MEASUREMENTS OF COOLING RATES OF FRUITS AND VEGETABLES

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By

Kamal El Din Hussein Motawi

AN ABSTRACT

Submitted to the College of Agriculture
Michigan State University of Agriculture and Applied Science
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ABSTRACT

Cooling fruits and vegetables is, naturally, a matter of great concern to both the food producer and the food processor since, in general, to achieve top quality in the finished product, it is essential to maintain the high quality of the raw product. This is usually done through effective refrigeration from the time of harvest until the time of manufacture.

The literature concerned with cooling performance makes little or no use of available mathematical and engineering information; therefore, this study of the measurements of cooling rates was pursued using the fundamental concepts of heat transfer, and applying the theoretical and empirical equations to the cooling of fruits and vegetables in an effort to establish the applicability of theory to practice in this important area of food technology.

The experiments included tunnel cooling, in which cold air at 31-32^{o}F was the heat transfer medium for cooling different sizes or fruit one at a time at different air velocities; water cooling, in which some fruits and vegetables were cooled in running cold water at 32-33^{o}F at different water flow rates; and a few heating tests in running hot water using a laboratory retort as a water bath.

Measurements of cooling rates, particularly with air cooling, suggest strongly that the theoretical model assumed, together with the fundamental thermal properties such as thermal diffusivity, thermal conductivity, and surface heat transfer coefficient of the object, can be used to predict the cooling equation. Although the results obtained show that the changes in these values with respect to each other are in the predicted directions, more precise knowledge

of the basic thermal properties of foods are needed before these relationships can be clearly established.

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INTRODUCTION

All fresh fruits and vegetables are alive and remain living throughout their entire period of salability or until processed. Being alive they respond to the environment in which they are held and have fairly definite limitations as to the conditions that they can tolerate.

They remain alive by utilizing reserve energy stored during growth. The process of breaking down food into carbon dioxide and water with the release of energy and uptake of atmospheric oxygen is known as respiration. Respiration, the complex collection of enzymatic and other chemical activities is accompanied by quality changes and the eventual death of the commodity.

These internal changes associated with life cannot be stopped but should be retarded if the fruit is to remain alive and quality is to be maintained at a high level for a prolonged period.

Cooling the commodity prior to shipment is commonly termed precooling. The goal of precooling is to provide environmental conditions that will result in minimum deterioration and yet keep the perishable commodity alive and fresh. Within the temperature range usually encountered the rate of deterioration of fruits and vegetables is increased from two to four fold for each 18°F(10°C) rise in temperature. Not only do higher temperatures accelerate ripening and respiration but they also accelerate decay. The activities of the organisms causing decay are accelerated by temperature in the same general way as is respiration of the produce, thus temperature reduction has the dual function of reducing both respiration and microbial spoilage. Temperature reduction through refrigeration is the most important of the environmental factors subject to control, and it is the most practical method of slowing deterioration. The significance of this dependence of the chemical reactions is related to the product storage life. The temperature differences between the commodity in the field and the cold storage are commonly 40-50°F though often higher; this fact means that deterioration rates are 5- to 25-fold lower at refrigerated temperatures -- one hour at field temperatures can result in as much deterioration as one day at refrigerator temperatures.

Very low temperature is not desirable for all products as some (principally those of tropical origin) are subject to chilling injury which results in a shortened storage life, failure to continue normal ripening, and increased susceptibility to decay.

This study is concerned, not with the final temperature of products already cooled, but with the possibility of predicting from available knowledge, the cooling curve of a particular product given the conditions under which it is to be cooled.

REVIEW OF LITERATURE

Ever since the cooling of fruits and vegetables became recognized as a desirable feature in their proper handling (and the sooner they are cooled, in general, the better the quality) , means have been sought to increase the speed of cooling and to achieve more uniform cooling of the products.

Cooling and precooling are accomplished through cold air or cold water as a transfer medium , by direct contact with ice or by evaporation of water from their surfaces as in leafy products (vacuum cooling).

All these methods of cooling are, however, not applicable to all perishables. Since the rate at which produce cool is affected by the method of cooling, it is desirable to describe briefy the common methods of cooling.

COOLING METHODS

1. <u>Air Cooling</u>

A. Still-air cooling or Room cooling: one of the commonest methods in which one relies on the heat being carried from the product to the ice or refrigerated surfaces chiefly by natural convection.

B. Faster methods of air cooling (Sainsbury, 1951; Guillou, 1960).

(1) Forced air cooling: The term 'forced-air cooling' is used here to designate the cooling of fruits or vegetables by use of a difference in air pressure to force air through stacked containers. Heat is believed to be carried away primarily by forced flow of air past the produce inside the containers rather than by flow past only

the outside of the containers as in room cooling. It can be done in many ways and it is affected by many factors such as fan location and product-container arrangement, which result in differences in heat transfer rates

(2) Ceiling-jet cooling (Guillou, 1960). Its principle is that of providing air ducts on the ceiling of a cooling room and nozzles to direct the air jets vertically downward. Heat is removed from the product by air flowing into the containers and around the individual articles.

(3) Tunnel cooling (Sainsbury, 1951) in which air is caused to flow into stacked containers by placing them in a tunnel through which air is moved at high velocity. It gave excellent results at the experimental level, but on commercial use it turned out to be expensive because of difficulty in controlling air leakage which necessitated excessive refrigeration.

II. Hydro-cooling

Fruits and vegetables may be cooled very rapidly by bringing them in contact with moving cold water. It is the fastest method for all products except leafy vegetables (Guillou, 1960). Finely chopped ice may be mixed with some products as they are packed. Direct contact with ice results in fast cooling, and, since the ice turns to water at the ice product interface, this method could be thought of as an inefficient form of hydrocooling.

III. Vacuum cooling

Leafy vegetables are cooled on a large scale by pumping away the air around them until moisture evaporates rapidly from the leaf surfaces.

The heat necessary for vaporization comes from the produce itself, and at an absolute pressure of 4.6 mm Hg (a usual final pressure in the pumping operation), the temperature of the produce approaches 32^{o}F, the equilibrium temperature of the liquid and vapor phases at that pressure. The warmer the produce, the more heat must be removed to achieve the same final temperature; consequently, more weight (moisture) loss is exhibited by warm produce than by cold. Cooling is faster in the leafy portions of a head of lettuce than in the fleshy core (Barger, 1961).

SURVEY OF PUBLISHED WORK

Dewey (1950) showed the effect of air-blast precooling on the moisture content of stems of cherries and grapes. He studied sweet and sour cherries and Concord grapes held in wooden tills precooled in air blast at 32-34°F with a relative humidity of 90 or 70%. In an air blast of about 770 fpm fruits were completely precooled in 30-50 minutes, whereas more than 7 hours were required for cooling both kinds of fruits in still air. The relative humidity of the air did not affect the cooling rate. The humidity of the air is of minor importance to moisture loss during precooling. The moisture loss from the stems of grapes were the same in moving and still air and in air of 70-90% humidity.

In tests reported by Redit and Smith (1953) on the cooling of southern California peaches after loading into railway vans temperatures were lowered to 61°F-65°F (16-18°C) in 5-14 hours (depending on product location in the car) by portable precooling fans, or the fans fitted in the vans (ice was used in both cases), or by mechanical refrigeration. Hydro-cooling (steri-cooling) the peaches in water containing hypochlorite, lowered their temperature to 45-55° (7-13°C) in 12-15 minutes and they did not become appreciably warmer during periods of up to one hour on the packing house floor at hot summer air temperature, or after loading in pre-iced railway vans. None of these precooling methods cooled the fruit to the extent desirable to delay ripening and prevent decay.

C. E. Wright (1953) reported that quick cooling cuts fresh vegetable losses. At the fresh vegetable packing plant of Chase Co., Sanford, Florida, two hydro-cooling units are used to bring the temperature of the packed product to near freezing temperatures within half an hour.

Allen and McKinon (1954) reported that 10-15 hours were required to cool the cherries near the outside of the package from a temperature of 65-70°F to 35°F in refrigerator cars when the circulating air temperature was maintained at 30-33°F. The fruit in the center of the package was 10-15° higher than that near the edges at the end of four hours and 1-5°F higher at the end of 18 hours. A period of 24 hours was considered necessary for complete cooling of the fruit at the center of the packages. Rates of cooling in both refrigerator cars and storage rooms were found to be 2.0 to 3.5°F per hour for cherries in the center of the packages, and 3.0 to 6.0°F per hour for the fruit near the edges of the container over a period of 8-10 hours. The average cooling rate at both center and edges of boxes over a period of 16-20 hours was slightly less than 2.0°F per hour. And these cooling rates were obtained in moderate air circulation. It was found that air velocity affects cooling rates: when air velocity is increased cooling rates increase too. The same thing is true with regard to the temperature (degrees F. drop/time) if the cooling medium is at constant temperature and cooling started at higher initial temperature. It was found also that cooling rates were not influenced by the maturity of the fruit. In hydro-cooling water is used as the cooling medium. The fruit may be immersed in a water bath or water may be flooded over and through the product either before or after packaging. The water is cooled by crushed ice or by refrigeration coils in the cooling tank system. Water temperature should be 32°F or slightly higher. Only seven minutes were required to reduce the temperature of Bing cherries from 65°F to 37° when immersed in the water bath ice melting at 32°F.

Pentzer (1940) precooled California cantalopes. Air was the medium used for heat exchange from the commodity to the refrigerating surface. In this case cooling depends upon several well-recognized factors, the most important of which are:

1. Volume, velocity and distribution of air
2. The difference in temperature between the commodity and the air used for cooling
3. The method of packing and stowing as it affects air circulation
4. Certain properties of the object to be cooled such as their size, shape, surfaces as they affect heat transfer, heat capacity, conductivity, and metabolic activity.

Precooling tests were conducted in a considerable number of railway cars.

The precooling rates with inside fan equipment reported by Pentzer are slightly higher than those obtained by Overholser and Moses (1928), but compare favorably with the rates obtained by Gaylord, Fawcett and Hienton (1935) in recent tests made on cantalopes with similar equipment. Cars precooled with truck-mounted mechanical refrigerating units had average cooling rates of 4.18°F and 4.10°F per hour for 9-3/4 and 8-1/2 hour periods, respectively. In non-precooled cars, in which the air movement was by natural circulation only, the cooling rates ranged in some cars from 1.1°F per hour for a period of about 13 hours to 2.24°F per hour for a period of 4 1/6 hours in other cars.

With all types of precooling in these tests cold air was blown over the top of the load, the direction of the air movement being from the top to the bottom of the load, towards the center of the car with portable car fans and towards the bunkers with the truck-mounted unit. The cooling rates in the middle and bottom layers were very similar, being slower in the bottom layers of product in all cars than in the top layer. Among the cars precooled with portable inside fans, the highest cooling rates obtained were 4.9 to 5.1°F per hour; the fruit was fairly warm when precooling was started. The coolest car when loaded, averaging 63.4°F, had the lowest cooling rate of all the fan cooled cars, amounting to 2°F per hour for an 8-1/2 hour cooling period. The average cooling rate for the 19 cars cooled with portable car fans was 3.58°F, indicating that under the conditions of these tests a reduction of 3.6°F per hour could be used as a guide in estimating the time required to precool cantalopes.

Pentzer, Asbury and Barger (1945) studied the effects of various factors on precooling rates of California grapes and their refrigeration in transit.

1. Type of equipment: In comparing the precooling rates obtained with various types of equipment, differences were found but none were so great that longer precooling would not have compensated for them. Even with the most efficient equipment time was the all-important factor.

2. Heavy and light chopping of ice: In tests made on the air circulation in refrigeration cars in transit, it was found that light chopped ice was better than heavy chopped ice.

3. Type of load: There is considerable evidence that crosswise loads are more difficult to cool because the ends of the boxes instead of the thinner and more open sides are exposed to the air channels.

4. Type of package: It was found that type of package affects the cooling rate to a great extent. Therefore it was suggested that the grapes be cooled to some extent before they are packed. Lugs of grapes without lids were cooled in a small tunnel in which air at 28 to 32°F was circulated at velocities of 400 to 500 ppm. Thermocouples were used to read temperatures of individual grapes in various parts of the lugs. In these tests it was found that 1 to 1-1/2 hours were required to cool the grapes throughout the package to temperatures of 40 to 45°F from initial temperatures of 75 to 80°F. They also showed that pads in the bottom of the lugs interferred to some extent with the circulation of air through the package and therefore retarded cooling. A more complete test was made in the small model tunnel cooler which was designed to cool lugs of grapes as they are conveyed in three tiers through it. Air entering the top of the tunnel was directed downward past the fruit. A centrifugal fan was used to give air velocity of about 600 fpm in the tunnel. Refrigeration was supplied by air from a cold-storage room. Air temperatures were not as low as desired but were probably representative of those that would be obtained under commercial conditions unless a greater amount of cooling surfaces was provided. The fruit cooled from about 70°F to 34°F-45°F in an hour. The grapes in the bottom and center of the lugs cooled the least. It was suggested that small slots or holes in the back bottom of the package might have aided cooling by providing an outlet for the air

forced into it. The results indicated that it is possible to cool unlided lugs of grapes sufficiently in one hour to meet the precooling requirements for this commodity, but to do this commercially would require a large volume of air maintained at low temperature.

Studies were reported by Gerhardt and Hukill (1945) on precooling practice at two storage temperatures and their relation to the condition and appearance of Bing cherries. The rates of cooling of packed fruit at 31°F and 44°F under otherwise identical conditions were reported to be the same. When an air blast of 375 fpm was used, cooling was 1.9 times as fast as in still air, and cooling in ice water at 32°F (0°C) was 145 times as fast in still air at 31°F. After 4 hours precooling fruit in an air blast at 44°F (7°C) had cooled as much as that in still air at 31°F. Loss in weight of the cherries was reduced by rapid cooling in ice water. Hydrocooling for 7 minutes at 32°F did not injure the appearance and condition of cherries.

Bethell and Challman (1950) reported on a mechanical refrigeration system for California fruit which is to be sent to eastern markets. In the case of plums, the fruit is placed in the quick chill room on the day it is picked and is cooled to 32°F (0°C) in 15 hours and then loaded into refrigerated railway vans, in which it is held at the same temperature during transport.

Rose and Gorman (1936) studied the handling, pre cooling and transportation of Florida strawberries. They found that the wetting of strawberries affects their rate of cooling. There were four test lots of one quart each; two quarts were dry and two were wet. One lot of each pair was held in still air, and the other two lots were placed in front of and about four feet away from a 14-inch electric fan running at such a speed that the rate of air movement over the berries averaged about 300 fpm. The temperature of the room where the tests were run was 41-42°F most of the time. The temperatures were obtained by means of thermocouples. It was found that fan-blown berries cooled much more rapidly than those in still air, and that wet berries cooled somewhat faster than the dry ones. Therefore the wetting of strawberries hastens the rate at which they cool. Wetting the berries by means of washing caused slight damage to the product. Cooling is gradual and several hours to a day or two may be required to reduce the temperature of the load to that of the air in the car. The rate of cooling depends chiefly on the difference between the two temperatures, but it is also affected by the quantity of the commodity to be cooled, the kind of container and the method of stacking or loading the packages in the car. When a crate of strawberries was placed in a cold storage room held at 32°F to 34°F, the most rapid cooling occurred during the first 8 hours, and the rate of cooling became gradually slower as the test was continued and the temperature of the room and the fruit approached each other, and the fruit was still about 2°F warmer than the air in the room, even at the end of 24 hours. The rate of cooling a carload of strawberries was of course much slower than for a single crate. The results obtained under standard refrigeration with 3 per cent of salt at all icing stations showed clearly that the fruit in this car required considerable time to cool. In all parts of the load where temperatures were taken, it cooled most rapidly during the first 18 hours after loading was completed. The fruit at the bottom of the car required approximately 22 hours to reach 30°F. The fruit at the top did not go below about 38°F during the entire transit period while it required 13-1/2 hours to reach 50°F and 39-1/2 hours to reach 38°F. This car was shipped March 24, and the outside temperature when loading was completed was 69°F. The average temperature of the top fruit was 60.4°F and of the bottom fruit 47.5°F.

Guillou (1960) reported that the performance of the precooling operation can be compared most conveniently in terms of half-cooling time. This is the time required for the temperature of the product to be reduced to one half of difference between product and cooling medium that existed at the beginning of the period considered. It is assumed that the cooling medium temperature is relatively constant during the period. If the cooling medium fluctuates considerably, a cooling coefficient may be determined from average product and average cooling medium temperatures during the period. This coefficient is convertable to half-cooling time. For a normal precooling operation using 33°F cooling medium, twice the half-cooling time will be required to reduce commodity temperature to 40°F if the initial temperature is not higher than 64°F. For initial temperatures up to 96°F three times the half-cooling time should be allowed to produce a final commodity temperature of 40°F.

Variations in cooling rates. Dewey (1950) and Guillou (1959) found the biggest variation in cooling rates and time of cooling occur as a result of the nature of commodity and density of the pack, type of package and method of loading. The time required for cooling varies with the temperature of the air blast to the heat load and also with the rate at which air moves freely over the commodity being cooled. Best results will be attained when air movement in excess of 500 fpm between the packages is used and if goods are not wrapped in paper and are designed to permit reasonable air movement through the container itself.

In his study on fruit, Sainsbury (1961) emphasized the importance of nearly uniform product temperature as possible during the storage period. 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, which is reported in terms of "half-cooling time." Air passage through the packages and the distance from the center of a pile of packages to the surface where the heat is removed are the factors of most importance; half-cooling time in a package where convection is negligible varies almost with the square of the distance. 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 $1^{o}F$ for a 30 hour half-cooling time, 2^{o} for a 60 hour half-cooling time, etc. He studied the effect the starting period (lag factor) had on the half-cooling time and it was found that the time required for the initial temperature to be reduced 50 percent at the center (the first half-cooling time Z_1) is greater than the time for reduction from 50 percent to 25 percent Z_2 or from 25 percent to 12.5 percent Z_3, of initial value. So the time to reduce the temperature from 50 percent to 25 percent of its initial value usually is the true characteristic cooling time, or half-cooling time. The lag factor calculated was greater than 1 in all cases.

STATUS OF COOLING STUDIES

In summary, studies of fruit cooling are, as a general rule, concerned with specific situations (for example, a special box in a particular location, stacked in a particular way) in which minor modifications are made (for example, the stacking arrangement). The reports of such work frequently make little or no reference to any fundamental aspects of heat transfer; often the temperature that is being measured is poorly defined (for example, "average" temperatures have been reported without mention of what is being averaged). In the cases of Guillou (1960), Sainsbury (1951), Gane (1937), and Thevener (1955) the simplification of Newtonian cooling is unjustifiably made.

Moreover, although the importance of rapid cooling is recognized, and although efforts are made to achieve rapid cooling, emphasis is frequently on the (or some) final temperature reached by the fruit. No calculations are made showing probable quality savings as a function of cooling, nor has the economic balance between the more expensive rapid cooling and quality been worked out or estimated. There is, finally, some lack in uniformity in reporting results and experimental conditions. Since previous researchers' attention has not been directed to fundamental aspects of heat transfer, it is not possible to reproduce any of these experiments because the important parameters governing heat transfer are often not even measured or reported. Lack of these elements make any engineering design impossible.

A logical approach to the cooling problem is to consider those elements of heat transfer that enter the solution of the differential equation governing the heat flow. These elements are shape of the product, initial temperature distribution in the product, temperature of the surroundings, thermal and other physical properties of the product, and boundary conditions between the product and the surroundings. Further, at the boundary one may imagine the problem to be one of measuring the surface transfer coefficient as a function of the cooling medium conditions (such as temperature and velocity) and of the product. The argument here is that the cooling situation is most completely and efficiently described in terms of these elements and that the solution to a particular problem might be achieved by analysis rather than experiment if fundamental parameters were known. The solution of the problem is not simple. In this study, attention has been directed to individual fruits; it is recognized that the problem of going from individual fruits to boxes of fruit and from boxes of fruit to stacked arrangements of boxes may prove formidable (Blaisdell, 1962).

The objective of this study is to examine heat transfer in single fruits under a variety of conditions and to deduce from the observed cooling curves the constants involved in the theoretical equations. Many simplifying assumptions have been made, perhaps so many that the solutions will not prove helpful in actual design situations in a real storage. The solution of that problem is left for further study. The objective here is to describe the problems involved in relating observed cooling curves to theoretical curves.

THEORY AND ANALYSIS OF COOLING CURVES

The analysis in the present study is confined to the cooling of spheres, the first simplifying assumption. The equation for the temperature, T, at any point, r, and any time, t, in a sphere of radius r_1, initially at a uniform temperature, T_o, placed in a constant temperature medium at T_c is:

$$\frac{T - T_c}{T_o - T_c} = 4 \frac{r_1}{r} \sum_{n=1}^{\infty} \frac{1}{M_n} \frac{\sin M_n - M_n \cos M_n}{2 M_n - \sin 2 M_n} e^{-M_n^2 \theta} \sin \left(M_n \frac{r}{r_1}\right) \quad \ldots\ldots \quad (1)$$

where M_n are the roots of $1-M_n \cot M_n = B$... (1a)

B = Biot number = $r_1 h/k$

h = surface heat transfer coefficient, Btu/hr-ft^2-^{o}F.

k = thermal conductivity (of the sphere), Btu-ft/hr-ft^2-^{o}F.

θ = Fourier modulus $A\, t/r^2$

A = thermal diffusity, k/Cw, ft^2/hr

C. = specific heat of sphere, Btu/lb-^{o}F.

w = density of sphere, lb/ft^3

(t, hr; r_1 and r, ft.)

The temperature at the center of the sphere, where $r = 0$, is given by:

$$\frac{T - T_c}{T_o - T_c} = 2 \sum \frac{\sin M_n - M_n \cos M_n}{M_n - \sin M_n \cos M_n} e^{-M_n^2 \theta} \quad \ldots\ldots\ldots\ldots \quad (2)$$

(The derivation of this equation is given in Schnider, 1955). At a time sufficiently long, all terms except the first are small and the cooling curve approaches asymptotically:

$$\frac{T - T_c}{T_o - T_c} = 2 \frac{\sin M_1 - M_1 \cos M_1}{M_1 - \sin M_1 \cos M_1} e^{-M_1^2 \theta} \quad \ldots\ldots\ldots\ldots (2a)$$

which, by transferring to base 10 and substituting for θ, becomes

$$\frac{T - T_c}{T_o - T_c} = 2 \frac{\sin M_1 - M_1 \cos M_1}{M_1 - \sin M_1 \cos M_1} 10^{\frac{-M_1^2 A t}{2.303 r_1^2}} \quad \ldots\ldots (3)$$

The asymptote (equation 3) will plot as a straight line on semi-logarithmic coordinates. The slope of the line, $\frac{1}{f}$, $\frac{-M_1^2 A}{2.303 r_1^2}$ and the intercept j, at t = 0 is $\left(2\frac{\sin M_1 - M_1 \cos M_1}{M_1 - \sin M_1 \cos M_1}\right)$. Ayrton and Perry (1878) have an excellent discussion treating the applied problem of calculating the fundamental constants h and k from the observed curves. Their treatment includes a discussion of four methods of handling the experimental data.

From the values r_1, C, and w, the intercept of the asymptote, and slope (1/f) one can calculate A and B, and ultimately, h and K as follows:

1 - From j get M_1

2 - From M_1 get B

3 - From f, r_1, and M_1 get $A = 2.303\ r^2/fm_1^2$

4 - From A, C, and w get k = ACw

5 - From k, B and r_1 get $h = kB/r_1$

(Curves for steps 1 and 2 and a table of some values of M_1 and B are given in the appendix).

The surface transfer coefficients calculated may be compared directly with published values, or through the Nusselt number, $Nu = \frac{hD}{k_s}$ where D is a characteristic dimension of the immersed solid ($D = 2\ r_1$ for spheres), and k_s is the conductivity of the surroundings, so that

$$Nu = \frac{kBD}{k_s r_1} = \frac{2Bk}{k_s}$$

Two common methods of reporting cooling in fruit and vegetables, are given below:

Sainsbury (1951)

$$\log\ (T - T_c) = -\frac{CR}{2.303}\ t + \log\ (T_o - T_c).$$

CR, or cooling rate, = the number of ^oF the fruit temperature is reduced per hour per ^oF temperature difference between the fruit and cooling medium (air).

Guillou (1960)

$$\log\ (T - T_c) = -\frac{\log\ 1/2}{Z}t\ +\ (T_o - T_c)$$

z = time to reduce the initial temperature difference between the object and its surroundings by one half, called the "half-cooling time."

The nomenclature (j and f) used in present study is that Ball and Olson. (1957).

Since the fundamental constants involved in the temperature equation (3) are to be derived from the experimental curves once the straight line asymptote to this curve is drawn, the two points (or other parameters) of a straight line become measures corresponding to the two undetermined coefficients in the second order differential equation. The results in this study are reported as the slope and intercept (when t = 0) of the straight line heating curve drawn on semi-logarithmic paper after the method of Ball and Olson (1957). Their equation is:

$$\frac{T - T_c}{T_o - T_c} = j\ 10^{\frac{-t}{f}}$$

where j is called the lag factor and f the heating (or cooling) rate.

The three methods (Sainsbury, Guillou, and Ball) may be compared.

Table (1) Comparison of Cooling Curve Parameters

NAME	INTERCEPT	SLOPE
Sainsbury (1951)	1	$\frac{-CR}{2.303}$ CR = cooling rate
Guillou (1960)	1	$-\frac{\log 1/2}{Z}$ Z = half-cooling time
Ball (1957)	j Lag Factor	$-\frac{1}{f}$ f = heating or cooling rate

The final point to make is that both Sainsbury and Guillou assume an intercept of 1. (Also Gane (1937) assumed j = 1 for air cooling and j = 2 for cooling in paraffin). This means that one of the two undetermined coefficients has been arbitrarily fixed. From a physical point of view it means that the entire resistance to heat transfer is in the surface layer. This situation corresponds to a very low Nusselt number as would be the case in most of the studies reviewed. At the other extreme, if the surface transfer coefficient is infinite, then j becomes 2 and M_1 is $\frac{\pi}{2}$. Real fruit (provided it is spherical) in real storage presumably lies somewhere in this region.

EXPERIMENTAL

Temperature measurements

In heating, hydrocooling, and air cooling, temperature measurements were made by means of 24-gage copper-Constantan thermocouples and a Brown recording potentiometer. All the tests were conducted by observing the temperature rise or reduction near the center[1] of individual products, except for peaches and plums for which the temperature was measured next to the pit. Each commodity was cut at the end of every run and examined to be sure the thermocouple was in or close to the center. Runs for which the thermocouple was more than 1-1/2 mm. from the center are not reported (peaches and plums excepted).

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[1]According to theory, the heating rates do not vary with location; the predicted reduction in lag factor at a distance 10% from the center (spheres) is a maximum of 2% as calculated from the following equation:

$$K = \frac{\sin (M_1 \ r/r_1)}{M_1 \ \ r/r_1}$$

which is the correction to j for positions other than the center, where r_1 is the sphere radius and r is the distance of the thermocouple from the center. The position error in any given location is a function of M_1 and will be a maximum when M_1 is a maximum, which in this work is pi.

The point of thermocouple insertion was sealed with wax to prevent the hot or cold water from getting into the fruit and to help hold the thermocouple in position. For air cooling the wax seal was also used so that the fruit remained dry and any possible erroneous reading caused by evaporation of juice from the opening where the thermocouple was inserted was avoided.

One thermocouple was reserved in all tests to record the cooling or heating medium temperature.

Frequency of reading and plotting varied with the rate of temperature change in the product tested. For instance, in grapes readings were taken about every half minute and every six minutes for apples and other larger fruits.

Air Cooling Experiment

Room cooling or cooling tests were conducted on pears and Red Delicious apples. Fruit of approximately the same weight and shape were selected. Uniform initial temperatures were achieved by holding the fruit at ordinary room temperatures overnight. The fruit was placed on a table in the cold room to cool. Air and fruit temperatures were recorded throughout the test period. Cooling rates were obtained and compared.

Forced air cooling (Tunnel cooling)

For these series of tests a tunnel of 38-7/8 inches long and 11-3/4 inches diameter was constructed from metal ducts. A 9-watt electric fan with 9-3/4 inch diameter blade to blow a draft of cold air past the fruit was fixed 7-1/2 inches from one end of the tunnel. This operation did not cause any appreciable rise in temperature of the air in the tunnel (less than 0.5^{o}F). The tunnel was placed in the cold room in which all the air cooling tests were done. Apples and pears were cooled by this device. The fruits were suspended one at a time near the center of the tunnel 6-1/2 inches from the end of the tunnel opposite the fan. It was held from its stem by a piece of wire attached to a hook fixed in the upper inside wall of the tunnel. Air velocity was controlled by varying the fan speed through a rheostat. The fruits were cooled at different air velocities, 300, 600 and 900 fpm. The fruits were selected as uniform in shape as possible and the initial temperatures were uniform and the same.

In air cooling of apples and pears some were weighed before and after cooling to see if moisture was lost. The weighing after cooling was made in the cold room to avoid gaining moisture by condensation on the surface of the fruit. The maximum loss observed was 0.2%.

Cooling room temperature and, therefore, the temperature of the air moving past the fruit, averaged 31°F, with a range of 3-4°F. The fluctuation occurred every 10 minutes, but the variation was small compared with the difference between the commodity temperature and the average air temperature which was used for plotting.

Air velocity was measured with an Alnor-thermo anemometer. With this equipment, a maximum air velocity of 1000 fpm. was possible. The air velocity was measured at four points, each 1/4 inch from the fruit in a plane perpendicular to the direction of air flow, one point on each side, one point above and one point below the fruit. The reported velocity is the average of these values. A typical pattern was 900 and 910 fpm on the sides, 920 fpm. above and 870 below. Thirty fpm was the maximum deviation of any of the four points measured from the reported average velocities.

<u>Hydrocooling and heating</u>

Hydrocooling and heating were conducted by using a laboratory retort as a water bath (see figure 1). The water was recirculated from

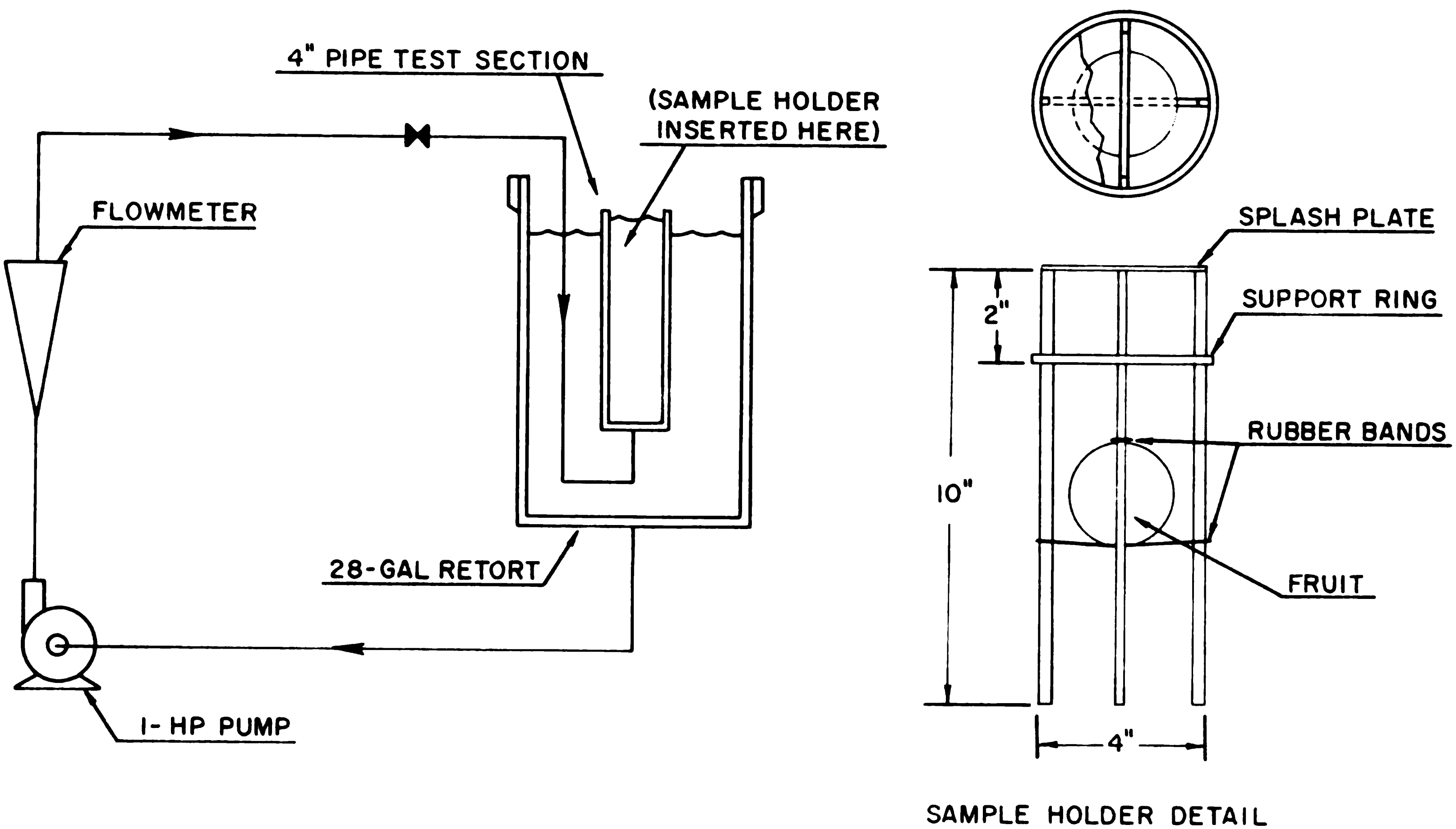


FIG. 1 SCHEMATIC DIAGRAM OF TEST APPARATUS

the retort through a 16-inch diameter pipe by a hydraulic pump; velocity was controlled by a volumeter. For cooling tests, the water bath (retort) was filled with crushed ice and water. The temperature of the water bath held between 32-33°F, although sometimes it tended to exceed this range by 0.5 to 1°F, but never for more than 2 minutes. Temperature was maintained by adding crushed ice at appropriate intervals. The water bath was heated with steam in the heating experiments. Bath temperatures were controlled by a "Taylor Automatic Controler."

The individual products were held in the sample holder by rubber bands stretched between opposite legs of the sample holder (see figure 1). The sample holder was placed in the upper end of the 4-inch pipe test section. For small fruits, such as grapes, the fruit was first put inside a small cylinder of hardware cloth which was then fastened in the sample holder.

Cooling and heating were also done by a spraying system added to the retort by which the water was showered over a layer of the product held on a screen with the level of water one inch underneath it. There was no difference between cooling or heating in a stream of water and the spraying system.

RESULTS

Air Cooling

The curves shown in Fig. 2 for apples cooled at 300, 600, and 900 ft/min, plotted on semi-logarithmic coordinates, are presented to illustrate the method of plotting and calculation. These curves are typical of all the cooling and heating curves made in this study.

The heating characteristics of pears and Red Delicious apples cooled in 31°F air at different air velocities are given in Table 2. The apples weighed 194 ± 1 gram. For these apples, the only fruits for which the weights are known, the radius of a sphere of equivalent volume was calculated (using a density of 51.2 lb/ft^3). The calculated radius, 3.81 cm. was very close to half the largest measured dimension; therefore, in subsequent analyses the value for radius was taken to be about half the largest dimension measured. The heating characteristics of two sizes of Red Delicious apples at two different air velocities, three apples at each size and each velocity, are given in Table 3. Qualitatively these results (Tables 2 and 3) agree with theoretical predictions: increasing air velocity yields smaller heating rates and larger lag factors (fruit size constant); as fruit size increases, heating rates increase and lag factors increase (velocity constant).

Surface heat transfer coefficients were calculated by four different sets of assumptions (See Table 4):

In calculation I, the observed j and f were assumed to be true and k and h were calculated; the calculated k's ranged from 0.266 to 0.554 $Btu\text{-}ft/hr\text{-}^{\circ}F\text{-}ft^2$.

In calculation II, A was assumed to be known and to be the same

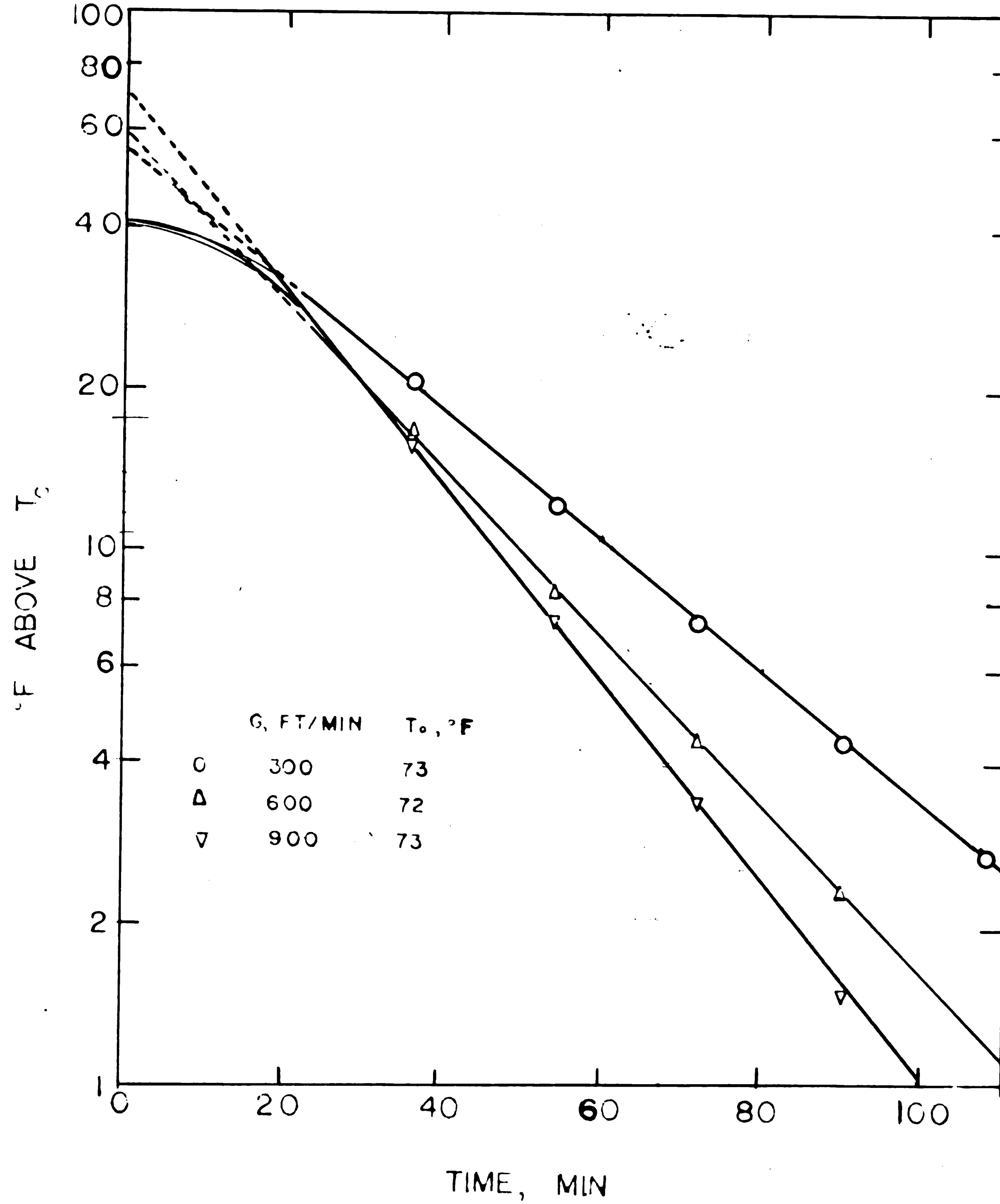
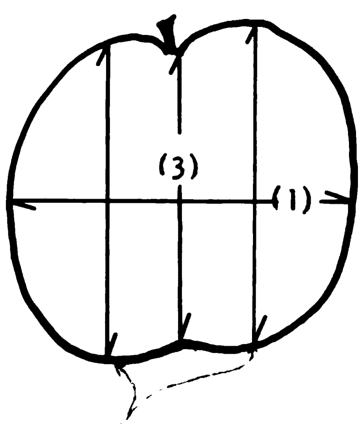


Fig. 2. Cooling curves for 3 apples of the same size cooled in 31°F air at different air velocities.

TABLE 2: AIR COOLING FOR RED DELICIOUS APPLES AND PEARS AT DIFFERENT AIR VELOCITIES AT AIR TEMPERATURE OF 31°F.

Item	Dimensions[a], cm (1)	(2)	(3)	Air velocity G, ft/min	Cooling rate, f, min	Lag factor j
Apples	7.5	7.5	4.0	0	164	1.16
	7.4	7.0	3.5	300	82	1.31
	7.5	7.2	4.0	600	64	1.49
	7.5	7.5	4.0	900	54	1.73
	(1)		(2)			
Pears	6.0		6.5	0	108	1.21
	6.0		6.4	300	66	1.31
	6.1		6.5	600	58	1.46
	6.0		6.7	900	43	1.6

a.



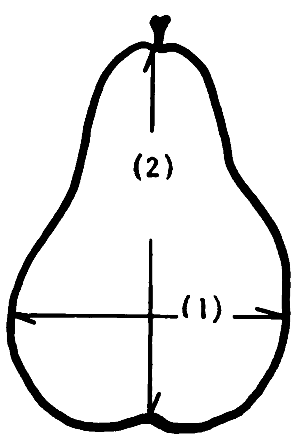


TABLE 3: COOLING DIFFERENT SIZES OF RED DELICIOUS APPLES AT DIFFERENT AIR VELOCITIES IN AIR AT 31°F.

Apple Size	Dimension[a], cm (1)	(2)	(3)	air velocity G, 300 ft/min. ft/min	lag factor j
Small	6.5	5.0	3.0	64.0	1.26
	6.4	5.0	3.0	58.0	1.30
	6.5	4.8	3.0	61.5	1.27
Large	7.8	7.3	4.0	103.0	1.12
	7.9	7.5	4.0	100.0	1.2
	7.7	7.4	4.2	96.0	1.31

Apple Size	Dimension, cm			air velocity G, 900 ft/min. ft/min	lag factor j
Small	6.4	5.0	3.1	37.0	1.7
	6.5	5.1	3.2	42.0	1.64
	6.4	4.8	3.0	40.5	1.67
Large	7.9	7.6	6.1	65.0	1.58
	7.7	7.3	4.0	63.0	1.63
	7.8	7.5	4.2	69.0	1.52

[a]See Table 2, page 28 for description of dimensions.

TABLE 4: COMPARISON OF CALCULATED SURFACE TRANSFER COEFFICIENTS FOR RED DELICIOUS APPLES AT DIFFERENT AIR VELOCITIES IN AIR AT 31°F
h, Btu/hr-°F-ft^2

r_1, cm	Assumptions[a]	Air velocity, ft/min			
		0	300	600	900
3.2[b]	I	-	4.76	-	10.5
	II	-	5.25	-	11.1
	III	-	3.59	-	6.06
	IV	-	4.85	-	8.86
3.6[b]	I	-	2.49	-	6.50
	II	-	3.22	-	5.45
	III	-	3.39	-	5.72
	IV	-	4.37	-	8.45
3.81	I	1.82	4.00	5.76	6.08
	II	1.90	4.80	6.95	10.1
	III	-	3.28	4.45	5.56
	IV	-	4.26	6.45	8.25

[a]Assumptions

I - observed j and f are correct
II - A = 0.00649 Btu-ft/hr-°F-ft^2 andf
III - Kramers (quoted in Zenz and Othmer, 1960).
IV - McAdams (1954).

[b]Based on the average of j and f of 3 apples

for all apples (These apples were taken from the same lot.). A was calculated from the equation A=k/Cw. C was assumed to be 0.89 Btu/lb-°F (Short and Bartlett, 1944); the density, w, 51.2 lb/ft^3, was based on a laboratory measurement of a McIntosh apple taken from a lot different from that from which the apples for cooling tests were taken; and k was calculated from Andersen's (1959) formula, $k=Mk_w + (1-M)\ k_s$, where M is the moisture fraction (assumed to be 0.84), k_s is the conductivity of the solids (assumed by Andersen to be 0.15 Btu-ft/hr-°F-ft^2), and k_w is the appropriate conductivity of water. Since the conductivity of water varies measurably in the range from 30° to 50°F (the temperature range, generally, in which the asymptote to the heating curve was approached), a weighted average value was used. Values of k for water were taken from Eckert and Drake (1959). Based on all these assumptions, the thermal diffusivity, A, for apples was calculated to be 0.00649 Btu-ft/hr-°F-ft^2.

In calculation III, h was calculated from Kramers' equation (cited in Zenz and Othmer, 1960): $hD/k_s = 2.0 + Pr^{0.15} + 0.66\ Pr^{0.31} Re^{0.5}$ where k_s is the conductivity of the surroundings, Pr is the Prandtl number (Cw/k), and Re is the Reynolds number DGw/μ (μ is viscosity)

$$h \text{ for air at } 32^{\circ}F = \frac{1.38 + 0.494\ (DG)^{0.5}}{D}$$

$$h \text{ for water at } 32^{\circ}F = \frac{39.5 + 79.2\ (DG)^{0.5}}{D}$$

(In these last two formulas D is in cm and G is in ft/min.)

In calculation IV, h was calculated from McAdams (1954) formula:

$kD/k_s = 0.37\ (Re)^{0.6}$ (for air only).

A comparison of calculated j's (same assumptions as calculation II above) and the observed j's is shown in Fig. 3 (water cooling results shown also in Fig. 3 are discussed below). The closest agreements are between calculations II and IV and between I and IV, the poorest between II and III and between IV and III. Kramers' equation (calculation III) is an empirical equation which combines results for water and air in a single equation; this feature is, perhaps, responsible for the relatively poor fit. The agreement between McAdams' equation (calculation IV) and calculation II (k calculated from fundamental physical properties, and the experimental f) is encouraging.

Water Cooling and Heating

The cooling characteristics of McIntosh apples of approximately identical size and pears cooled in 31° running water at different water flow rates of 84, 150, and 200 lb/min are given in Table 5; these flow rates correspond, for apples, to average velocities of 22.5, 40.0, 53.5 ft/min. Heating rates decrease and lag factors increase with increasing flow rates.

Calculated surface heat transfer coefficients obtained by three sets of assumptions are given in Table 6. These assumptions are the same as those used for the air cooling calculations, except that the density of McIntosh apples was taken to be 49.5 lb/ft^3. The agreement between calculations I and II is fair: II gives higher coefficients than I, as was generally the case for the air cooling calculations, however, Kramers' equation predicts coefficients that seem far too high.

The heating characteristics for McIntosh of different sizes heated

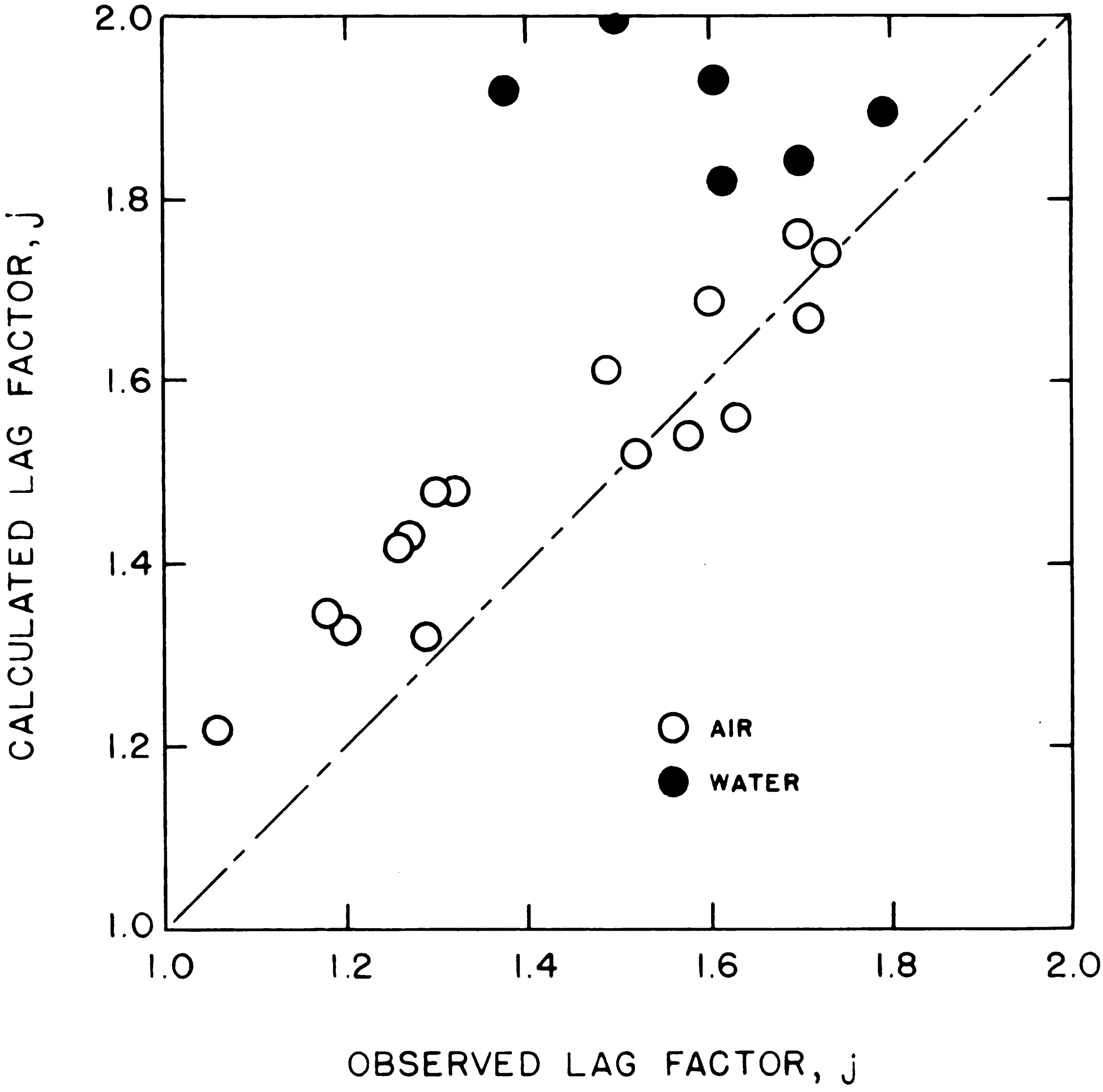


Fig. 3. Comparison of observed and calculated lag factor for apples.

TABLE 5: HYDROCOOLING McINTOSH APPLES AND PEARS AT 31°F AT DIFFERENT WATER FLOW RATES°

Item	Dimensions[a], cm.			Water flow rate ft/min	Cooling rate f, min	Lag factor j
Apple	1	2	3			
	7.0	6.3	3.6	22.5	38.4	1.62
	7.0	6.5	3.8	40.0	37.2	1.7
	7.0	6.5	3.8	53.5	36.0	1.79
Pears	1	2				
	6.0	6.5		22.5	33.4	1.29
	6.0	6.4		40.0	31.3	1.33
	6.0	6.5		53.5	27.4	1.41

[a]See Table 2, page 28, for description of dimensions.

TABLE 6: COMPARISON OF CALCULATED SURFACE TRANSFER COEFFICIENT FOR McINTOSH APPLES COOLED AT DIFFERENT WATER FLOW RATES AT 31°F
h, Btu/hr-°F-ft^2, r_1 = 3.5 CM.

Assumption[a]	Flow rate ,G, ft / min		
	22.5	40	53.5
I	10.40	12.29	14.83
II	14.9	16.4	18.3
III	148	195	224

[a]Assumption

I - observed j and f are correct

II - A = .00685-Btu-ft/hr-°F-ft^2 and observed f

III - Kramers (quoted in Zenz and Othmer, 1960).

in water at 122°F (velocity of 53.5 ft/min) are given in Table 7; surface heat transfer coefficients calculated by the same three methods as above are shown in Table 8. For calculation II, the conductivity of the apple was adjusted to account for the higher conductivity of water at the temperatures prevailing during heating. At the constant flow rate, heating rates increased with increasing size and lag factors decreased.

The cooling characteristics of different sizes of cucumbers cooled in water at 33°F. and flow rate of 84 lb/min. are given in Table 9; with the increasing size, cooling rates increased and lag factors decreased.

The heating characteristics for grapes, plums and peaches heated in water at 130°F and at different flow rates are summarized in Table 10.

Note that at a given flow rate, the heating rates increase with fruit size, and lag factors decrease; as flow rate increases, then, for a given fruit, heating rates decrease and lag factors increase.

The results of hydrocooling and heating tests of both cucumbers and peaches are shown in Table 11. Although the heating rates are higher on heating than on cooling, the difference is not as large as might be expected by the change in thermal diffusivity at the higher temperature. (This change in heating rate was observed for apples.)

TABLE 7: HEATING DIFFERENT SIZES OF McINTOSH APPLES AT 122°F AND WATER FLOW RATE OF 53.5 FT/MIN

r_1	Dimensions[a], cm.		Heating rate, f,min	Lag factor, j
	(1)	3.6		
2.9	(2)	5.8	20.5	1.61
	(3)	3.7		
	(1)	7.0		
3.5	(2)	6.2	26.5	1.50
	(3)	3.8		
	(1)	7.5		
3.75	(2)	6.5	34.5	1.38
	(3)	3.7		

[a]See Table 2, page 28, for description of dimension.

TABLE 8: COMPARISON OF HEAT TRANSFER COEFFICIENT (h), Btu/hr-°F-ft^2 FOR DIFFERENT SIZES OF McINTOSH APPLES AT WATER FLOW RATE OF 53.5 FT/MIN

	Assumption[a]		
r_1 cm	I	II	III
2.9	16.4	10.1	42
3.5	14.3	6.05	69
3.75	9.8	4.05	27

[a]Assumption

I - observed j and f are correct

II - A = 0.00762 Btu-ft/hr-°F-ft^2 and observed f.

III - Kramers (quoted in Zenz and Othmer, 1960)

TABLE 9: COOLING DIFFERENT SIZES OF CUCUMBERS AT BATH TEMPERATURE OF 33°F AND WATER FLOW RATE OF 84 LB/MIN

Diameter cm	Length cm	Cooling rate, f, min	Lag factor j
3.0	8.6	9.2	1.42
3.2	10.1	11.4	1.33
3.5	11.2	14.4	1.23
5.0	13.5	22.8	1.07

TABLE 10: HEATING GRAPES, PLUMS AND PEACHES AT DIFFERENT WATER FLOW RATES AT 130°F

Water flow rate	Grapes		Plums		Peaches	
lb/min	f, min	j	f, min	j	f, min	j
50	3.6	1.40	16.0	1.30	23.5	1.10
100	3.2	1.54	15.0	1.47	22.5	1.15
150	3.0	1.64	14.5	1.60	21.0	1.20
200	2.8	1.75	14.0	1.86	21.0	1.20

TABLE 11: HEATING AND COOLING CUCUMBER AND PEACHES UNDER IDENTICAL CONDITIONS AT FLOW RATE OF 84 LB/MIN

	Cucumber		Peaches	
	Heating	Cooling	Heating	Cooling
Diameter or Weight	3.2 cm	3.2 cm	125 g	124 g
Length, cm	10.0	10.0		
Initial temp. °F	76	76	78	77
Bath temp. °F	120	32	120	33
Initial temp. difference, °F	44	44	42	44
f, min	11.0	11.25	19	22
lag factor, j	1.36	1.34	1.58	1.33

DISCUSSION AND RECOMMENDATIONS

The data presented in Table 2 do verify Dewey's (1950) and Guillou's results (1959) that the shortest characteristic cooling time is associated with the higher air velocities and that the slowest cooling is associated with the lowest air velocity. Here f is proportional to the characteristic cooling time, as shown in Table 1. This trend can also be seen from the cooling curves presented in Figure 2 which shows the change of f and j values for three apples of the same size from the same variety, with the change of air velocity. The lag factor j, which characterizes the beginning stage of cooling, was arbitrarily fixed in the Sainsbury (1951) and Guillou (1960) studies to be 1.

The results obtained from the experimental data in the present study show that this assumption is not justified, since the values obtained for j were more than 1. Moreover, although j approaches 1 as h approaches zero, there is no a priori reason for fixing the value at 1 for all circumstances. At the other extreme, for which j approaches 2 as h approaches infinity, one finds that Gane (1937) assumed $j = 2$ even though from a plot of his published data the curve has a j measurably less than 2.

The real problem is that the slope (whether called cooling rate, or half-cooling time) is a function of both h and k; they are not independently determinable from the slope of the curve. This dependence means that k, over which one has no control in a particular instance, and which probably varies within rather narrow limits for a given variety of fruit and probably not much more for all fruits, has not been measured when half-cooling time has been measured, and that half-cooling time is not a constant for a particular fruit, but a constant only for the very special set of cooling conditions under which it was measured.

Study of the data presented in Table 4 of the comparison of surface heat transfer coefficients, h, for different sizes of apples at different air velocities does indicate that h increases with increasing air velocity in all cases. This trend is in the direction predicted by Kramers' equation. Kramers' equation also predicts a decrease in h with an increase in size for a constant air velocity. The data varifies this trend in all but three instances.

In calculation I of the observed h, in which it was assumed that the observed f and j were true, the range of values obtained for A was rather large although the apples were from the same variety. It seems unlikely that specific heat and density would vary enough from apple to apple to give this calculated range in A's. Probably one has here a measure of the over-all experimental variation. But, even so, the change in observed h values for the tested apples are generally in the predicted direction both assumptions I and II as shown in Table 4. In the other methods of calculation for h different values were obtained, but the difference was not so great. These differences may be due to the values of some constants as specific heat; in this study the specific heat of 0.89 Btu/lb-^{o}F was taken from Short and Bartlett (1944) for apples of 83.7% moisture, and since the moisture content and specific heat for the apples tested in this study were not determined the true values may be different from those used in the calculations.

In calculation I values for h compare reasonably with those calculated by the other three different methods. But it is hard to say which is more correct since there is no agreement on a particular method as to which gives the correct answer and can be used as a standard. All methods are based on the principle of heat transfer, but they differ in the assumptions made, so the values obtained by these calculations are different but not widely so.

Figure 3 shows a comparison of the observed j's and calculated j's (assumption II) which are obtained by using the assumed values of A, k, h, and working back through M_1, to get j.

The observed and calculated j's compare best at higher air velocities, but less well at the lower air velocities.

For pears as far as f and j values are concerned, all that is noted about apples can be said about pears; however, for calculating h and k one needs to solve the heat transfer equation for the boundary conditions of a pear which, so far as the author knows, have not been described.

Study of Table 5 for the cooling rates of apples cooled by running cold water shows that it is rather obvious that cooling rates are smaller than those for the same size apples even at the highest air velocity used which means that hydrocooling is fairly rapid when compared with the data presented in Table 2 for air cooling. It is obvious also (Table 6) that surface heat transfer coefficients for the hydrocooled apples are higher than those in air cooling. This result is characteristic of objects cooled by direct contact with a liquid which makes it the most rapid method for cooling such types of fruit.

A comparison of surface heat transfer coefficients for hydrocooled apples, observed and calculated by the different methods, compared reasonably except by Kramers' equation which predicts very high values.

There are a number of possible explanations for these very high predicted values. First, one can certainly question Kramers' equation since it is a smoothed (from many experiments) equation forced to give the best fit for air and water. Second, as j approaches 2, M_1 approaches pi and the Biot number changes very rapidly; that is, experimental incertainty increases at high j values.

Tables 7 and 8 show the change in heating rates for different sizes of McIntosh apples when heated in running hot water, and a comparison of surface heat transfer coefficients. These results compare reasonably with those obtained in hydrocooling the same size apples (Table 6); the difference due primarily to the high conductivity of water and secondarily to variety difference (density). Kramers' equation still gives high values for h, but not as high as in hydrocooling. It should be noted also that a different weighted k value for water between 75-122°F was used in calculation for h in heating tests.

In hydrocooling cucumbers, cooling rates were determined for different sizes of cucumber (see Table 9). The changes are in the same general direction as for apples and pears, decreasing j and increasing f with increased fruit size. Probably the heat transfer constants (h and k) could be best determined by assuming that the cucumber is a cylinder. However, the same question arises as to what values to take for specific heat, density, moisture content, radius and length.

When grapes, plums and peaches were heated in hot water at 130°F, heating rates varied with the size of the product and water flow rate as was expected (see Table 10).

Table 11 shows that heating and cooling rates of cucumbers of the same size under nearly identical conditions are almost the same although one would expect heating rates, f, to be somewhat smaller because the conductivities are surely not the same. It was noted that the texture of cucumbers did not seem to be affected on heating. On the other hand, heating and cooling rates of peaches of the same weight, were not the same. In heating f was smaller than f in cooling, as might be expected. However, it was noticed that the peaches were badly softened on heating. This difference between heating and cooling rates of peaches may be due to a change in the thermal properties of peach tissues as a result of heating.

All the data, with the important exception of hydrocooled apples, strongly suggest that the theoretical model has a relationship close enough to real fruit to be of some value in predicting cooling rates (given, for example, k and h). It seems obvious now that the key test of this relationship between model and fruit rests on the measurement of k (and therefore, c and w) and r_1 for each particular test fruit. That these fundamental considerations have escaped the attention of researchers for over 30 years seems a little incredible.

It is contended here that the experimental, analytical, and theoretical approach outlined in this thesis have merit in cooling studies. It is recommended that this work be pursued as follows:

1. With apples (or, perhaps, oranges) one should measure weight, specific heat, density, moisture content and cooling rates and from these determine k and h under the test conditions. These data should settle the question of correspondence between theory and reality as well as give some measure of experimental variation.
2. If the above shows agreement, continue with other "spherical" fruits and find k and h under various test conditions.
3. Find k for various fruits and vegetables and determine variation in k among fruits of the same lot.
4. Try some experiments with irregular fruits such as pears and try to find if a shape factor correction can be used to the spherical case.

APPENDIX

i. Definition of symbols used in this study

ii. Table I - Lag factor in spheres

iii. Figure A - Lag factor, j, as the coefficient of the first term of the series expansion for heat transfer in spheres.

iv. Figure B - Solution of $1 - M_1 \text{ Cot } M_1 = B$

DEFINITION OF SYMBOLS USED IN THIS STUDY

A Thermal diffusivity, k/Cw, ft^2/hr

B Biot number = r_1h/k

C Specific heat (of sphere), Btu/lb^{o}F

D Diameter, cm

f Reciprocal of the slope of the heat penetration curve, whether for cooling or heating, with $\log_{10}(T-T_c)$ or $\log_{10}(T_h-T)$ plotted against time.

G Flow rate fpm in air cooling, fpm or lb/min in hydrocooling

h Surface heat transfer coefficient, Btu/hr-ft^2-^{o}F

j The lag factor of the heat penetration curve, equal to $\frac{T'_o-T_c}{T_o-T_c}$ in cooling and $\frac{T_h-T_o}{T_h-T'_o}$ in heating.

k Thermal conductivity, Btu-ft/hr-ft^2-^{o}F

r Distance from center of a sphere, cm

r_1 Radius of sphere, cm

T_h Temperature of the heating bath, ^{o}F

T_c Temperature of the cooling bath, ^{o}F

T_o Initial (uniform) temperature, ^{o}F

T'_o Intercept on the time equals zero axis of the asymptote to the heat penetration curve

T Temperature ^{o}F at time t

t Time, minutes

w Density of sphere, lb/ft^3

z Half-cooling time or characteristic cooling time

μ Viscosity

A PARTIAL TABLE OF LAG FACTORS IN SPHERES

Lag factor, $j = 2\ \dfrac{\sin M_1 - M_1 \cos M_1}{M_1 - \sin M_1 \cos M_1}$

Biot number, $Bi = 1 - M_1 \cot M_1$

M_1, rad.	M_1, ° '	j	Bi
0.6	34 22.6	1.037	0.1230
0.7	40 6.4	1.050	0.1690
0.8	45 50.2	1.065	0.2229
0.9	51 34.0	1.084	0.2858
1.0	57 17.7	1.105	0.3580
1.1	63 1.5	1.128	0.4401
1.2	68 45.3	1.153	0.5335
1.3	74 29.1	1.182	0.6391
1.4	80 12.8	1.213	0.7584
1.5	85 56.6	1.247	0.8936
1.6	91 40.4	1.284	1.0468
1.7	97 24.2	1.325	1.2209
1.8	103 7.9	1.368	1.4199
1.9	108 51.7	1.415	1.6490
2.0	114 35.5	1.465	1.9153
2.1	120 19.3	1.517	2.2282
2.2	126 3.0	1.572	2.6013
2.3	131 46.8	1.629	3.0550
2.4	137 30.6	1.687	3.6201
2.5	143 14.4	1.746	4.3468
2.6	148 58.1	1.804	5.3217
2.7	154 41.9	1.859	6.7113
2.8	160 25.7	1.909	8.8756
2.9	166 9.5	1.951	12.770
3.0	171 53.2	1.982	22.05
3.1	177 37.0	1.998	75.49
π	180	2.000	

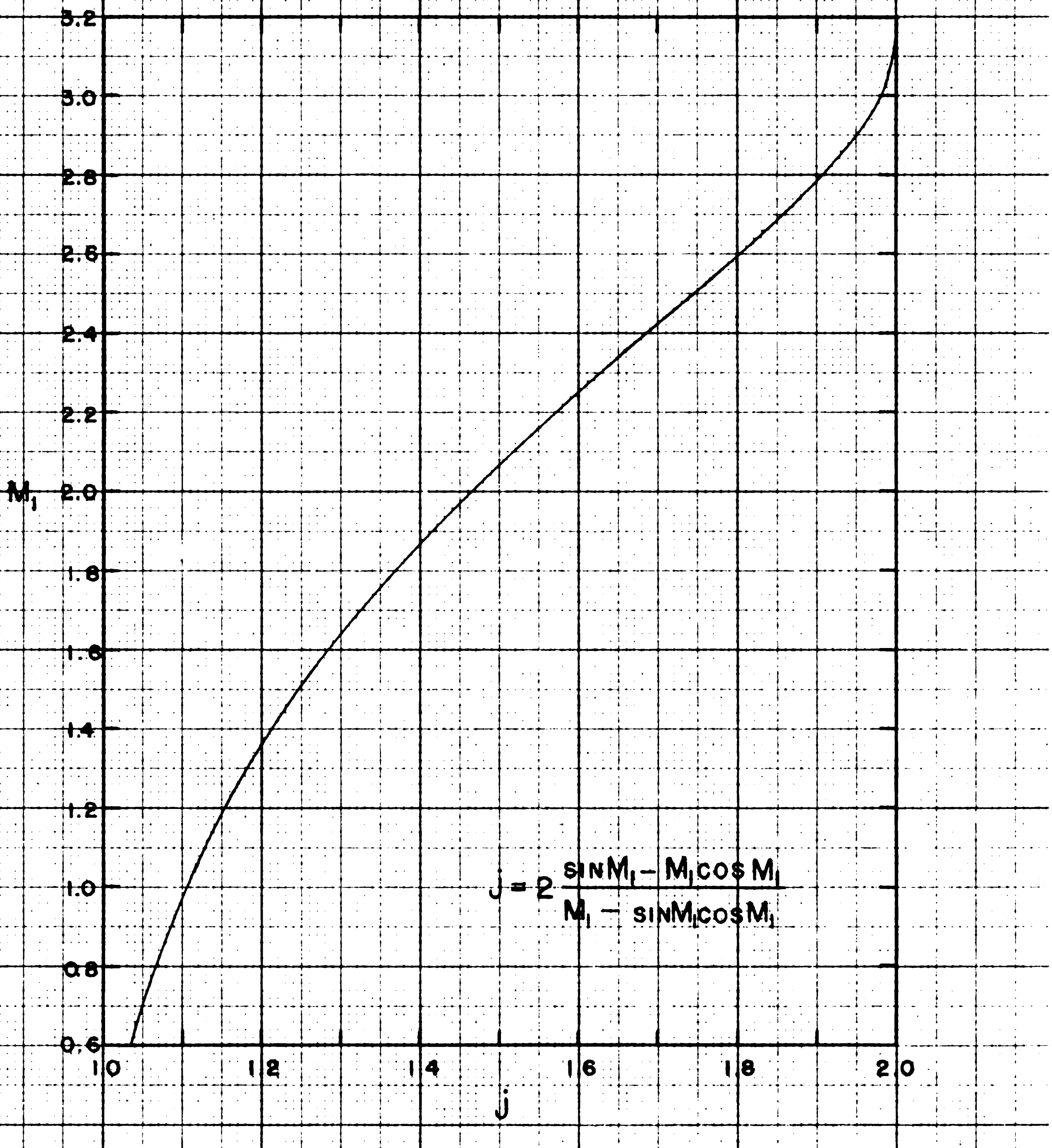


Fig. A Lag factor, j, as the coefficient of the first term of the series expansion for heat transfer in spheres.

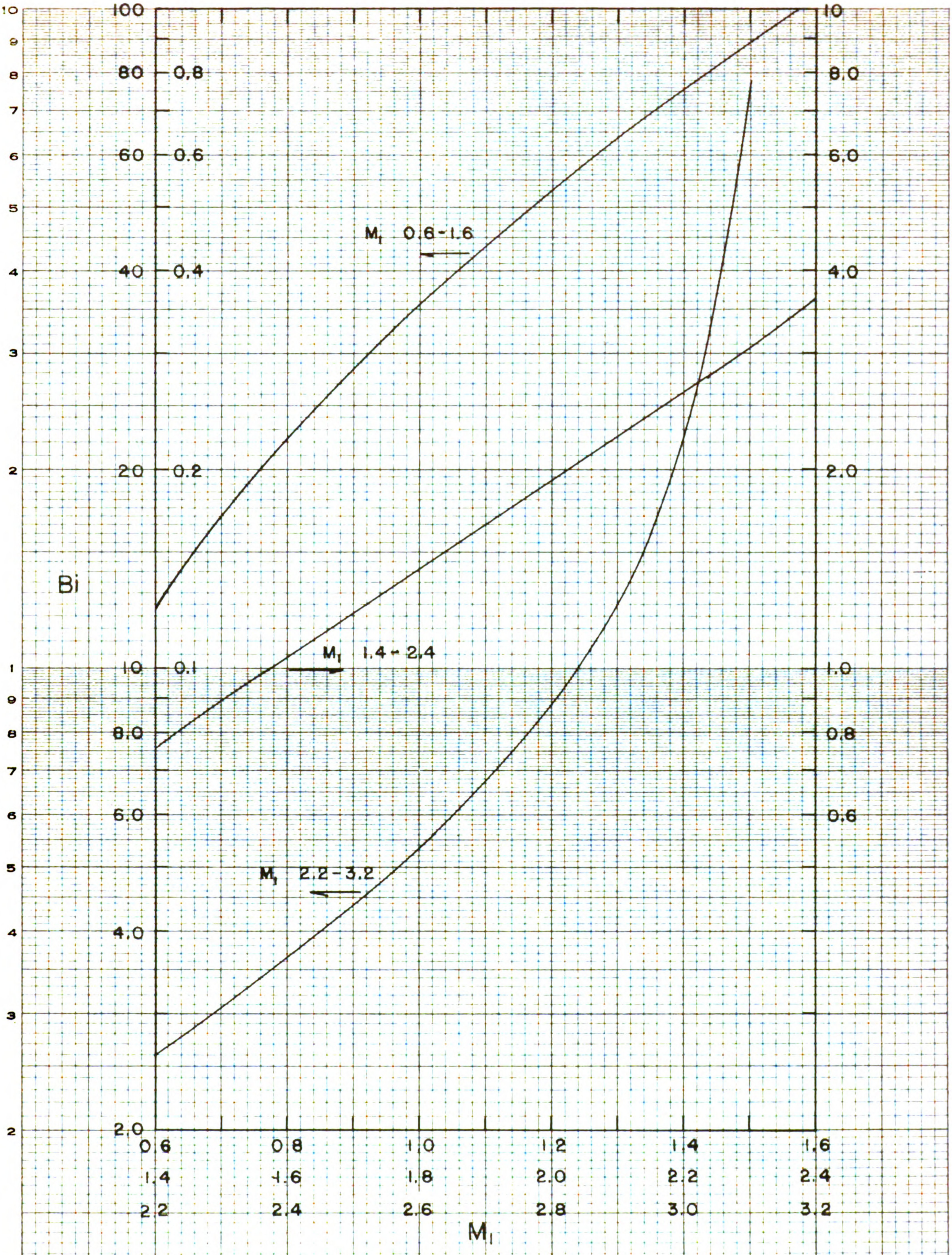


Fig. B Solution of $1 - M_1 \cot M_1 = Bi$

LITERATURE CITED

Andersen, S. A. (1950). Automatic Refrigeration. MacLaren & Son Ltd. for Donfoss, Nordborg, Denmark.

Anonymous. (1953). Ice and Refrigeration. New grape pre-cooling and storage plant refrigerated with ice. Vol. 124, No. 2, page 221.

Anonymous. (1953). Ice and Refrigeration. Chill-vac Process speeds chilling of lettuce from field to refrigerator cars. Vol. 125, No. 3.

Anonymous. (1954). Industrial Refrigeration. New pre-cooling processes Florida sweet corn. Vol. 127, No. 6, pages 13-16.

Ayrton, W. E. and J. Perry (1878). Experiments on the heat-conductivity of Stone on Fourier's "Theorie de la chaleur." Philosophical Magazine, London 5th Series Vol. 5, pages 214-267.

Ball, C. O. (1957). Sterilization in Food Technology. McGraw-Hill, New York, Inc.

Barger, W. R. (1961). Factors Affecting Temperature Reduction and Weight-Loss in Vacuum-Cooled Lettuce. Marketing Research Report 469 - AMS,USDA.

Bethell, W and A. Challman. (1950). Accurate precooling control sends better fruit to the market. Ice and Refrig. Vol. 118, No. 5, pages 17-19.

Blaisdell, J. L. Personal communication.

Bratley, C. O. (1946). Refrigeration of pre-packed fruits and vegetables. Refrig. Eng. Vol. 52, No. 4, pages 561-570.

Cardinell, H. A. (1949). Peaches refrigeration pays dividends. Ice and Refrig. Vol. 117, No. 4, pages 45.

Dewey, D. H. (1950). The effect of air blast pre-cooling on the moisture content of stems of cherries and grapes. Proc. Am. Soc. Hort. Sci. Vol. 56, pages 111-115.

Eckert, R. G. and Drake, R. J. Jr. (1959). Heat and Mass Transfer 2nd ed. McGraw-Hill, Book Co. Inc. New York. pp. 530.

Fisher, D. F. (1938). A review of precooling practice. Refrig. Eng. Vol. 35, No. 4, pages 238-243.

Friedman, B. A. and W. A. Radspinner (1956). Vacuum cooling of fresh vegetables and fruits. USDA Agr. Mar. Serv. H. T. and Office report (198).

Gane, R. (1937). The thermal conductivity of the tissue of fruits. Report of the Food Investigation Board for the year 1936. His Majesty's Stationery Office, London, page 211.

Gaylord, F. C., K. I. Fawceet and T. E. Hienton (1935). Pre-cooling fresh fruits in refrigerator cars. Agr. Eng. Vol. 16, pages 113-115.

Gerhardt, F. and W. V. Hukill (1945). The storage response of bing cherries to air movement, temperature and hydrocooling. Refrig. Eng. Vol. 49, No. 4, pages 275-277.

Guillou, R. (1960). Coolers for fruits and vegetables. University of California. California Agr. Exp. Sta. Bull. (773).

Hartline, B. F. (1952). Pre-cooling (hydrocooling) and package icing Illinois sweet corn. Ice and Refrig. Vol. 122, No. 2, pages 37-40.

Kethley, T. W., W. R. Cown and F. Bellinger (1950). An estimate of thermal conductivities of fruits and vegetables. Refrig. Eng. Vol. 58, No. 1, pages 49-50.

Leggett, J. T. and Sutton, G. E. (1951). Engineering progress at the University of Florida. Vol. 1, No. 5, Bull (43).

Link, H. L. and H. M Pancoast (1949). Antiseptic cooling retains top quality in perishables. Food Ind. Vol. 21, No. 6, pages 57-61.

Lloyed, J. W. and H. M Newell (1929). Observations on the refrigeration of some Illinois fruits in transit. Illinois Agr. Exp. Sta. Bull. (334).

Mallison, E. D. and W. T. Pentzer (1938). Body icing in transit. Refrigeration of vegetables. USDA Tech. Bull. (627).

Mann, C. W. and William, C. (1936). Refrigeration of oranges in transit from Claifornia. California USDA Tech. Bull. (505).

Marshall, Roy E. (1954). Cherries and Cherries Production. Inter-Science Publisher, New York, New York. Chapter XI, pages 171-186.

McAdams, W. H. (1954). Heat Transmission. McGraw-Hill Book Co. Inc., New York. 532 pp.

McKay, A. W., G. L. Fischer and A. E. Nelson (1921). Handling and transportation of cantalopes. USDA Farmers Bull. (1145).

Nicholas, R. C. and L. J. Pflug (1961). Heat processing characteristics of fresh cucumber pickle products. II. Heating rates of whole pickles. The Mich. Agr. Exp. Sta. Quart. Bull. Vol. 43, No. 3, pages 522-531.

Nicholas, R. C. and I. J. Pflug (1961). Heat processing characteristics of fresh cucumber pickle products. III. Heating rates of slices. The Mich. Agr. Exp. Sta. Quart. Bull. Vol. 43, No. 4, pages 808-819.

Pentzer, W. T., C. E. Asbury and W. R. Barger (1945). Pre-cooling California grapes and their refrigeration in transit. USDA Tech. Bull. No. 899.

Pentzer, W. T., R. L. Perry, G. C. Hanna, J. S. Wiant and C. E. Asbury (1936). Pre-cooling and shipping of California asparagus. University of California Agr. Exp. Sta. Bull. No. (600).

Pentzer, W. T., J. S. Wiant and J. H. MacGillivary (1940). Market quality and condition of California contalope as influenced by maturity, handling and pre-cooling. Tech. Bull. No. (730).

Pflug, I. J. and R. C. Nicholas (1960). Heat processing characteristics of fresh cucumber pickles products. Heating rates of spears. The Mich. Agr. Exp. Sta. Quart. Bull. Vol. 43, No. 2, pages 407-414.

Rear, J. C. (1959). A. S. R. E. Air Condition-Refrigeration Data Book. Precooling. Vol. 1, chapter 31, page 8.

Redit, W. H., M. A. Smith and P. L. Benfield (1955). Tests on hydrocooling and refrigeration of peaches in transit from Georgia and South California in 1954. AMS-62. USDA Agr. Mar. Serv.

Rose, D. H. and E. A. Gorman (1936). Handling, pre-cooling and transportation of Florida strawberries. USDA Tech. Bull. No. (525).

Sainsbury, G. F. (1951). Improved fruit cooling methods. Refrig. Eng. Vol. 49, No. 5, pages 464-469.

Sainsbury, G. F. (1961). Cooling apples and pears in storage rooms. USDA Agr. Mar. Serv. Marketing Research Report No. 474.

Schneider, P. J. (1955). Conduction Heat Transfer. Addison-Wesley Publ. Co. Inc. Reading, Massachusetts. 395 pp.

Schomer, H. A. (1953). Refrigeration of pre-packed fresh fruits and vegetables. Refrig. Eng. Vol. 61, No. 7, pages 742-744.

Thevonot, R. (1955). "Pre-cooling," Paper 0.10 IXth International Congress of Refrigeration, Paris. 31 Aug. -7 Sept.

Wright, C. E. (1953). Quick-cooling cuts fresh vegetables losses. Food Eng. Vol. 25, No. 1, pages 94-95.

Zenz, F. A. and D. E. Othmer (1960). Fluidization and Fluid-Paricle Systems. Reinhold Publ. Corp. New York, 513 pp.