Initial and final temperature of the fruit; (2) fruit size; (3) temperature and flow rate of the cooling water; (4) conveyor speed; (5) ambient temperature; (6) protection from solar radiation and air movement through the cooler; (7) in the case of mechanical refrigeration, tonnage capacity of the system; and (8) arrangement of fruit in the cooler.

Previous research, observation, and experience have pointed out the effects of some of these factors. In addition, tests have been made to determine the effects of detergents in the water and of fruit maturity on cooling rates. However, a thorough and detailed analysis and evaluation, based on fundamental heat transfer principles, have not been made heretofore.

The recent trend toward tray or carton packing has, in some instances, resulted in the use of an immersion-type hydrocooler. In this method, the fruit is conveyed through a vat of agitated chilled water. Theoretically, the water must be agitated to achieve maximum cooling effectiveness. If the performance of this nonconventional hydrocooler is to compare favorably with that of the conventional flood-type hydrocooler, provision must be made for circulation of an adequate amount of water at the required temperature. Time-temperature relations, evaluated with respect to water temperature and volume of flow, should be of value for this purpose.

The principal objectives of this research were: To determine the fundamental and actual heat transfer characteristics of peaches as related to hydrocooling; and to use this information, along with a general understanding of thermal engineering principles, as a basis for recommendations that will produce more efficient equipment and operating techniques.

Review of Studies by Other Researchers

Performance data have been obtained by other researchers on the operation of conventional hydrocoolers under typical packinghouse conditions.

In 1954, Toussaint et al. (*13*) found, from a study of 12 packinghouses in the sandhills of North Carolina, that operating practices varied considerably among packinghouses. As an example, they found final "pit" temperatures varying from 44° F. to 57.5° F. They further reported that 20 pounds of ice was melted for each bushel of peaches cooled 30 degrees F., if a minimum of 1,000 bushels were cooled in a day. The ice cost under these conditions was $0.072 per bushel. By combining fixed and variable costs with cost of ice, Toussaint and associates found that it cost $0.128 to hydrocool one bushel of peaches in a shed having an annual volume of 30,000 bushels, and $0.206 per bushel in a shed having an annual volume of 10,000 bushels.

Redit et al. (*9*) conducted packinghouse studies in Georgia and South Carolina in 1954. They found considerable variation in cooling coefficients (ranging from 3.32 to 6.91) among hydrocoolers of the same type. Tests in immersion-type coolers resulted in lower coefficients than in conventional flood-type coolers. Ice consumption, as measured in four of the tests, averaged 0.88 pound per bushel for each degree F. of temperature reduction. Use rates ranged from 0.68 to 1.18 pounds of ice per bushel per degree F. Redit and associates reported that the efficiency of the hydrocoolers studied ranged from 30 to 53 percent. This means that, in the case of the least efficient, 70 percent of the refrigerating effect of the melting ice was not utilized for cooling peaches. On this basis, assuming $8 per ton for ice, it would cost $0.18 per bushel, for ice alone, to cool fruit 37.5 degrees. If all the refrigerating effect from the melting ice could be utilized, ice cost would be $0.053 per bushel.

Sainsbury (*11*), in 1955, introduced the term "half-cooling time"[2] to characterize the cooling rate. Use of this term is based on a logarithmic function of temperatures of product and cooling fluid during the cooling period in question. In hydrocooling peaches, during the first several minutes of the cooling period, the reduction in mass-average temperature is not a linear logarithmic function. For this reason, the half-cooling time factor does not lend itself for use in evaluating the effectiveness of a hydrocooling system.

Guillou (*3*), in comparing cooling rates by various methods, showed that 8 to 14 minutes are required to half-cool certain peaches (temperature measurement at the pit) in a hydrocooler, while 1 hour is required to cool the same fruit by forced air cooling and 6 hours are needed for conventional room cooling methods.

Laboratory Studies of Heat Transfer Characteristics

Fruit size, physical properties, temperature difference between the fruit and the cooling water, and water flow rate are the primary factors that affect the cooling rate of peaches in a conventional flood-

---

[2] Half-cooling time is the time required to reduce the temperature difference between the object and the cooling fluid to one-half its initial value.

type hydrocooler. Design, construction, and operation of hydrocooling systems are predicated upon the rate of heat removal or product heat load. Because of the limited amount of data describing the thermal properties and characteristics of peaches, designers and builders of hydrocooling systems are presently guided largely by experience and trial-and-error processes. Fundamental data, acquired by scientific means and put into a readily usable form, should enhance the development and use of improved equipment and methods for more efficient and less costly hydrocooling of peaches.

Coefficients

Description and Use

The two principal means of heat transfer from peaches being hydrocooled are: (1) Conduction from the inside of the fruit to the surface, and (2) convection from the surface to the cooling water. Rate of heat flow by conduction through a homogeneous substance is characterized by a term called thermal conductivity.[3]

Thermal diffusivity[4] is another term often used advantageously, particularly when expressing heat flow in the transient state. The thermal diffusivity "constant" has utility through its use in established relationships to predict the temperature at any time under any specified cooling condition at any point in any given size of homogeneous solid that conforms to a definable geometric configuration. The term "effective" thermal diffusivity is a more precise characterization for whole peaches, consisting of components having dissimilar physical properties and not conforming to an expressible geometric configuration. Convective film or surface coefficient[5] is used to describe the rate of heat flow from the surface of a substance to fluid flowing across its surface. It is used here to compare the actual rate of heat transfer from the surface of peaches to the maximum possible rate of heat transfer as dictated by the rate of heat flow from inside the fruit to its surface. Maximum heat flow occurs when the surface quickly assumes a temperature very nearly equal to that of the cooling fluid.

Review of Literature

A few investigators have measured the thermal diffusivity ("effective") of certain whole specimens of fresh fruits and vegetables by the method described in this report. Gane, in 1936 (*2*), perhaps the first to use this technique, reported values of thermal diffusivity for several fruits and vegetables, including oranges and grapefruit. His findings constituted the available information in the field for some time, but his investigations were limited and a search of the literature failed to reveal any subsequent efforts on his part in this direction. In 1950, Kethley et al. (*8*) measured the "average thermal diffusivity" of peach flesh by extracting, in the shape of a sphere, homogeneous portions from the fruit. Their tests were conducted under conditions of rapid freezing within the temperature range of 80° to 0° F. Turrell and Perry (*14*), in 1957, reported measured values of "effective" thermal diffusivity for Marsh grapefruit, Eureka lemons, and Valencia, Washington, and Navel oranges. Agreement among the mean values as reported in those investigations tends to validate the experimental procedure. However, the absence of repeated tests under controlled conditions suggests the need for more comprehensive study. To this end, the objectives set forth below were pursued.

---

[3] Thermal conductivity is defined as the time rate of heat flow through a unit area of a homogeneous substance under the influence of a unit temperature gradient.

[4] Thermal diffusivity is a thermal property that describes the heat transfer characteristic of a substance during transient heating or cooling.

[5] Film coefficient of heat transfer is the rate of heat transfer from a unit area of a surface to a fluid in contact with it, per unit difference in temperature between the surface and the fluid.

Objectives

Objectives of this study were:

(1) To measure the "effective" thermal diffusivity of several shipping varieties of whole peaches.

(2) To determine if diffusivity varies significantly among varieties and with maturity within varieties.

(3) To estimate film coefficients of heat transfer from the surface of peaches to water under maximum cooling conditions.

(4) To develop prediction equations to determine the temperature distribution within various sizes and varieties of peaches cooled under any specified condition.

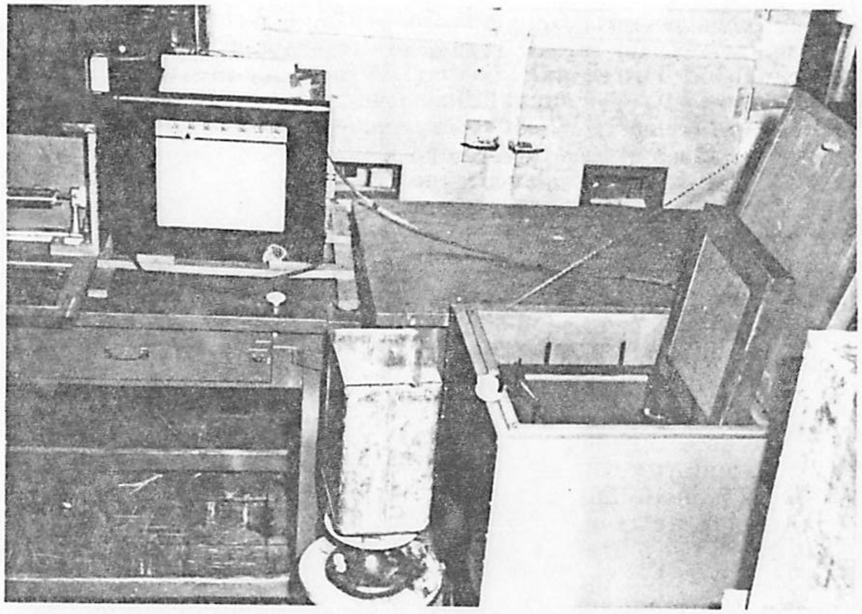
Experimental Procedure

Tests were conducted during the 1960 and 1961 seasons. The test procedure, equipment, and instrumentation were essentially the same for both years. Some refinement in technique was made for the 1961 tests in an effort to control some of the variation encountered previously, and to assure that the tests were valid. Unbrushed fruit was used in all tests.

The equipment and instrumentation used included: (1) A sealed, insulated test chamber, through which water at a constant temperature was rapidly circulated; (2) a refrigeration system; (3) a stopwatch; and (4) a recording potentiometer (fig. 1). Fused thermocouple junctions were constructed of 36 a.w.g. copper constantan thermocouple wire. Temperature measurements were taken at the center, at ¼-inch increments along the radius, and on the surface (fig. 2). The test specimen of known size was warmed to an initial uniform temperature of approximately 90° F., then suddenly plunged into an agitated cold water bath at 35° F.

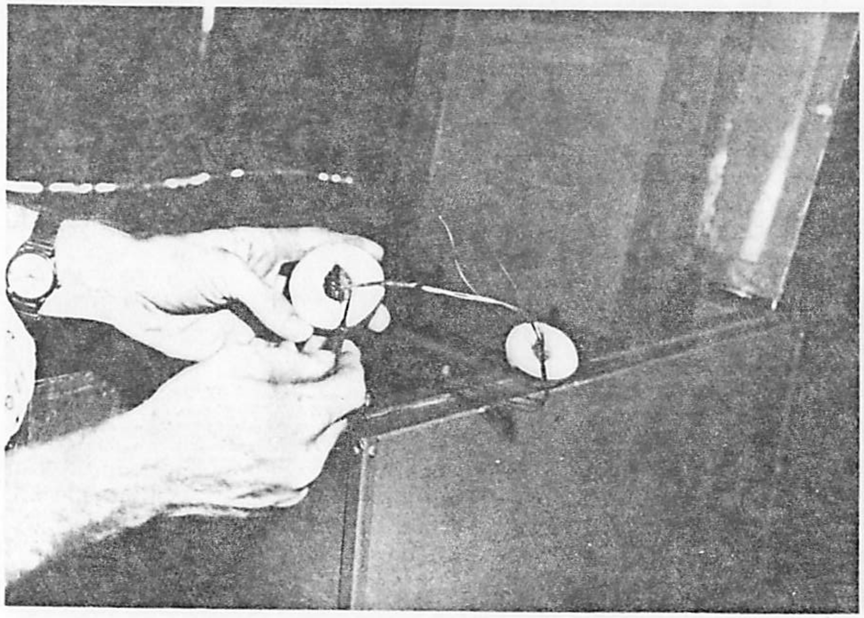
In 1 minute, the initial center temperature was recorded. The center and other temperature points were subsequently recorded periodically throughout the test. Twelve minutes were allowed for the specimen to achieve an analytically describable condition of transient heat flow. By the use of relationships given by Williamson and Adams (*15*), the "effective" thermal diffusivity was computed (see appendix, p. 31). By measuring the density of each specimen and assuming the specific heat to be 0.9 B.t.u. per (lb.) (° F.), the corresponding thermal conductivity was computed. Density was measured by the water displacement technique.

In 1960, values of "effective" thermal diffusivity were determined from 10 runs of Dixie Gem, Red Haven, and Hale Haven varieties. Analysis of the data showed significant differences among varieties.



BN-18333

FIGURE 1.—Laboratory apparatus for testing heat transfer characteristics of peaches.



BN-18336

FIGURE 2.—Test peach showing thermocouple probe inserted into center of fruit through hole drilled into seed.

The test data revealed that possible variation in maturity or in size or shape among varieties could have produced this effect.

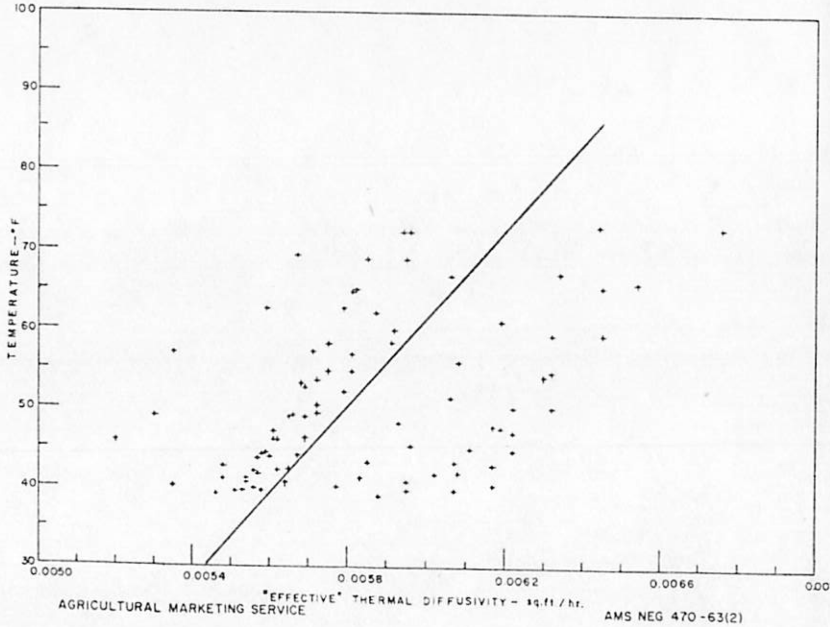
To explore further the questions raised as a result of the 1960 tests, 10 runs were made on each of the following six varieties: Dixie Gem, Red Haven, Hale Haven, Cardinal, Early Red Free, and Elberta. Maturity was evaluated in terms of hardness per gram of sample weight, measured with an electronic recording shear-type pressure meter. Size was held as uniformly as possible within varieties. Analyses for differences among varieties and the effect of hardness and fruit size were made.

Results and Discussion

Table 1 lists the results of the 1960 and 1961 tests. Values of "effective" diffusivity and conductivity are computed means of all observations by variety, within the fruit temperature range from 80° F. to 40° F. The influence of temperature on diffusivity can be examined for each variety by plotting temperature, as the independent variable, against diffusivity, from the following linear regression equations computed for each variety:

(1) Hale Haven........................ $t=55{,}500.0\,\alpha-271.67$
(2) Red Haven......................... $t=82{,}456.4\,\alpha-369.19$
(3) Dixie Gem......................... $t=52{,}386.3\,\alpha-227.70$
(4) Cardinal.......................... $t=47{,}817.6\,\alpha-209.04$
(5) Elberta........................... $t=39{,}102.7\,\alpha-157.78$
(6) Early Red Free.................... $t=37{,}706.6\,\alpha-149.62$

Figure 3 shows the relation of temperature to diffusivity for the Hale Haven variety.



AGRICULTURAL MARKETING SERVICE

AMS NEG 470-63(2)

FIGURE 3.—Influence of temperature on "effective" thermal diffusivity for Hale Haven peaches.

Coefficients to express the correlation between temperature and diffusivity suggest a satisfactory fit of individual data points to the average regression line as obtained for each variety. Coefficients of variation among runs within varieties indicate validity of the experimental procedure and suggest reliability in the experimental results.

Differences in values of "effective" thermal diffusivity among varieties were found to be statistically significant. However, when considered in the sense of variation in actual cooling time, it is likely that the differences as compared by the curves of figure 4 have a negligible significance in practice. Therefore, the average mean "effective" thermal diffusivity for the six varieties listed in table 1 can be used in practice to predict expected cooling rates. The equations for the curves of figure 5, representing the mean mass-average temperature for the six varieties, were developed by Smith and Bennett (*12*). Values for these curves were computed by use of the prediction equations given in the appendix.

Variation in maturity, as measured by hardness, produced no measurable variation in experimental thermal conductivity. A slight correlation was found between fruit size (which varied statistically among varieties) and thermal conductivity, but hardly of sufficient magnitude to be of any significance, especially if the results were affected by experimental error. It is possible that slight differences in shape, size, and other physical characteristics among varieties tested produced systematic errors which led to the resultant variation among varieties in experimental values. A more detailed examination of the thermal characteristics of peach flesh is needed before positive conclusions can be drawn concerning this phenomenon.

An average film coefficient of heat transfer from the surface of a peach immersed in a well-agitated water bath at 35° F. was found to be approximately 120 B.t.u. per (hr.) (sq. ft.) (° F.). Experience and observation have shown that this is about an optimum value for

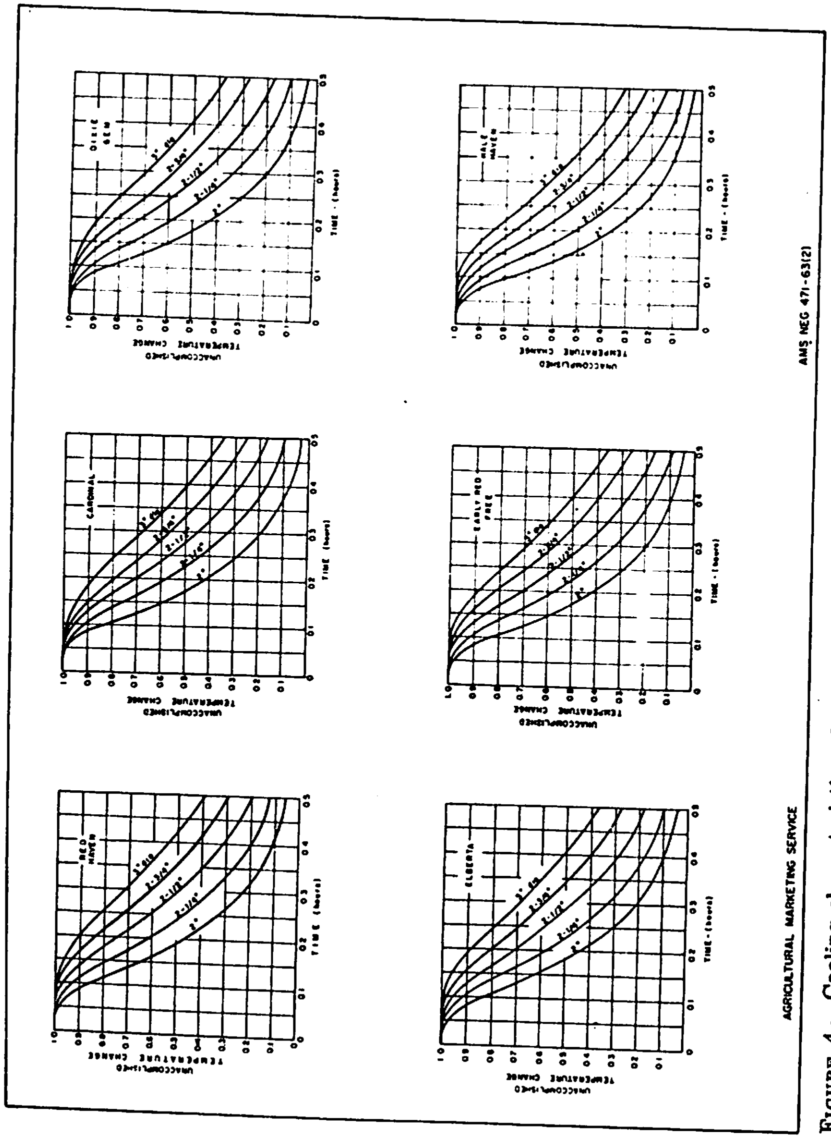
TABLE 1.—*Test results to determine thermal properties of six varieties of peaches as listed*

Year	Variety	Effective [1] thermal diffusivity	Density [1]	Thermal [2] conductivity
		Sq. ft./hr.	*Lb./cu. ft.*	*B.t.u. (hr.) (sq. ft.) (°F./ft.)*
1960	Hale Haven	0.005794	59.9830	0.3128
	Red Haven	.005160	59.4160	.2759
	Dixie Gem	.005121	60.7078	.2798
Average		.005358	59.9846	.2892
1961	Hale Haven	.005799	59.0840	.3084
	Red Haven	.005097	60.2410	.2763
	Dixie Gem	.005305	58.2314	.2780
	Cardinal	.005442	59.4090	.2910
	Elberta	.005320	59.6978	.2858
	Early Red Free	.005387	60.0715	.2912
Average		.005393	59.4558	.2885

---

[1] Average of total observations for each variety.

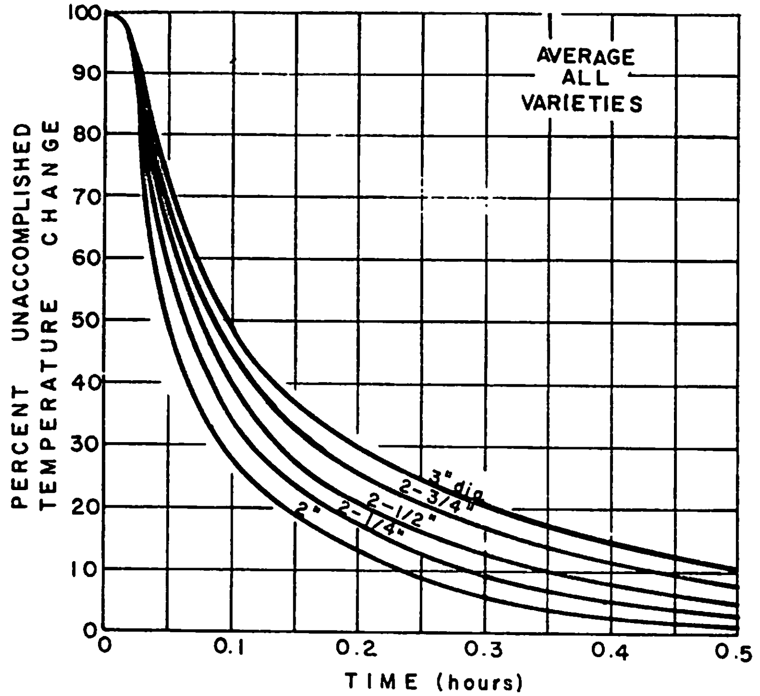
[2] Computed by assuming specific heat equals 0.9 B.t.u./lb. ° F.



AGRICULTURAL MARKETING SERVICE

AMS NEG 471-63(2)

FIGURE 4.—Cooling characteristics of six peach varieties, based on experimentally determined values of "effective" thermal diffusivity. Temperature at center of fruit.



AGRICULTURAL MARKETING SERVICE .AMS NEG 472-63(2)

FIGURE 5.—Calculated mass-average temperature of peaches during ideal cooling.

hydrocooling peaches. This is roughly equivalent to a theoretical surface coefficient calculated at a mean water velocity of 15 feet per minute and a film temperature of 35° F. While the film coefficient from the surface of peaches can be increased by increasing the mean velocity of water across the surface, the difference between the water and surface temperature will decrease proportionately with the result that the rate of heat flow from the surface of the fruit will remain virtually unchanged. Because of restricted heat flow from within to the surface of peaches, imposed by their thermal property, and because of limitations by virtue of a minimum temperature of the cooling water, there will be no perceptible increase in the rate of heat removal.

Effect of a Wetting Agent on Cooling Rate

Background

Addition of a wetting agent alters the physical properties of water. Theoretically, when other factors are held constant, the film coefficient of heat transfer from a surface to a fluid increases as the dynamic viscosity of the fluid is reduced. Considering the surface characteristics of a peach, the film coefficient will logically increase as the capacity of water to form a smooth, bubble-free film on its surface becomes greater. This argument leads to the possible conclusion that in hydrocooling, the rate of heat transfer from the surface of peaches, and hence the cooling rate, can be increased by adding a wetting agent to the water.

In a study conducted to compare cooling rates to rate of water circulation, with and without a wetting agent, Harris (7) found that 5.5 gallons per minute per square foot of cross-sectional area, containing 250 parts per million of a commercial wetting agent, cooled the fruit as fast as 24 gallons per minute without a wetting agent. At a flow rate of 3 gallons per minute per square foot, the cooling rate increased considerably when a wetting agent was added to the cooling water. These results were obtained in a test chamber similar to the conventional flood-type hydrocooler.

From studies discussed previously in this report, it was found that the film coefficient of heat transfer of a single peach immersed in an agitated water bath is sufficient to cool the peach at a maximum rate as dictated by the minimum water temperature and the thermal conductivity of the peach flesh. This condition is valid only when the mean velocity across the surface exceeds 15 feet per minute. Surface temperature measurements during the cooling process suggest that this condition is satisfied in a conventional flood-type hydrocooler.

In view of the findings and hypothesis described, a laboratory study was conducted to determine if a practical advantage could be gained through the use of a wetting agent in the cooling water of a conventional flood-type hydrocooler.

Experimental Procedure

A hydrocooling test chamber (fig. 6) was designed and constructed to simulate the cooling method employed by commercial flood-type hydrocoolers. Spray nozzles to provide uniform distribution at varying flow rates were employed instead of a flood pan and screen. Flow was measured with a bellows-type, pressure-differential recording flow meter (fig. 7).

Five runs each, with and without a wetting agent, were made, using firm ripe fruit of the Elberta variety contained in bushel baskets. Water temperature was held constant at 35° F. Initial fruit temperature and fruit size were maintained as uniformly as possible throughout the tests. Low-pressure spray nozzles were used to provide for uniform coverage at a flow rate of 2.5 and 5 gallons per minute per square foot. At flow rates of 7.5, 10, and 15 gallons per minute, sprinkler-type nozzles were used. A wetting agent approved by the Food and Drug Administration as commercially acceptable for use in food products was applied at a concentration of 250 ppm. Foam was controlled with an antifoam agent.

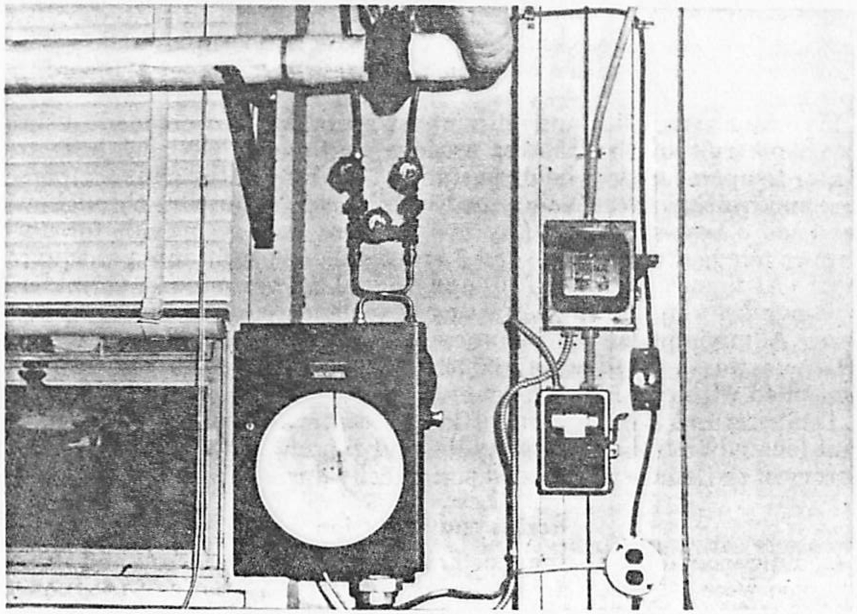
Temperatures were measured in the center and on the surface of fruit located at the bottom, middle, and top of the basket. Thermal history of the fruit was recorded periodically during the cooling process.

Results and Discussion

Cooling coefficients, film coefficients of heat transfer, and heat removed were computed for each treatment, on the basis of the mass-average temperature, by methods described in the appendix. Cooling coefficients were computed for a constant cooling time of 30 minutes. The results are given in table 2. From the data of table 2 and the curves of figure 8, it is noted that the addition of a wetting agent had

BN-18335

FIGURE 6.—Laboratory test chamber for simulated immersion and flood-type hydrocooling studies.



BN-18334

FIGURE 7.—Flow meter.

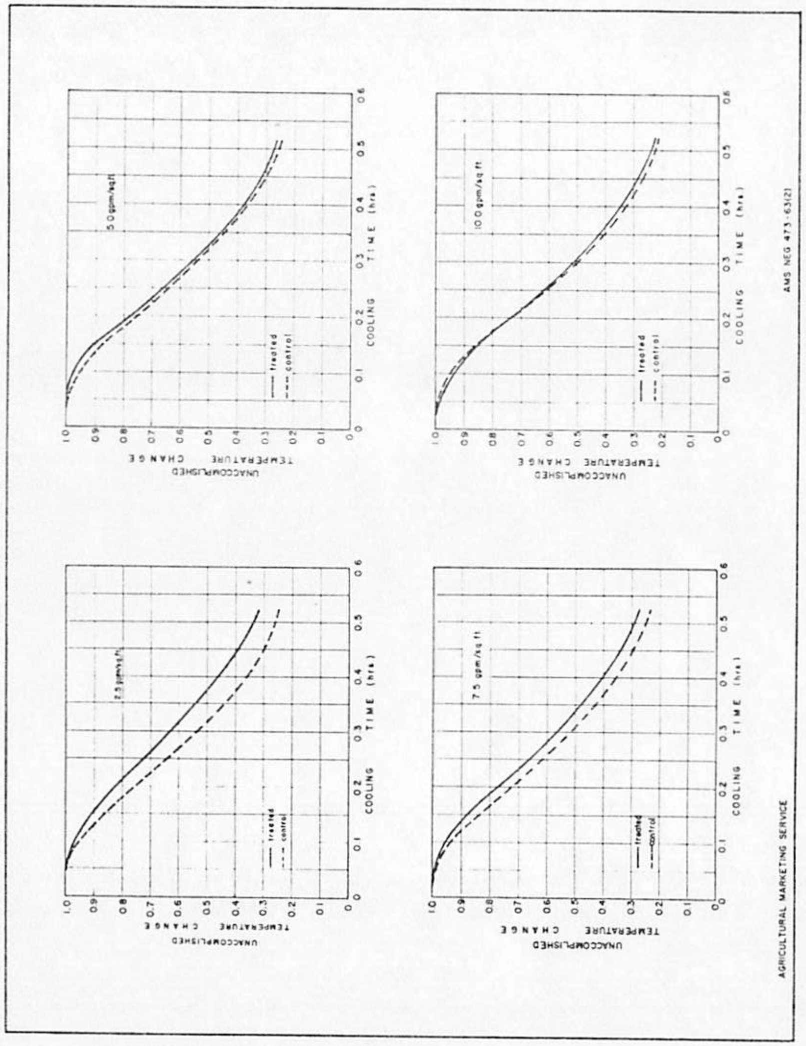


FIGURE 8.—A comparison of the effect of a wetting agent (treated) to no wetting agent (control) in the cooling water at specified flow rates on 2½-inch-diameter Elberta peaches. Temperature measured at center.

TABLE 2.—*Hydrocooling characteristics of 2½-inch-diameter Elberta peaches: Comparison of a wetting agent at 250 ppm with no wetting agent in cooling water at 35° F. Results of laboratory studies in experimental test chamber*

Water flow rate	Wetting agent used	Mass-average temperature		Cooling[1] coefficient	Average film coefficient	Heat[2] removed
		Initial	Final			
gpm/sq. ft.		*° F*	*° F*	*° F./hr. ° F*	*B.t.u./hr. sq. ft. ° F*	*B.t.u./lb.*
2. 5	Yes	92. 6	42. 3	5. 46	61	45. 3
2. 5	No	97. 1	40. 4	7. 03	100	51. 0
5. 0	Yes	92. 4	43. 0	5. 61	43	44. 5
5. 0	No	93. 0	40. 3	6. 13	50	47. 4
7. 5	Yes	93. 2	40. 1	6. 76	66	47. 8
7. 5	No	92. 3	38. 6	7. 65	100	48. 3
10. 0	Yes	94. 7	39. 3	6. 49	125	49. 9
10. 0	No	91. 5	38. 4	7. 22	110	47. 8
15. 0	No	90. 5	38. 9	7. 00	120	46. 4

[1] Based on arithmetic mean temperature difference for 30 minutes cooling time.
[2] Assumed specific heat of peaches equals 0.9 B.t.u./lb. °F.

negligible effect on the cooling rate at each of the water flow rates studied. The observed differences are, in all probability, attributable more to experimental variation than to treatment effects.

Flow Rate and Water Temperature as Related to Cooling

Scope and Purpose

A 68-foot-long by 85-inch-wide hydrocooler equipped with two 7.5-horsepower pump motors delivers 6,400 gallons per minute (gpm) of water to the flood pans. At the design rate of 15 gallons of water per minute per square foot of cross-sectional area, heat added to the water through the two pumps, in 8 hours' operation, is equivalent to that required to melt 1 ton of ice. More than 3 tons of mechanical refrigeration is needed to absorb the heat added through the two pumps. In addition, heat is added to the water from surroundings by conduction, convection, and radiation in proportion to the quantity of water circulated.

From this point of view, the argument can be raised that efficiency of a hydrocooling system might be increased by reducing the quantity of water circulated. On the basis that the assumed reduction in extraneous heat gain to the system results from reduced water circulation, more of the refrigeration capacity available can be converted into useful work and hence the system efficiency will be increased. But, because cooling effectiveness is also a function of water circulation rate, reduction in amount of water circulated should not be accomplished to the extent that system effectiveness is reduced.

Another possible means of increasing hydrocooling system efficiency is by recirculating the cooling water over the fruit, one or more times, before it is returned to the ice tank or cooling coils. In this manner, the fruit is subjected to cooling water at progressively lower temperatures, possibly ranging from 45° to 35° F., as it proceeds through the cooling tunnel. This process, simulating a parallel-flow heat exchanger, might be termed "staging." Perhaps six or eight stages could be employed. Again, the advantages gained by "staging" must suffice to more than offset any subsequent decrease in cooling effectiveness.

In an effort to gain insight into the feasibility of reduced water circulation rates or "staging" on an applied scale, laboratory research was conducted to study the relationship of water temperature and flow rate to rate of cooling peaches, under conditions simulating those in conventional flood-type hydrocoolers and in immersion.

Experimental Procedure

Flooding.—The equipment and measuring instruments described in the section on wetting agents were employed in the tests described here.

Firm ripe peaches of the Elberta variety were tested at flow rates of 2.5, 5.0, 7.5, 10.0, and 15.0 gpm per square foot of cross-sectional area with water temperature held constant at 35° F. Firm ripe peaches of the Hale Haven variety were tested at flow rates of 5, 10, and 15 gpm per square foot of cross-sectional area at water temperatures of 35°, 40°, 45°, and 55° F. Overhead-spray and sprinkler-type nozzles were adjusted to direct the shower over 1 square foot of cross-sectional area of the fruit contained in ¾-bushel baskets. Temperature was measured at the center and on the surface of peaches of known diameter, located at the top, in the middle, and on the bottom center line of the basket.

Immersion.—To determine the cooling characteristics of bulk fruit immersed in an agitated water bath, Hale Haven peaches in 25-pound wire mesh containers were tested at water flow rates of 20, 40, and 60 gpm and at water temperatures of 35° and 45° F. The tests were not designed to measure water flow in terms of either approach or mean velocity through the void spaces surrounding the fruit. However, as a matter of interest, a reasonable estimate of mean velocity through the voids is somewhere between 5 and 15 feet per minute at maximum flow. Temperature was measured at the center and on the surface of fruit located at the intake, in the middle, and on the exhaust side of the container.

Results and Discussion

Flooding.—Cooling coefficients and rate of heat removal for each treatment of water flow rate and temperature in the simulated "flooding" tests are listed in table 3. These data were computed from the mean mass-average temperature of the three specimens from each test.

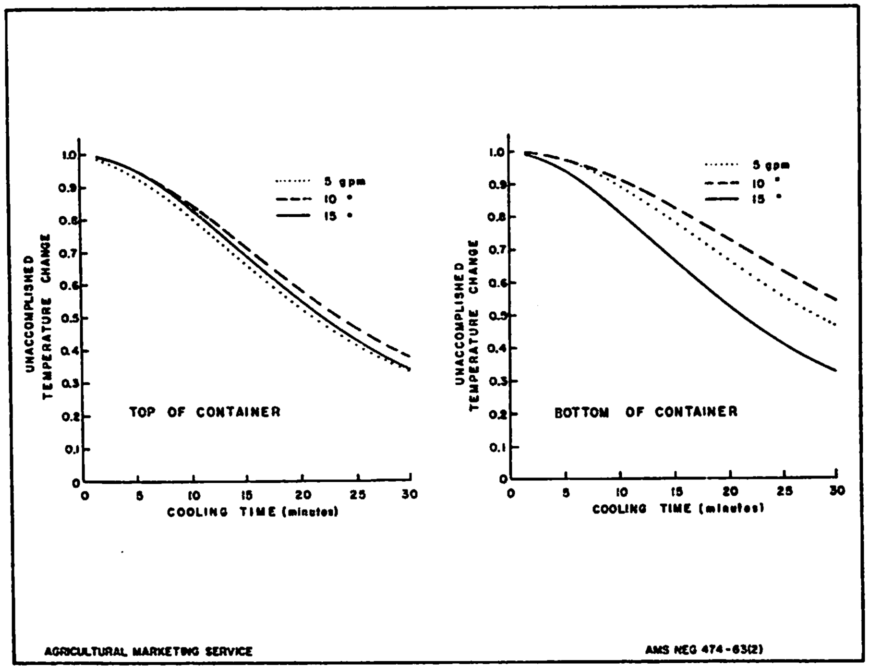
The data in table 3 and the curves of figures 9, 10, and 11 indicate that cooling rate of peaches under laboratory test conditions simulating a conventional flood-type hydrocooler is optimum at a water flow rate of 15 gpm per square foot of cross-sectional area, and at a temperature of 35° F.

As in the case of figure 4, figures 9 and 10 show the relationship between cooling time and unaccomplished temperature change. The temperature was normalized to allow a clearer presentation of the test results. As used here, it can be defined as the difference between the temperature at the center of the fruit and that of the water, divided by the difference in initial uniform temperature of the fruit and that of the

Table 3.—*Cooling characteristics of 3-inch-diameter Hale Haven peaches at various water temperatures and flow rates, in experimental test chamber using overhead sprinkler nozzles to simulate flooding*

Water flow rate	Water temperature	Fruit temperature		Cooling[1] coefficient	Heat[2] removed
		Initial	Final		
gpm/sq. ft.	*° F.*	*° F.*	*° F.*	*°F/hr. °F*	*B.t.u./lb.*
5	35	87.9	46.8	3.78	37.0
10	35	85.0	43.6	4.00	37.3
	40	82.0	48.7	3.39	28.0
	45	82.0	49.1	5.18	28.9
15	35	90.5	39.4	6.58	45.7
	45	89.0	50.9	6.26	35.9
	55	88.2	57.9	5.00	27.3

[1] Based on arithmetic mean difference for 30-minute cooling time.
[2] Assumed specific heat of peaches equals 0.9 B.t.u./lb. ° F.



AGRICULTURAL MARKETING SERVICE AMS NEG 474-63(2)

Figure 9.—Effect of water flow rate on cooling 3-inch-diameter Hale Haven peaches using shower nozzles for coarse spray. Temperatures measured at the center of fruit located at the top and bottom of ¾-bushel baskets.

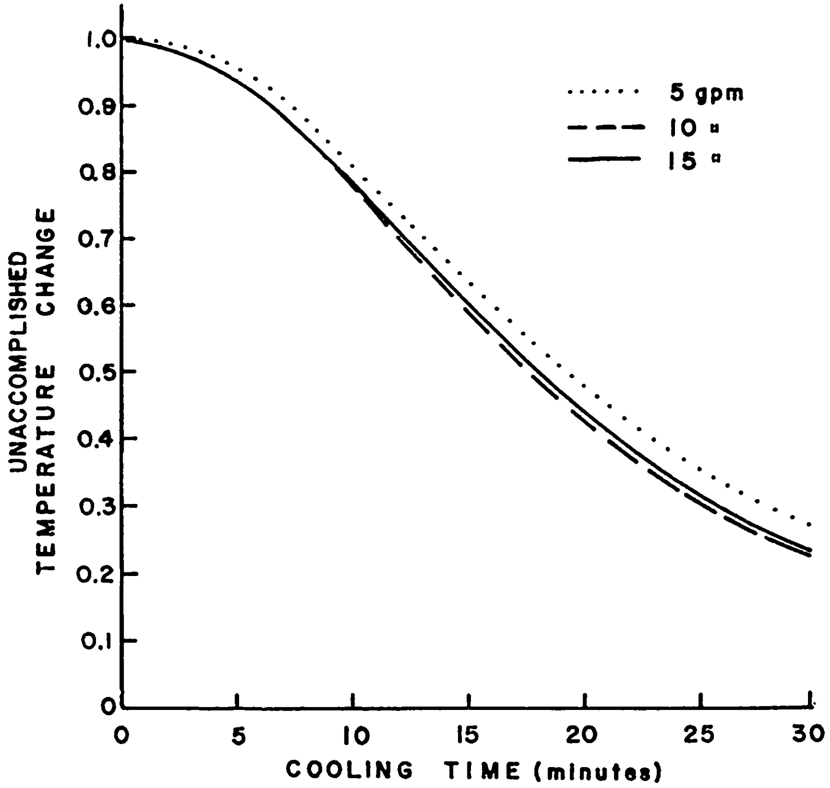
cooling water. Water temperature must be held constant. Absolute temperature can be readily computed by use of the formula:

$$R=\frac{t_c-t_w}{t_i-t_w}$$

Where

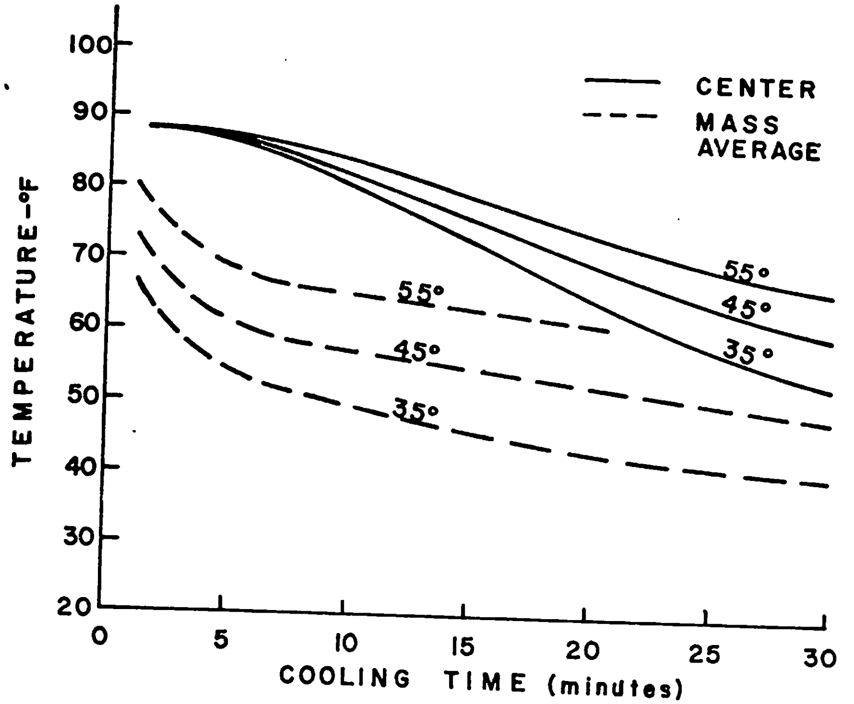
R = percent unaccomplished temperature change or temperature ratio
t_c = temperature at the center
t_i = initial uniform temperature
t_w = temperature of the cooling water

Varying the water flow rate from 5 to 15 gpm, using coarse spray, produced a negligible effect on the cooling rate of 3-inch-diameter Hale Haven peaches located in the top of the container, but caused appreciable differences for fruit in the bottom of the container (fig. 9). This effect can possibly be attributed to spray characteristics causing inadequate distribution of water in the bottom portion of the container at the lower flow rates. In contrast, the water flow rate with fine spray had no significant effect upon the cooling rate of 2½-inch-diameter Elberta peaches in the bottom of the container (fig. 10). While fruit size could be a factor, the more plausible explanation for this contrast is that, in the latter case, at the 5-gpm rate, the spray nozzles dispersed the water into finer particles, resulting in a more uniform distribution and a higher film coefficient of heat transfer.



AGRICULTURAL MARKETING SERVICE AMS NEG 475-63(2)

Figure 10.—Effect of water flow rate on cooling 2½-inch Elberta peaches, using spray nozzles for fine spray. Temperature measured at the center of fruit located on the bottom of ¾-bushel baskets.



AGRICULTURAL MARKETING SERVICE AMS NEG 476-63(2)

Figure 11.—Effect of water temperature on cooling 3-inch-diameter Hale Haven peaches. Center and mass-average temperatures. Average of top, middle, and bottom of ¾-bushel baskets.

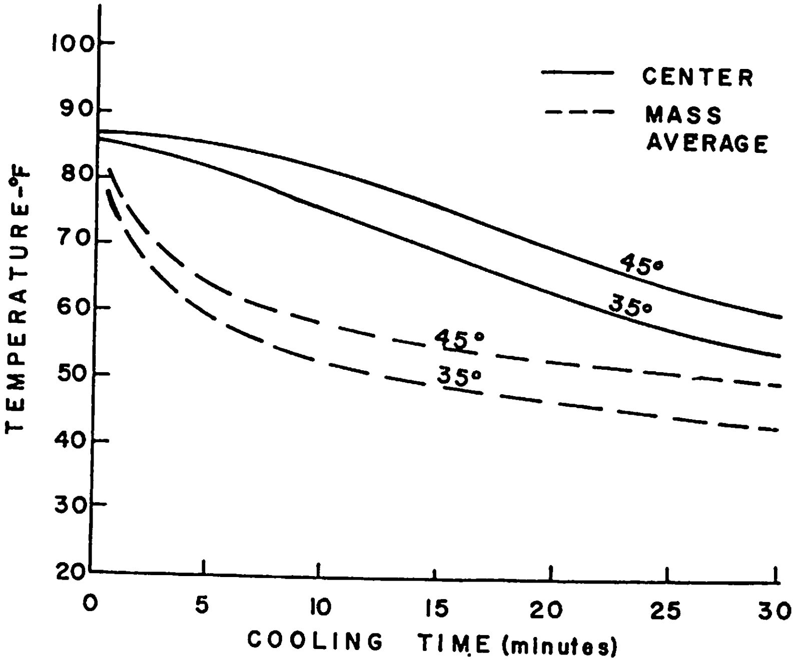
The rate of temperature reduction at the center and at the mass-average point of 3-inch Hale Haven peaches with respect to water temperature is shown in figure 11. These tests were made at a water flow rate of 15 gpm. It is seen, as expected, that cooling is most rapid with the lower water temperature. This should not discount the possibility that "staging" can be effectively practiced with a resulting increase in efficiency of the hydrocooling system. A more thorough investigation of this point should be made under actual operating conditions.

Immersion.—On the assumption that a cooling coefficient of about 6.5° F. per (hr.) (° F.) is optimum for 3-inch-diameter peaches, the results given in table 4 and the curves of figure 11 suggest that the approach velocity should be equal to or greater than 15 feet per minute for cooling by immersion to be comparable with flooding. The curves of figure 12 show temperature reduction at the center and at the mass-average point. They represent the average of all flow rates tested and of the three positions in the container. These are laboratory results. The design of a commercial hydrocooler, based on the immersion-cooling principle, should take into account rise in water temperature. The length of the cooling vat to accomplish a given change in water temperature should vary directly with the 0.4 power of the velocity (*3*).

Table 4.—*Cooling characteristics of 3-inch-diameter Hale Haven peaches: Results of laboratory studies in experimental test chamber, simulating bulk cooling by immersing in an agitated water bath*

Water flow	Water temperature	Mass-average fruit temperature		Cooling coefficient [1]	Heat removed [2]
		Initial	Final		
gpm	*°F*	*°F*	*°F*	*°F/hr.*	*B.t.u./lb.*
20	35.0	85.0	43.5	4.44	37.4
40	35.0	85.0	42.0	4.92	38.7
20	45.0	88.0	49.4	6.04	34.7
40	45.0	86.0	48.8	6.19	33.5
60	45.0	86.0	50.7	4.68	31.8

[1] Based on arithmetic mean temperature difference and 30-minute cooling time.
[2] Assumed specific heat equals 0.9 B.t.u./lb. ° F.



AGRICULTURAL MARKETING SERVICE AMS NEG 477-63(2)

Figure 12.—Effect of cooling by immersion in an agitated water bath on 3-inch-diameter Hale Haven peaches.

Conclusions

Heat Transfer Coefficients

The "effective" thermal diffusivity was measured for six varieties of peaches. Statistical analysis yielded significant differences among varieties. While no effect from maturity was found, a slight correlation existed between size of fruit and "effective" thermal diffusivity. Size also varied significantly among varieties. Dissimilar physical properties among varieties, such as shape and volumetric ratio of flesh to seed, could have some effect on the thermal property of the fruit. Hale Haven, for example, is more nearly spherical than other varieties tested. It also has a larger flesh-to-seed ratio at maturity. Deviation of the fruit from a true spherical shape likely produced systematic variation in the test results, of sufficient magnitude to yield statistically significant differences among varieties under critical analysis. This does not preclude the possibility that differences in maturity among varieties, as perhaps indicated by size, or other physical or biological properties could produce the effect obtained in the test data.

While these findings may have academic significance, in practice the differences can be assumed to be negligible. An average of the six varieties tested constitutes a reasonable measure of "effective" thermal diffusivity for whole firm ripe peaches, for practical application.

Wetting Agents

In an experimental test chamber using overhead-spray and sprinkler-type nozzles to simulate a conventional flood-type hydrocooler, the addition of a wetting agent to the water at 250 ppm did not increase the cooling rate at any of the water circulation rates tested. This may be attributed to the fact that the nozzles were selected to assure a uniform distribution of finely dispersed water particles over the test area. In cases where particle size is large and distribution is not uniform, use of a wetting agent might prove advantageous. However, it would seem more practical to design hydrocoolers to attain a fine, uniform coverage of water by mechanical means.

Water Temperature and Flow Rate

For conventional flood-type hydrocoolers, a water circulation rate of 15 gpm per square foot of cross-sectional area was found to be most effective. While cooling is most rapid at 35° F., some advantage might be gained by recirculating the cooling water several times before returning it to the ice tank for chilling.

Cooling by immersion shows promise for practical application provided the approach velocity is not less than 15 feet per minute.

Applications

Predicting Cooling Rates

The time required to achieve any desired temperature reduction of peaches in a hydrocooler varies with size, cooling characteristics, initial and final temperature of the fruit, and temperature of the cooling water. As in the case of most conventional flood-type hydrocoolers, where the temperature of the fruit surface remains essentially constant and approximates the temperature of the cooling fluid, the cooling characteristic can be expressed by the "effective" thermal diffusivity.

As discussed under the heading of "coefficients," the "effective" thermal diffusivity was found to vary statistically among varieties studied. Because of the small effect of temperature with respect to cooling time, these differences can be neglected in practice. An average of the six varieties tested provides a reasonable measure of the "effective" thermal diffusivity for all firm ripe peaches. A chart (fig. 13) was prepared on the basis of these experimental results. The chart can be used to predict the time required to achieve a specified final mass-average temperature of peaches having a given size and given initial temperature. It has application only where the surface temperature meets the conditions described in the preceding paragraph. Computations for the chart were based on average "effective" thermal diffusivity of 0.0054 square foot per hour, and a water temperature of 35° F.

To illustrate use of the chart, the following example is given:

Problem:

Peaches of uniform size having a maximum diameter of 2⅝ inches, as measured through the center perpendicular to the suture, and an initial temperature of 84.5° F. are to be hydrocooled for 15 minutes.

Conditions:

Cooling water temperature =35° F.

Surface temperature remains constant, and essentially equal to that of the water.

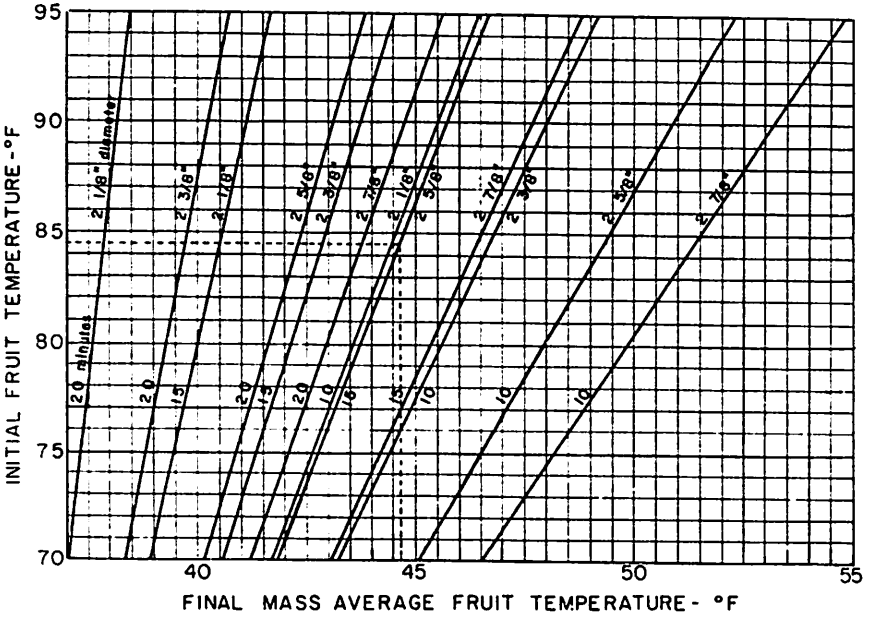
Find:

Final mass-average temperature.

Solution:

Locate the point on the vertical axis where the initial temperature equals 84.5° F. From this point, construct a line, moving from left to right, parallel to the horizontal grid. Through the point where the construction line intersects with the curve corresponding to 15 minutes and 2⅝-inch diameter, construct another line parallel to the vertical grid. At the point where the vertical construction line intersects with the horizontal axis, the mass-average temperature is found to be 44.7° F.

If the final mass-average temperature is specified, the time required to cool a peach of a given size to the specified temperature can be found at the point where the vertical and horizontal lines intersect with the curve corresponding to the appropriate fruit size. Should the intersection occur at some point between curves of corresponding size, an interpolation for the correct cooling time can be made. For example, in the problem just presented, if a final mass-average temperature of 43.5° F. had been specified, the point of intersection would have occurred midway between the 15- and 20-minute curves for a 2⅝-inch-diameter peach. By interpolation, the cooling time is found to be 17.5 minutes. Formulas and tables for computing center and mass-average temperatures for any variety of conditions are given in the appendix.



AGRICULTURAL MARKETING SERVICE AMS NEG 478-63(2)

Figure 13.—Relation between initial and final mass-average temperature of fruit, size of fruit, and cooling time when cooled ideally with water at 35° F.

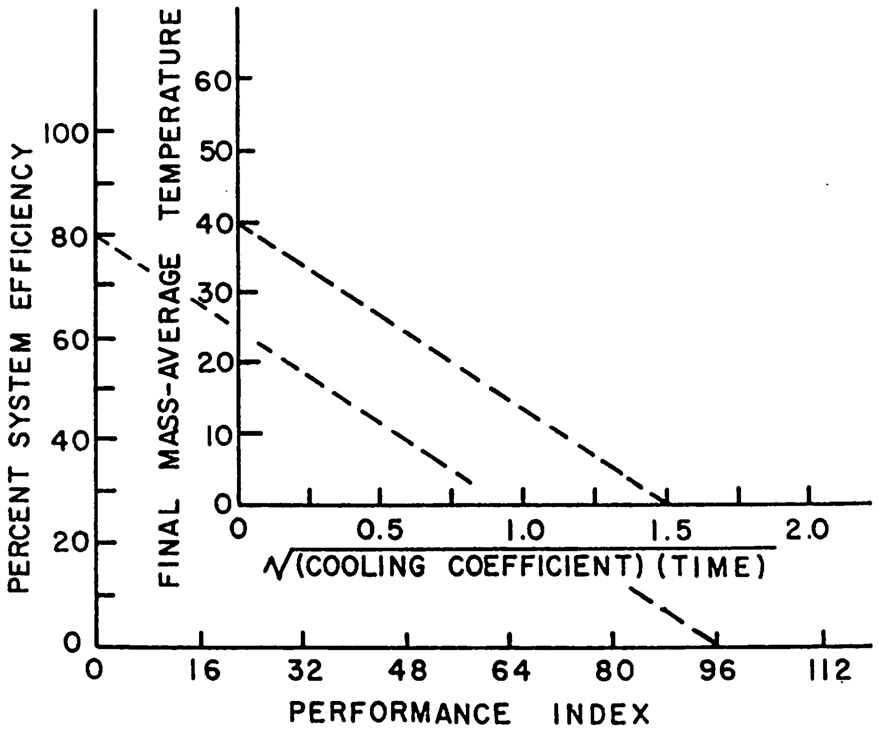
Performance Index

Hydrocooling system performance may be defined as the extent to which a particular system under specific operating conditions produces an optimum fruit temperature reduction at the least cost.

The three factors that best characterize the performance of a hydrocooling system are: (1) Cooling coefficient,[6] (2) hydrocooling system efficiency,[7] and (3) final mass-average fruit temperature.[8] Any one of these three alone does not adequately describe the total effectiveness and efficiency of a system. Mathematically, hydrocooling system performance may be evaluated as an index that takes into account each of the above three factors. This index may be used as a standard or guide for evaluating hydrocooling operations. The function of hydrocooling is to cool the product fast and as efficiently as possible. The principal criterion, however, is the accomplishment of adequate temperature reduction. If this is not done, the purpose of hydrocooling has been defeated. For this reason, major emphasis is placed upon final fruit temperature in the expression given for determining the performance index. The index must be used with caution. Unless examined in the light of its determinants, it can lead to erroneous conclusions.

If the product of the cooling coefficient and time, hydrocooling system efficiency, and final mass-average temperature is known, or can be measured, the overall performance index of a hydrocooling system in operation can be computed by use of the formula given on page 35 in the appendix. From the chart (fig. 14), the performance index can be determined graphically in the following manner:

Construct a line that intersects the calculated value of cooling coefficient x time on the horizontal axis and the final mass-average temperature on the vertical axis. Parallel to this line, construct



AGRICULTURAL MARKETING SERVICE AMS NEG 479-63(2)

Figure 14.—Relation of hydrocooler performance index to hydrocooling system efficiency, final mass-average temperature, and the product of cooling coefficient x time. Chart can be used for a graphical solution of performance index where the other factors are known.

---

[6] Cooling coefficient, as used in this report, can be defined as the mass-average temperature reduction accomplished in a given cooling time for each degree of temperature difference between the peach and the cooling water.

[7] Hydrocooling system efficiency, as used in this report, is defined as the ratio of product heat load to the heat absorbed by the melting ice or the total mechanical refrigeration capacity available.

[8] Mass-average temperature of a peach is that temperature which denotes the total heat contained in the peach at any time during a cooling process.

another line (as shown) that intersects the vertical axis at the point corresponding to the calculated percent hydrocooling efficiency. The performance index is found at the point of intersection between the second parallel line and the bottom horizontal axis.

Predicting Cooling Loads

The refrigeration requirement for a hydrocooling system can be estimated by computing the total heat load of the system. The total heat load consists of (1) product load, (2) load from containers, (3) electrical load, and (4) gain from surroundings.

The product heat load to be removed in cooling 400 bushels per hour (48 pounds per bushel) of 2½-inch-diameter peaches, initially at 80° F., in 15 minutes is 650,000 B.t.u. per hour.

The container heat load is variable, depending upon size and type of container. As a rule of thumb, weight of wooden or fiberboard containers may be estimated to be ⅒ that of the product weight, and to have a specific heat of 0.3 B.t.u. per pound °F. (*3*). On this basis, the container heat load for the case described is 21,600 B.t.u. per hour, or about 3.5 percent of the product load.

In a hydrocooler, the electrical load comes from that portion of heat energy that is added to the system through pump and conveyor motors. However, load produced by the conveyor motor comprises such a small percentage of the total load that it can be considered negligible. One 7.5-horsepower pump motor is required for a conventional flood-type hydrocooler having a capacity of 400 bushels per hour based on a 15-minute cooling time. A motor of this size adds heat to the water, through the pump, at a rate of 19,087 B.t.u. per hour. The electrical heat load therefore amounts to about 3 percent of the product load.

Approximately 10 percent of the product heat load may be attributed to sources necessary to perform the operation. Additional heat load to the system comes from outside sources.

Packinghouse Studies

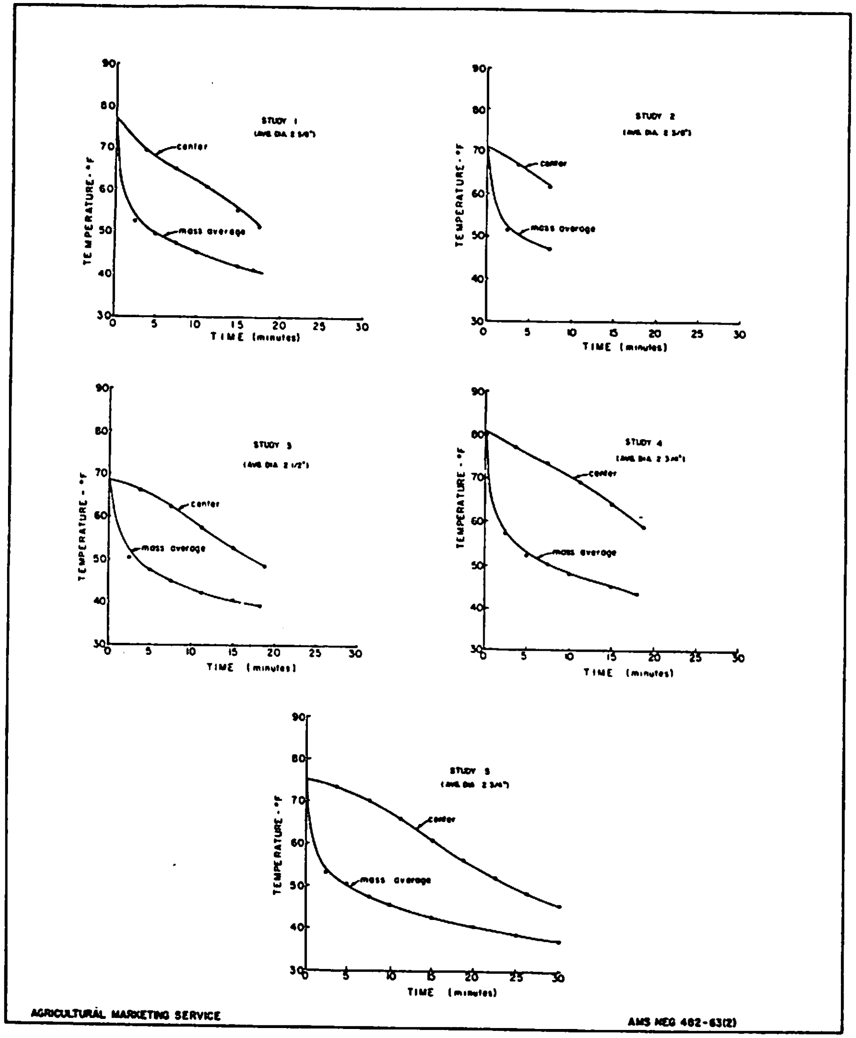
Performance criteria were established for existing hydrocooling systems from studies in packinghouses in Georgia and South Carolina during the 1960 and 1961 seasons. Five packinghouses, four in Georgia and one in South Carolina, were selected on the basis of size, type of refrigeration, and location. Thermal history during the cooling process was recorded by the use of thermocouples that remained connected to a recording potentiometer as the fruit under study passed through the cooling tunnel. The thermocouples were constructed of 36 a.w.g. copper-constantan connected to 24 a.w.g. copper-constantan lead wire. Center and surface temperatures were measured with the fruit located at the bottom and top center line of the containers. The containers varied in type, including ¾-bushel baskets, wire-bound bruce boxes, and field boxes. All hydrocoolers studied, while varying somewhat in construction details, are of the same conventional flood-type design.

Description and observations of performance data from the hydrocoolers studied are given in table 5.

TABLE 5.—*Description of equipment and performance data from studies of hydrocooling systems in peach packinghouses in Georgia and South Carolina (1960–61)*

Study	Hydrocooler capacity [1]	Refrigeration		Heat-absorbing capacity	Time in cooler	Fruit diameter [3]	Water	Temperature of fruit				Cooling coefficient [7]	Hydrocooling system efficiency	Performance index
		Ice [2]	Mechanical					Initial	Final					
									Center		Mass avg.			
	Bu/hr.	*Lb./hr.*	*Tons*	*B.t.u./hr. (1000)*	*Mins.*	*Inches*	*° F*	*° F*	*° F*		*° F*	*° F/hr.° F*	*%*	*Unit*
1	558	----------	200	2,400	18	2⅝	35	77.0	[4] 52.0	[5] 52.0	[6] 40.2	7.00	46	53.3
2	900	9,000	----------	1,296	7.5	2⅜	35	72.5	62.5	64.0	47.0	9.12	90	65.5
3	620	----------	120	1,440	20	2½	33	70.0	49.0	49.0	37.9	6.94	71	91.5
4	300	5,500	----------	792	17	2¼	35	82.0	62.2	63.1	45.0	6.95	72	72.0
5	470	----------	200	2,400	45	2¾	33	76.0	37.5	39.3	34.3	4.82	42	74.6

[1] Based on actual operated conveyor speed.
[2] Values reported by operators.
[3] Measured through the center, perpendicular to the suture.
[4] Fruit at top of container.
[5] Fruit in bottom of container.
[6] Computed from average of top and bottom center temperatures.
[7] Computed on the basis of mass-average temperature.



AGRICULTURAL MARKETING SERVICE

AMS NEG 482-63(2)

FIGURE 15.—Center and mass-average temperatures of peaches 2⅜ to 2¾ inches in diameter, in the middle of container during typical cooling in conventional flood-type hydrocoolers.

It is noted from the table that final fruit temperature is reported in terms of its mass-average. Predicted values of mass-average temperature were computed according to the method reported by Smith and Bennett (*12*) on the basis of fruit size, initial fruit temperature, time in the cooler, and cooling water temperature. Actual values of mass-average temperature were computed from measurements recorded, initially and finally, at points in the center and on the surface of the fruit.

Note from the data of study 1 (table 5) that the mass-average temperature of a peach 2⅝ inches in diameter was reduced from 77° to 40.2° F. in 18 minutes, compared to a reduction from 76° to 34.3° F. in 45 minutes in study 5. This, as illustrated by the curves of figure 15, provides a comparative evaluation of the characteristic initial rapid cooling rate that decreases as cooling time increases.

The cooling coefficient is informative and useful when considered in the presence of cooling time. In the absence of knowledge about cooling time, the term can be misleading. Note, for example, the large diversity between the cooling coefficients of studies 2 and 5 (table 5). The coefficient, in each case, is a reasonable expression of the cooling rate for the period of time the fruit was in the cooler. However, if the time allowed for cooling were not considered, one would logically assume that the hydrocooler of study 2 is doing a more effective job of cooling than that of study 5. If computed on the basis of equal cooling time, the two hydrocoolers would have very nearly the same cooling coefficient.

Both the cooling coefficient and hydrocooling system efficiency of study 5 are low. Each of these can, to some extent, be attributed to the length of time in the cooler. In this case, economy was sacrificed to achieve a minimum final fruit temperature. While the performance rating is good, it would likely have been advantageous to maintain a closer balance between total heat load and refrigeration capacity available. As a contrast, the efficiency and cooling coefficient are high for study 2, but performance does not measure up to standard. Final fruit temperature was too high. An increase in cooling time from 7.5 to 10 minutes would have resulted in a final mass-average temperature of approximately 45° F. with a subsequent increase in performance index to 100, assuming other conditions remained equal.

Performance indices listed in table 5 were computed by the method described in this report.

Literature Cited

(1) CARDINELL, H. A., and MITCHELL, A. E.
1948. PACKING HOUSE TRIALS TO REDUCE PEACH ROT. Mich. Agri. Exp. Sta. Quarterly Bul. 30 (4): pp. 460–467.

(2) GANE, R.
1936. THE THERMAL CONDUCTIVITY OF THE TISSUE OF FRUITS. Report of Food Investigations Board, London, pp. 211–212.

(3) GUILLOU, RENE
1960. COOLERS FOR FRUITS AND VEGETABLES. Calif. Agr. Exp. Sta. Bul. 773, 1960. 65 pp. illus.

(4) ———
1958. SOME ENGINEERING ASPECTS OF COOLING FRUITS AND VEGETABLES. ASAE Transactions, Vol. 1, No. 1, pp. 38–39, 42.

(5) GURNEY, H. P., and LURIE, J.
1923. CHARTS FOR ESTIMATING TEMPERATURE DISTRIBUTIONS IN HEATING OR COOLING SOLID SHAPES. Indus. and Engin. Chem. Vol. 15, No. 11, pp. 1170–1172.

(6) HARDENBURG, R. E.
1962. PEACH QUALITY CONTROL AFTER HARVEST. Reprint from *Peach Times*. Vol. 7, No. 8, 8 pp.

(7) HARRIS, HUBERT, and SPIGNER, R. L.
HYDROCOOLING PEACHES. Mimeograph. Ala. Poly. Inst. Agr. Exp. Sta.

(8) KETHLEY, T. W., COWN, W. B., and BELLINGER, F.
1950. AN ESTIMATE OF THERMAL CONDUCTIVITIES OF FRUITS AND VEGETABLES. Ga. Inst. Tech. Ga. Expt. Sta. Reprint No. 40, Vol. XII No. 3.

(9) REDIT, W. H., SMITH, M. A., and BENFIELD, P. L.
1955. TESTS ON HYDROCOOLING AND REFRIGERATION OF PEACHES IN TRANSIT FROM GEORGIA AND SOUTH CAROLINA. U.S. Dept. Agr., Agr. Mktg. Serv. AMS–62, 23 pp. illus.

(10) Redit, W. H., Smith, M. A., Ceponis, M. J., and Ramsey, G. B.
1956. PEACH HYDROCOOLING, SHIPPING, AND FUNGICIDAL TESTS. PART II. U.S. Dept. Agr., Agr. Mktg. Serv. AMS-199, pp. 6-20 illus.

(11) Sainsbury, G. F.
1955. COMMERCIAL EXPERIENCE WITH HIGH SPEED PRECOOLING OF SOFT FRUITS. Ninth International Congress of Refrigeration proc. 0.12. Paris, France.

(12) Smith, R. E., and Bennett, A. H.
1962. MASS AVERAGE TEMPERATURES OF FRUITS AND VEGETABLES DURING TRANSIENT COOLING. Paper No. 62-911, ASAE winter meeting, Chicago, Ill.

(13) Toussaint, W. D., Hatton, T. T., and Abshier, George
1955. HYDROCOOLING PEACHES IN THE NORTH CAROLINA SANDHILLS. N. Car. Agr. Exp. Sta. Agr. Econ. Inf. series No. 39. 46 pp. illus.

(14) Turrell, F. M., and Perry, R. L.
1957. SPECIFIC HEAT AND HEAT CONDUCTIVITY OF CITRUS FRUIT. American Soc. Hort. Sci. proc., Vol. 70, pp. 261-265.

(15) Williamson, E. D., and Adams, L. H.
1919. TEMPERATURE DISTRIBUTION IN SOLIDS. Physical Review, Vol. 14, No. 2, pp. 99-114.

Appendix

Definition of Symbols

Symbol	*Quantity*	*Unit*
α	thermal diffusivity	sq. ft. per (hr.)
C	cooling coefficient	° F. per (hr.) (°F.)
c_p	specific heat	B.t.u. per (lb.) (°F.)
D	diameter of fruit	ft.
D_1	diameter of inner surface of spherical shell	ft.
D_2	diameter of outer surface of spherical shell	ft.
E	hydrocooling system efficiency	%
F	conversion factor	—
h	film coefficient of heat transfer	B.t.u. per (hr.) (sq. ft.) (°F.)
k	thermal conductivity	B.t.u. per (hr.) (sq. ft.) (°F. per ft.)
m	integer	—
μ	dynamic viscosity	lbs. per (ft.) (hr.)
ϕ	performance index	—
q	rate of heat flow per unit area	B.t.u. per (hr.) (sq. ft.)
q'	rate of heat flow per unit area from surface	B.t.u. per (hr.) (sq. ft.)
Q	total heat removed	B.t.u. per (lb.)
ρ	density	lb. per cu. ft.
R	radius of sphere	ft.
t	temperature at any point in peach	°F.
t_c	temperature at center of peach	°F.
t_{fma}	final mass-average temperature	°F.
t_i	initial peach temperature	°F.
t_{ma}	mass-average temperature	°F.
t_s	surface temperature of peach	°F.
t_1	temperature on inner surface of spherical shell	°F.
t_2	temperature on outer surface of spherical shell	°F.
R_{ma}	mass-average temperature reduction	°F.
Δt	mean temperature difference between mass-average fruit and water	°F.
$\Delta t'$	temperature difference between cooling fluid and fruit surface	° F.
τ	time	hrs.
v_m	mean velocity through smallest cross-sectional area	ft. per hr.
v_∞	approach velocity	ft. per hr.
r	distance from center of peach to some point along the radius	ft.

Analytical Procedure

"Effective" Thermal Diffusivity

The method of measuring thermal diffusivity of homogeneous, symmetrical solids involves the determination of the temperature-time relation at the center of a substance whose surface is heated or cooled either at a uniform rate or very suddenly. The expressions developed by Williamson and Adams (*15*) for making this determination in the case of a sphere, whose surface temperature suddenly changes from its initial uniform temperature to a constant but different value from its original temperature, states that

$$\frac{t_c-t_s}{t_i-t_s}=2\sum_{m=1}^{m=\infty}(-1)^{m+1}e^{-\frac{4\alpha\tau}{D^2}m^2\pi^2} \qquad \text{I}$$

Gurney and Lurie (*5*) presented charts that are useful for a graphical determination of the relation between unaccomplished temperature change $(t_c-t_s)/(t_i-t_s)$ and the thermal properties and dimensions of the substance in question. They state that "if the surface of the body instantly assumes the temperature of the surrounding media," then "the ratio of the thermal conductivity, k, to the product of the surface conductivity (film coefficient), h, and the radius, R, equals zero"; or

$$\frac{k}{(h\times R)}=0.$$

In determining thermal diffusivity by the method of Williamson and Adams, it is valid to assume that the surface temperature suddenly becomes essentially equal to that of the surrounding fluid under circumstances where $h\times R$ is infinitely greater than k. Surface temperatures as measured on test peaches suddenly plunged into a well-agitated water bath at 35° F. satisfy this condition.

The term "effective" thermal diffusivity was assigned to values reported in this bulletin because the characteristic shape and anatomy of peaches fails to conform precisely to stipulated conditions of symmetry and homogeneity.

Values of "effective" thermal diffusivity for each test peach were determined at specified time intervals during a test run. The procedure involved calculation of unaccomplished temperature change, $\left(\frac{t_c-t_s}{t_1-t_s}\right)$, at the specified times, from measured values of center, surface, and initial uniform temperature. From table 6, the corresponding value of $4\alpha\tau/D^2$ was found. For a test specimen of known diameter, at a specified time, the "effective" thermal diffusivity was readily obtained. Values of "effective" thermal conductivity were computed from the equation

$$k=\alpha\rho C_p \qquad \text{II}$$

Mass-Average Temperature

The curves of figure 4, p. 11, were prepared from data computed by use of the equation

$$\frac{t-t_s}{t_i-t_s}=F(4\alpha\tau/D^2) \qquad \text{III}$$

Having specified fruit diameter and cooling time, and utilizing the average experimental value of "effective" thermal diffusivity, values of $4\alpha\tau/D^2$ were computed. By reference to table 6, the appropriate conversion was obtained for the unaccomplished temperature change at the center of fruit of various sizes, at the specified cooling times.

The general expression developed by Williamson and Adams to determine the time-temperature relation at any point in a solid sphere at some initial uniform temperature, subjected to a sudden change in surface temperature, states that

$$\frac{t-t_s}{t_i-t_s}=\frac{2}{\pi}\sum_{m=1}^{m=\infty}\frac{\frac{R}{r}\sin\frac{m\pi r}{R}}{m(-1)^{m+1}}e^{\frac{-4\alpha\tau}{D^2}m^2\pi^2} \qquad \text{IV}$$

As reported by Smith and Bennett (*12*), the mass-average temperature of peaches during a normal hydrocooling process occurs initially at a point along the radius equal to 0.76 of the distance from the center to the surface. The data listed in table 7 were computed from equation IV by substituting 0.76r for x and solving for values of $4\alpha\tau/D^2$ ranging from 0.0300 to 0.5000. By referring to this table and employing the same procedure given in the preceding paragraph, predicted values of unaccomplished temperature change at the mass-average point were found.

The chart in figure 16 was developed by transposing equation III and solving for the predicted mass-average temperature at the stipulated values of fruit size, cooling time, and initial uniform temperature. By transposing and substituting t_{ma} for t the equation becomes,

$$t_{ma}=[F(4\alpha\tau/D^2)(t_i-t_s)]+t_s \qquad \text{V}$$

In solution of the equation, the thermal diffusivity was taken as the average of all varieties tested and the surface temperature was assumed to remain constant at 35° F.

Film Coefficients

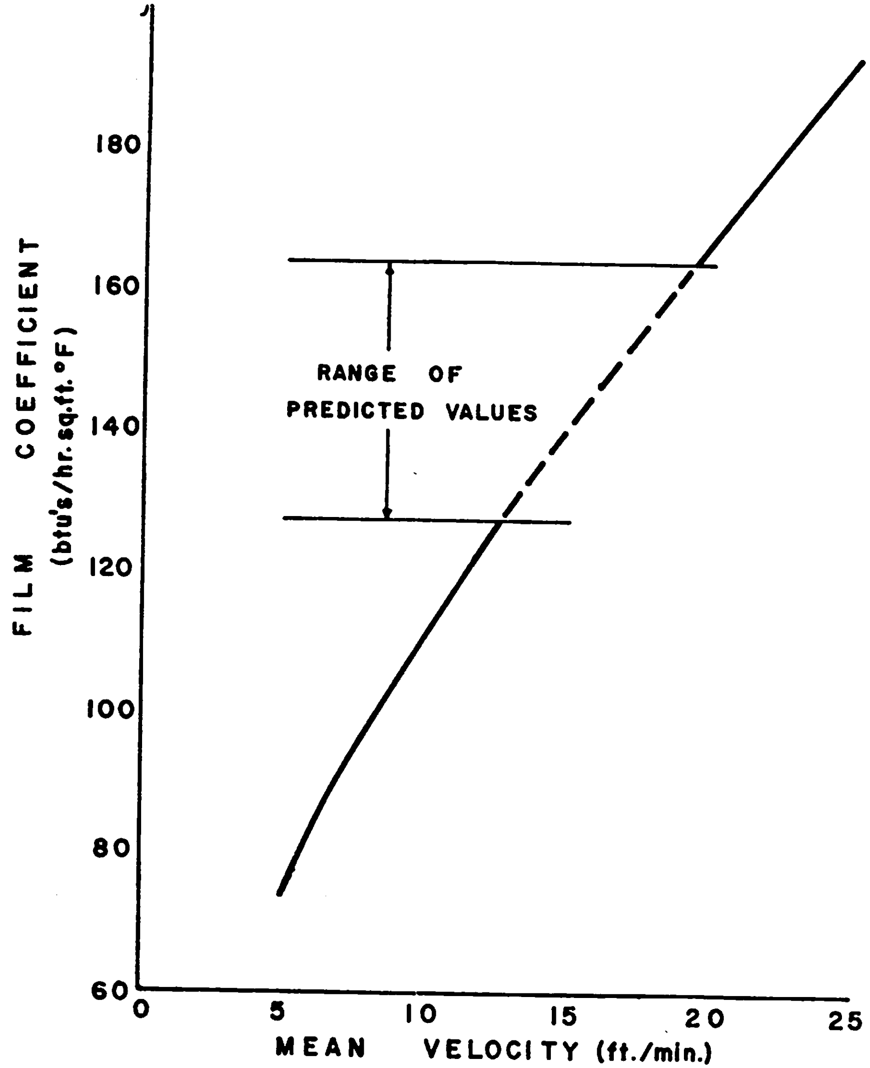
The convective characteristics of cooling peaches with a fluid in turbulent motion can be assumed to be approximately analogous to the heating or cooling of fluids flowing normal to banks of staggered tubes. For this case, the expression to determine the film coefficient of heat transfer is given by the equation,

$$\frac{hD}{k}=0.33\left(\frac{v_mD\rho}{\mu}\right)^{0.6}\left(\frac{\mu c_p}{k}\right)^{\frac{1}{3}} \qquad \text{VI}$$

In equation VI, the physical properties of the fluid-density, dynamic viscosity, specific heat, and thermal conductivity are taken at film temperature. The velocity term in the equation refers to the mean velocity through the smallest free cross-sectional area. With respect to an individual tube, this quantity can be represented as an approach velocity. The tests on peaches cooled in an agitated water bath were made with individual specimens. The equation to express the heating or cooling of fluids flowing across the surface of a single sphere is,

$$\frac{hD}{k}=0.37\left(\frac{v_\infty\rho D}{\mu}\right)^{0.6} \qquad \text{VII}$$

By use of equation VII, the approach velocity to an individual specimen in an agitated water bath was estimated by a process of



AGRICULTURAL MARKETING SERVICE AMS NEG 483-63(2)

FIGURE 16.—The relation of mean velocity to the theoretical film coefficient from the surface of tube banks to water. Broken line indicates the range of estimated values from the surface of peaches to water under ideal cooling conditions.

trial and error. Results were compared with those obtained from the solution of equation X.

Equation VIII expresses the rate of steady-state heat flow per unit area through a homogeneous spherical shell of some given thickness. If the temperature at the inner and outer surfaces of the spherical segment and the respective diameters are known, the rate of heat flow through the segment may be calculated,

$$q=\frac{2k(t_1-t_2)}{(D_2-D_1)\frac{D_2}{D_1}} \qquad \text{VIII}$$

Utilizing Newton's basic equation for computing the rate of heat flow per unit area from the surface,

$$q'=hA\Delta t' \qquad \text{IX}$$

and assuming steady-state heat flow at any finite point in time, then $q=q'$.

By equating equations VIII and IX, equation X may be derived:

$$h=\frac{2k(t_1-t_2)}{\Delta t'(D_2-D_1)\frac{D_2}{D_1}} \qquad \text{X}$$

The average film coefficient during a given cooling period may be obtained by computing h for a number of equal time intervals during a cooling process. Values listed in table 2 were computed by this method.

Cooling Coefficient

The cooling coefficient is used to express the effectiveness of a cooling system. It has particular utility in comparing two or more cooling methods, provided that the factors that affect cooling rate are coordinated to enable evaluation on an equality or control-point basis. The equation is

$$C=\frac{R_{ma}}{\tau\Delta t} \qquad \text{XI}$$

The amount of heat removed from peaches as listed in tables 2, 3, and 4 was computed by use of equation XII,

$$Q=C_pR_{ma} \qquad \text{XII}$$

Performance Index

The performance index is introduced in this report as a suggested criterion for evaluating the combined efficiency, cooling effectiveness, and temperature reduction obtained from the operation of a hydrocooling system. It is given by the equation

$$\phi=\frac{32E\sqrt{\tau C}}{t_{fma}} \qquad \text{XIII}$$

Table 6.—*Values of* $\frac{t_c-t_s}{t_i-t_s}$, *corresponding to various values of* $\frac{4\,\alpha\tau}{D^2}$, *at the center of solid homogeneous spheres in the case of sudden temperature change at the surface*

$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$	$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$	$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$
0.0300	0.998435	0.1775	0.345249	0.3250	0.080925
0.0325	0.996835	0.1800	0.336867	0.3275	0.078978
0.0350	0.995235	0.1825	0.328865	0.3300	0.077030
0.0375	0.992174	0.1850	0.320863	0.3325	0.075176
0.0400	0.989114	0.1875	0.313228	0.3350	0.073322
0.0425	0.984280	0.1900	0.305592	0.3375	0.071557
0.0450	0.979446	0.1925	0.298308	0.3400	0.069792
0.0475	0.972720	0.1950	0.291023	0.3425	0.068092
0.0500	0.966013	0.1975	0.284077	0.3450	0.066432
0.0525	0.957480	0.2000	0.277131	0.3475	0.064836
0.0550	0.948945	0.2025	0.270508	0.3500	0.063234
0.0575	0.938776	0.2050	0.263886	0.3525	0.061712
0.0600	0.928606	0.2075	0.257574	0.3550	0.060190
0.0625	0.917037	0.2100	0.251261	0.3575	0.058741
0.0650	0.905487	0.2125	0.245246	0.3600	0.057292
0.0675	0.892807	0.2150	0.239230	0.3625	0.055914
0.0700	0.880127	0.2175	0.233498	0.3650	0.054534
0.0725	0.866591	0.2200	0.227766	0.3675	0.053221
0.0750	0.853055	0.2225	0.222305	0.3700	0.051909
0.0775	0.838909	0.2250	0.216844	0.3725	0.050660
0.0800	0.824762	0.2275	0.211643	0.3750	0.049409
0.0825	0.810223	0.2300	0.206440	0.3775	0.048221
0.0850	0.795683	0.2325	0.201487	0.3800	0.047031
0.0875	0.780936	0.2350	0.196531	0.3825	0.045904
0.0900	0.766190	0.2375	0.191813	0.3850	0.044766
0.0925	0.751392	0.2400	0.187093	0.3875	0.043690
0.0950	0.736596	0.2425	0.182600	0.3900	0.042611
0.0975	0.721877	0.2450	0.178106	0.3925	0.041586
0.1000	0.707158	0.2475	0.173827	0.3950	0.040560
0.1025	0.692620	0.2500	0.169547	0.3975	0.039583
0.1050	0.678082	0.2525	0.165472	0.4000	0.038607
0.1075	0.663806	0.2550	0.161398	0.4025	0.037778
0.1100	0.649531	0.2575	0.157519	0.4050	0.036748
0.1125	0.635580	0.2600	0.153638	0.4075	0.035864
0.1150	0.621630	0.2625	0.149945	0.4100	0.034979
0.1175	0.608053	0.2650	0.146251	0.4125	0.034137
0.1200	0.594476	0.2675	0.142734	0.4150	0.033295
0.1225	0.581306	0.2700	0.139217	0.4175	0.032494
0.1250	0.568136	0.2725	0.135869	0.4200	0.031692
0.1275	0.555397	0.2750	0.132520	0.4225	0.030879
0.1300	0.542658	0.2775	0.129333	0.4250	0.030166
0.1325	0.530366	0.2800	0.126145	0.4275	0.029490
0.1350	0.518073	0.2825	0.123010	0.4300	0.028714
0.1375	0.506234	0.2850	0.120076	0.4325	0.028022
0.1400	0.494396	0.2875	0.117187	0.4350	0.027331
0.1425	0.483015	0.2900	0.114298	0.4375	0.026673
0.1450	0.471633	0.2925	0.111548	0.4400	0.026015
0.1475	0.460706	0.2950	0.108798	0.4425	0.025389
0.1500	0.449780	0.2975	0.106180	0.4450	0.024763
0.1525	0.439304	0.3000	0.103562	0.4475	0.024167
0.1550	0.428827	0.3025	0.101070	0.4500	0.023571
0.1575	0.418792	0.3050	0.098578	0.4525	0.023003
0.1600	0.408757	0.3075	0.096206	0.4550	0.022436
0.1625	0.399154	0.3100	0.093833	0.4575	0.021896
0.1650	0.389550	0.3125	0.092175	0.4600	0.021356
0.1675	0.379872	0.3150	0.089317	0.4625	0.020841
0.1700	0.371183	0.3175	0.087168	0.4650	0.020327
0.1725	0.362408	0.3200	0.085018	0.4675	0.019838
0.1750	0.353631	0.3225	0.082972	0.4700	0.019349

Table 6.—*Values of* $\frac{t_c-t_s}{t_i-t_s}$, *corresponding to various values of* $\frac{4\,\alpha\tau}{D^2}$, *at the center of solid homogeneous spheres in the case of sudden temperature change at the surface*—Continued.

$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$	$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$	$\frac{4\,\alpha\tau}{D^2}$	$\frac{t_c-t_s}{t_i-t_s}$
0.4725	0.018882	0.4825	0.017106	0.4925	0.015276
0.4750	0.018417	0.4850	0.016686	0.4950	0.015118
0.4775	0.017754	0.4875	0.016295	0.5975	0.014754
0.4800	0.017530	0.4900	0.015883	0.5000	0.014390

Table 7.—*Values of unaccomplished temperature change corresponding to various values of* $\frac{4\alpha\tau}{\mathrm{D}^2}$ *at the mass-average temperature point of peaches in the case of cooling with negligible surface resistance*

$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$	$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$	$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$
0.0300	0.569582	0.1375	0.149465	0.2450	0.051123
0.0325	0.544137	0.1400	0.145695	0.2475	0.049875
0.0350	0.520680	0.1425	0.142028	0.2500	0.048658
0.0375	0.498979	0.1450	0.138461	0.2525	0.047470
0.0400	0.478834	0.1475	0.134992	0.2550	0.046312
0.0425	0.460076	0.1500	0.131615	0.2575	0.045182
0.0450	0.442556	0.1525	0.128330	0.2600	0.044080
0.0475	0.426149	0.1550	0.125131	0.2625	0.043005
0.0500	0.410744	0.1575	0.122017	0.2650	0.041956
0.0525	0.396245	0.1600	0.118986	0.2675	0.040932
0.0550	0.382568	0.1625	0.116033	0.2700	0.039934
0.0575	0.369640	0.1650	0.113157	0.2725	0.038960
0.0600	0.357397	0.1675	0.110356	0.2750	0.038010
0.0625	0.345779	0.1700	0.107628	0.2775	0.037083
0.0650	0.334738	0.1725	0.104969	0.2800	0.036178
0.0675	0.324226	0.1750	0.102379	0.2825	0.035296
0.0700	0.314204	0.1775	0.099854	0.2850	0.034436
0.0725	0.304636	0.1800	0.097394	0.2875	0.033596
0.0750	0.295488	0.1825	0.094997	0.2900	0.032777
0.0775	0.286732	0.1850	0.092660	0.2925	0.031978
0.0800	0.278340	0.1875	0.090382	0.2950	0.031198
0.0825	0.270288	0.1900	0.088161	0.2975	0.030437
0.0850	0.262556	0.1925	0.085997	0.3000	0.029695
0.0875	0.255122	0.1950	0.083886	0.3025	0.028971
0.0900	0.247968	0.1975	0.081829	0.3050	0.028265
0.0925	0.241079	0.2000	0.079822	0.3075	0.027576
0.0950	0.234438	0.2025	0.077866	0.3100	0.026904
0.0975	0.228032	0.2050	0.075958	0.3125	0.026248
0.1000	0.221848	0.2075	0.074098	0.3150	0.025608
0.1025	0.215874	0.2100	0.072284	0.3175	0.024984
0.1050	0.210100	0.2125	0.070515	0.3200	0.024375
0.1075	0.204515	0.2150	0.068790	0.3225	0.023781
0.1100	0.199110	0.2175	0.067107	0.3250	0.023201
0.1125	0.193877	0.2200	0.065466	0.3275	0.022636
0.1150	0.188807	0.2225	0.063866	0.3300	0.022084
0.1175	0.183894	0.2250	0.062305	0.3325	0.021545
0.1200	0.179129	0.2275	0.060782	0.3350	0.021020
0.1225	0.174508	0.2300	0.059297	0.3375	0.020508
0.1250	0.170023	0.2325	0.057849	0.3400	0.020008
0.1275	0.165669	0.2350	0.056436	0.3425	0.019520
0.1300	0.161441	0.2375	0.055058	0.3450	0.019045
0.1325	0.157334	0.2400	0.053713	0.3475	0.018580
0.1350	0.153344	0.2425	0.052402	0.3500	0.018128

TABLE 7.—*Values of unaccomplished temperature change corresponding to various values of* $\frac{4\alpha\tau}{D^2}$ *at the mass-average temperature point of peaches in the case of cooling with negligible surface resistance*—Continued

$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$	$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$	$\frac{4\alpha\tau}{D^2}$	$\frac{t_{ma}-t_s}{t_i-t_s}$
0. 3525	0. 017686	0. 4025	0. 010797	0. 4525	0. 006591
0. 3550	0. 017255	0. 4050	0. 010534	0. 4550	0. 006431
0. 3575	0. 016834	0. 4075	0. 010277	0. 4575	0. 006274
0. 3600	0. 016424	0. 4100	0. 010027	0. 4600	0. 006121
0. 3625	0. 016023	0. 4125	0. 009782	0. 4625	0. 005972
0. 3650	0. 015633	0. 4150	0. 009544	0. 4650	0. 005826
0. 3675	0. 015252	0. 4175	0. 009311	0. 4675	0. 005684
0. 3700	0. 014880	0. 4200	0. 009084	0. 4700	0. 005546
0. 3725	0. 014517	0. 4225	0. 008863	0. 4725	0. 005411
0. 3750	0. 014164	0. 4250	0. 008647	0. 4750	0. 005279
0. 3775	0. 013818	0. 4275	0. 008436	0. 4775	0. 005150
0. 3800	0. 013482	0. 4300	0. 008230	0. 4800	0. 005025
0. 3825	0. 013153	0. 4325	0. 008030	0. 4825	0. 004902
0. 3850	0. 012832	0. 4350	0. 007834	0. 4850	0. 004783
0. 3875	0. 012520	0. 4375	0. 007643	0. 4875	0. 004666
0. 3900	0. 012215	0. 4400	0. 007457	0. 4900	0. 004552
0. 3925	0. 011917	0. 4425	0. 007275	0. 4925	0. 004441
0. 3950	0. 011626	0. 4450	0. 007098	0. 4950	0. 004333
0. 3975	0. 011343	0. 4475	0. 006925	0. 4975	0. 004228
0. 4000	0. 011067	0. 4500	0. 006756	0. 5000	0. 004125

U.S. GOVERNMENT PRINTING OFFICE [illegible]