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Edited by

D. R. HELDMAN

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LETTER FROM THE EDITOR

As of June 1, 1984, I have assumed new and different responsibilities. This change involves not only a new position but a change in location from East Lansing, Michigan to Camden, New Jersey. After 20 years as a faculty member in Food Engineering at Michigan State University, I am moving to an administrative role in corporate research and an affiliation with the Campbell Soup Company. Although this change will certainly influence my day-to-day activities, it does not influence my commitment to the goals and objectives of the Journal of Food Processing Engineering. In fact, I am anticipating that the experience associated with my new position will bring a new dimension to the Journal and to the contributors and readers of the Journal.

My new position provides an excellent opportunity for extension and application of the many research areas I have pursued over the past twenty years. It should provide an opportunity to develop both basic and applied research in areas closely associated with Food Process Engineering such as thermal processes, freezing and refrigeration processes, extrusion processes, concentration and dehydration processes as well as a variety of similar operations. The challenge will be to thoroughly explore the opportunities for improvement of product quality while optimizing process efficiency, to interact with Product Development in a manner that will lead to Process Development in the most efficient manner and to identify those process technologies that will have potential application and use in the food industry.

The Journal of Food Process Engineering is in its seventh year of publication. During these development years the progress has been slow but there has been continuing encouragement from both contributors and readers. The current steady flow of manuscripts provides the basis for publication of four issues of the Journal per year containing high quality technical papers in the area of Food Process Engineering. I would like to take this opportunity to express my appreciation to the Editorial Board of the Journal of Food Process Engineering. This group of individuals plays a significant role in several areas of Journal operation. The Board has been quite helpful in identification of authors for research manuscripts, the coordination of manuscript reviews, the preparation of book reviews and in providing advice and support to the editor. Without these types of dedicated individuals the Journal could not continue. I would also like to use this opportunity to express my appreciation to John O'Neil and his staff at Food and Nutrition Press for their excellent support and encouragement.

At this point I would like to encourage readers of the Journal to forward their comments and suggestions about the Journal of Food Process Engineering. We are always looking for ways to improve the Journal and to better serve both contributors and readers. I will look forward to receiving your correspondence at my new address.

DENNIS R. HELDMAN
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Campbell Place
Camden, New Jersey 08101 USA

MEETINGS

NOVEMBER 1984

11/8	Sanitation and Quality Assurance Seminar. Sponsored by Food Sanitation Institute, Tri-State Chapter. Allgauer's Fireside Restaurant, Northbrook, IL. Contact: T. Topalis, Quaker Oats Company, Barrington, IL 60010.
11/11-11/14	IFT Workshop on Research Needs. Harrison Conference Center, Glencove, NY. Contact: Dr. William W. Marion, Iowa State University, Ames, IA 50010.
11/25-11/30	Annual Meeting of the American Institute of Chemical Engineers. San Francisco Hilton and St. Francis Hotels, San Francisco, CA. Contact: Henry G. Schwartzberg, Dept. of Food Engineering, University of Massachusetts, Amherst, MA.

DECEMBER 1984

12/11-12/14	Winter Meeting of the American Society of Agricultural Engineers. Hyatt Regency Hotel, New Orleans, LA. Contact: M. A. Purschwitz, American Society of Agricultural Engineers, 2950 Niles Rd., POB 410, St. Joseph, MI 49085.

A REVIEW ON PREDICTING FREEZING TIMES OF FOODS

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ABSTRACT

Heat transfer during freezing of a food material involves a complex situation of simultaneous phase transition and changing thermal properties. Models for predicting freezing times range from relatively simple analytical equations based on a number of assumptions and approximations, to the more versatile numerical methods which require the use of a sophisticated computer. The necessity for having a consistent definition for freezing time, the nature of the freezing process, different prediction models and thermo-physical properties of importance are discussed in view of the mathematics of freezing time computations. In this review, attention has been focused on established analytical models which can be solved without resorting to computer techniques. The review points out the need for further refinement of the existing Plank-type models to facilitate accurate freezing time estimations under a wide range of practical conditions.

INTRODUCTION

Although freezing has been a recognized preservation method for centuries, and the frozen food industry has been established since the beginning of this century (Desrosier and Tressler 1977), serious consideration of the mathematics of freezing has taken place only in the past decade or two. Food engineers dealing with freezing are often faced with two major tasks; estimating the refrigeration requirements for a freezer system and designing the necessary equipment and processes to accomplish rapid freezing. It is recognized that the quality of frozen products is largely dependent on the rate of freezing. In general, slow freezing of food tissues results in formation of larger ice crystals in the extra-cellular spaces while rapid freezing produces small ice crystals distributed throughout the tissue (Fennema 1966). Formation of these

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ice crystals, particularly the larger ones, damages the cellular structure and upon thawing, the food material will have a poorer texture (Fennema and Powrie 1964). Fluctuating temperatures during storage may result in further damage to food texture. Therefore, it is necessary to predict the freezing times or rates during the freezing process and to know the temperature history of the material during frozen storage, in order to optimize the design of freezing equipment and to exercise control over the quality of the end product. It is common practice to rely on empirical experiences for these predictions.

The complexity of the problem is generally due to the dependence of freezing time on a number of thermo-physical properties which in turn depend on factors such as variety, maturity/age, growing practice and composition of the material. These thermo-physical properties also change during the freezing process. Over the years, many mathematical models have been proposed for predicting freezing times of foods. However, due to complexities of the freezing process, these models are usually based on a number of assumptions and approximations. Hence, the accuracy of any prediction model depends on how closely the experimental conditions match the assumptions.

The objective of this paper is to review the published literature on freezing time prediction models and to point out the relative merits of each. Attention has been focused mainly on simple Plank-type models which do not require computer-aided solutions, although a discussion of other methods has also been included. Background information on freezing time definition, nature of the freezing process and thermo-physical properties of importance is also included in the review.

FREEZING TIME DEFINITION

Lack of a consistent definition for freezing time is one of the major problems in the published literature on freezing of foodstuffs. This apparent deficiency is a result of several factors. Since the temperature distribution within the product during the freezing process varies considerably, freezing time has to be defined with respect to a given location. The "thermal center" or the location which cools most slowly is commonly used as the reference location. In conduction cooling, the geometric center is taken as the thermal center. Since food materials do not possess a well-defined freezing point due to the presence of dissolved solids and the water-binding nature of food components, a range of temperature, in which most of the latent heat is released, has to be considered. The temperature range from −1 to −5 °C is considered the zone of maximum ice crystal formation (International Institute of Refrigeration 1972). Long (1955) referred to the time taken to cross this zone as the "thermal arrest time'' because of the very slow rate of change in temperature in this zone during the freezing process.

Four major methods have been identified (Fennema *et al.* 1973) to describe the freezing rates; 1) time-temperature methods, 2) velocity of the ice front, 3) appearance of the specimen and 4) thermal methods. The time-temperature methods, measuring temperature change per unit time, or time to traverse a given range of temperature, are used more often than other methods. Temperature change per unit time is the appropriate choice when quality of the frozen product is the primary concern because the rate of freezing governs the size of ice crystals formed, and hence, product quality. However, this rate varies during the process of freezing and an average value will not adequately describe the nature of the freezing process. The thermal arrest time or the duration of the freezing process from start to finish, both representing the time needed to traverse a range of temperature, are the most frequently used definitions of the freezing time. Both have serious limitations. If the freezing operation is to be started at 20 °C and be completed at –20 °C, the heat load above and below the freezing point would account for approximately 40% of the latent heat or 30% of the total heat load. Hence, freezing time will vary depending on the initial and final temperature of the material. This points out the need to define two reference temperatures between which the freezing time is considered. With defined reference temperatures, a further requirement would be to actually begin the cooling process at the initial reference temperature because it has been reported (Long 1955; Ramaswamy 1979) that the time interval between two intermediate temperatures (such as the thermal arrest time) is dependent on the initial temperature of the material. Long (1955) and Ramaswamy (1979) found that higher initial temperatures resulted in shorter thermal arrest times when freezing fish and apples, respectively.

The various methods employed to express freezing time or rate have been tabulated by Fennema and Powrie (1964). The current definition of nominal freezing time (International Institute of Refrigeration 1972) of a given product of specified dimensions and an initial uniform temperature of 0 °C is the time it takes for the ''thermal center'' to reach a temperature 10 C° below the initial freezing point. The effective freezing time is the total time required to lower the temperature of the product from its initial value to a given temperature at the thermal center. The freezing rate of a food mass is the ratio between the minimum distance from the surface to the thermal center, and the time elapsed between the surface reaching 0 °C and the thermal center reaching 10 C° lower than the temperature of initial ice formation at the thermal center. Although not without limitations, the effective freezing time (International Institute of Refrigeration 1972) appears to be the more acceptable definition of freezing time. Henceforth, for the purpose of discussion which follows, this definition will be adopted.

NATURE OF THE FREEZING PROCESS

According to Holdsworth (1968), the freezing process can be divided into three distinct phases; a precooling period in which the material is cooled from its initial temperature (Ti) to the freezing point (Tf), a phase change period in which all the latent heat is released and a tempering period in which the temperature is lowered further to the target temperature (Tc). The factors contributing to the heat load in the precooling period are the thermal properties of the unfrozen materials and the temperature difference (Ti−Tf). The tempering period is governed by the properties of the frozen material and the temperature difference (Tf−Tc). Crystallization of water to ice characterizes the phase change period. The process is one of nucleation and crystal growth. Further, due to the presence of dissolved solids and the interaction of other food constituents with relatively large amounts of water contained in the food material, the freezing point will be somewhat depressed below that of pure water, the magnitude of depression being dependent on the nature of the food.

Theories concerning the depression of freezing point, nucleation and crystal growth have been reviewed by Fennema *et al.* (1973) and Heldman and Singh (1981). According to Fennema and Powrie (1964), four factors are significant with respect to freezing rates; 1) the temperature differential between the product and the cooling medium, 2) the modes of heat transfer to, from and within the product, 3) the size, shape and type of package containing the product and 4) the size, shape and thermal properties of the product.

An average freezing rate (w) has been suggested by Leniger and Beverloo (1975) to determine the nature of the freezing process. By definition, $w = d/(2t)$. If w is greater than 5 cm/hr, the freezing process is considered fast; if between 1 and 5 cm/hr, it is moderately fast and at less than 1 cm/hr, it is slow. In most cases, the aim is to achieve an average freezing rate of at least 2 cm/hr (Leniger and Beverloo 1975).

Another phenomenon observed during the freezing process is supercooling, in which the material temperature falls below its freezing point without the phase change actually occurring (Fennema and Powrie 1964). Following supercooling, the temperature increases to the original freezing point and normal freezing continues. This period, however, is not taken into account in any of the prediction models.

PREDICTION OF FREEZING TIMES

Various aspects of freezing time predictions have been reviewed in part by a number of researchers (Bakal and Hayakawa 1973; Brennan *et al.* 1976;

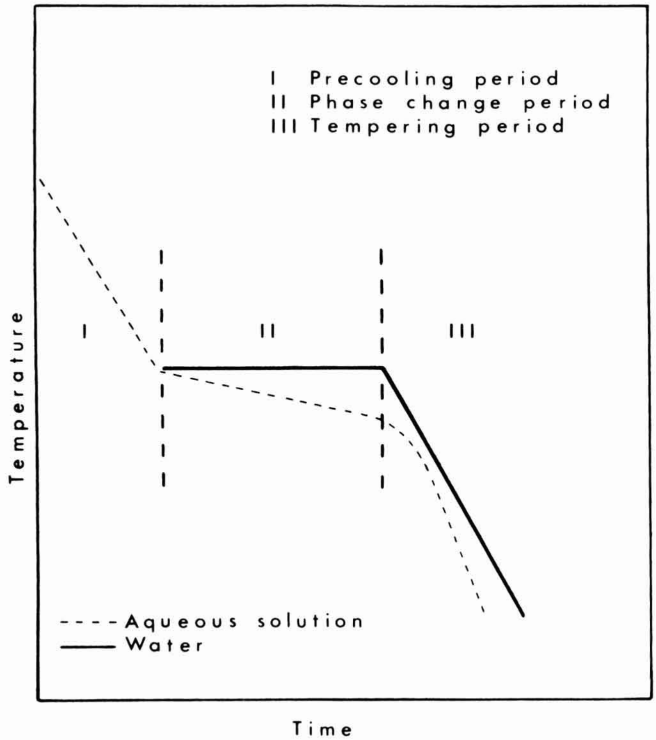

FIG. 1. TYPICAL FREEZING CURVES FOR WATER AND AN AQUEOUS SOLUTION (ADAPTED FROM BAKAL AND HAYAKAWA (1973)).

Carslaw and Jaeger 1959; Charm 1978; Cleland and Earle 1976b, 1977a,b; Hayakawa 1977; Heldman and Singh 1981; Ramaswamy 1979; Rebellato *et al.* 1978). Considerable information is available in the published literature on heat transfer rates into objects of various shapes during heating or cooling. However, these do not generally include the phase change phenomenon and, hence, are of limited application for freezing time predictions. The relatively large influence of the precooling and tempering periods make freezing time predictions more difficult to compute. In general, the prediction models are based on a number of assumptions which attempt to overcome some of these difficulties. Some common assumptions are; 1) the material to be frozen has a uniform initial temperature and is cooled by a medium of constant temperature, 2) heat transfer is governed by conduction within the material and by a constant and uniform surface heat transfer coefficient, 3) thermophysical properties of the material do not vary in the unfrozen or frozen states, although they may be distinctly different for the two states and 4) the food material possesses a definite freezing point at which all the latent heat is released.

Hayakawa (1977) classified the restrictive assumptions imposed for deriving analytical or numerical solutions into five major classes; boundary conditions, initial conditions, density considerations, physical properties of the material and the movement of the frozen mass. Each of these classes further contained from two to four variations in order to cover a wide range of applicable conditions. An additional class to include variations in target temperature would make this classification system more complete. Each solution or test situation would have to accommodate at least one condition from each class.

Bakal and Hayakawa (1973) separated the procedures for determining freezing times into three groups; 1) experimental models which involve evaluation of freezing times through actual measurement of food temperature during the freezing operation, 2) theoretical models obtained by solving heat transfer equations under appropriate boundary conditions and 3) semi-theoretical models which are based on a combination of the first two methods.

Experimental determination of freezing times is probably the most widely used method because of its simplicity and accuracy and it is almost the perfect method for a particular situation under study. It simply involves monitoring the temperature of the material at its thermal center until the target temperature is reached. However, the data on freezing times obtained cannot be generalized and it is practically impossible to carry out experimentation under the multiplicity of conditions that may be encountered in food freezing operations.

Use of theoretical formulas offers a more general method for predicting the freezing times and these methods could be reasonably accurate if proper boundary conditions and the variability in the factors involved are taken into account. Arriving at simple formulas which can accommodate these conditions is a very difficult task. To some extent, this may be achieved by making a number of compromises. More general predictions are possible by resorting to numerical methods to solve the heat conduction equations using sophisticated computer techniques. These include finite difference and finite element methods which are very versatile and can take into account practically any kind of condition, provided that it is known (Bonacina and Comini 1973; Charm 1978; Cleland and Earle 1977a, 1979a,b; Heldman 1974a; Heldman and Gorby 1975a; Hohner and Heldman 1970, and Rebellato *et al.* 1978).

The third method is often more popular than the first two because it uses a mathematical basis and a modification of the theoretical model based on experimental results. These methods are not without limitations, but they are more versatile than the experimental methods alone and simpler than the numerical methods. Various modifications of the original model suggested by

Plank (1913, 1941) come under this category (Cleland and Earle 1976b, 1977a, 1979a,b; De Michelis and Calvelo 1982, 1983; Hung and Thompson 1983; International Institute of Refrigeration 1972; Levy 1958; Mascheroni and Calvelo 1982; Mellor 1976; Mott 1964; Nagaoka *et al.* 1955; Plank 1963; Ramaswamy 1979).

The various methods for freezing time prediction are discussed below with special emphasis on simple models of Plank-type form.

Simple Models

Plank's Model. The model proposed by Plank (1913, 1941) is the earliest and most widely used method for freezing time prediction. It is based on three simple relationships, one describing convective heat transfer from the cooling medium to the surface of the body, for example, with an infinite slab (Eq. 1):

$$q = -\ hA(Ta-Ts) \qquad (1)$$

a second one describing the liberation of latent heat at the freezing point (Eq. 2):

$$q = ALp'(dx/dt) \qquad (2)$$

and the third one for conductive heat transfer through the frozen material (Eq. 3):

$$q = -\ k'A(Ts-Tf)/x \qquad (3)$$

Eliminating Ts between Eq. 1 and 3, the heat transfer in series can be described as (Eq. 4):

$$q = \frac{-A(Ta-Tf)}{(1/h + x/k')} \qquad (4)$$

Eq. 2 and 4 can then be equated and A eliminated on both sides to give (Eq. 5):

$$Lp'(dx/dt) = \frac{(Tf-Ta)}{(1/h + x/k')} \qquad (5)$$

By rearranging and integrating Eq. 5 between x=0 and x=d/2, the final form of Plank's equation expressing the freezing time for an infinite slab is obtained as (Eq. 6):

$$t = \frac{p'L}{(Tf-Ta)}\left[\frac{d}{2\,h} + \frac{d^2}{8\,k'}\right] \tag{6}$$

The general form of Plank's equation is written as (Eq. 7):

$$t = \frac{p'L}{(Tf-Ta)}\left[\frac{P\,d}{h} + \frac{R\,d^2}{k'}\right] \tag{7}$$

where P and R are constants depending on the geometric shape of the material being frozen. These are 0.500 and 0.125 for an infinite slab, 0.250 and 0.0625 for infinite cylinder and 0.167 and 0.0416 for a sphere, respectively. When extending the equation to a brick-shaped solid, P and R values must be evaluated from a chart of the type illustrated by Ede (1949) and cited in a number of later publications (Bakal and Hayakawa 1972, 1973; Heldman and Singh 1981). For this situation the dimension d in Eq. 7 becomes the shortest dimension of the brick. B1 and B2 are factors such that, when multiplied by d, yield the second largest and the largest dimensions of the brick, respectively. The chart can then be used to obtain P and R values.

There are some additional assumptions involved in the derivation of Plank's equation. These are; 1) the temperature of the material to be frozen remains at the freezing point from start to finish of the freezing process, 2) there is a steady state heat transfer between the cooling medium and the material and 3) all water in the product is completely in the liquid phase prior to the freezing operation. Because of these assumptions, Plank's model does not take into account the heat to be removed during precooling and tempering periods.

In spite of the limitations discussed above, Ede (1949) found that Plank's model predicted freezing times with reasonable accuracy. Earle and Fleming (1967) also reported that the freezing times of lamb and mutton carcasses calculated by Plank's model were in close agreement with experimental values. They reported that the prediction accuracy could be improved by replacing the latent heat factor by the total enthalpy change between the initial and final temperatures. It is now generally accepted that the model underestimates freezing time in most practical situations (Cleland and Earle 1977a; Heldman and Singh 1981; Hung and Thompson 1983; Ramaswamy 1979). Based on experimental results, many empirical modifications have been suggested for Plank's equation to take into account the precooling and tempering periods. Most of these attempt to replace the latent heat factor (L) in Eq. 7 by an appropriate proportion of the total enthalpy difference.

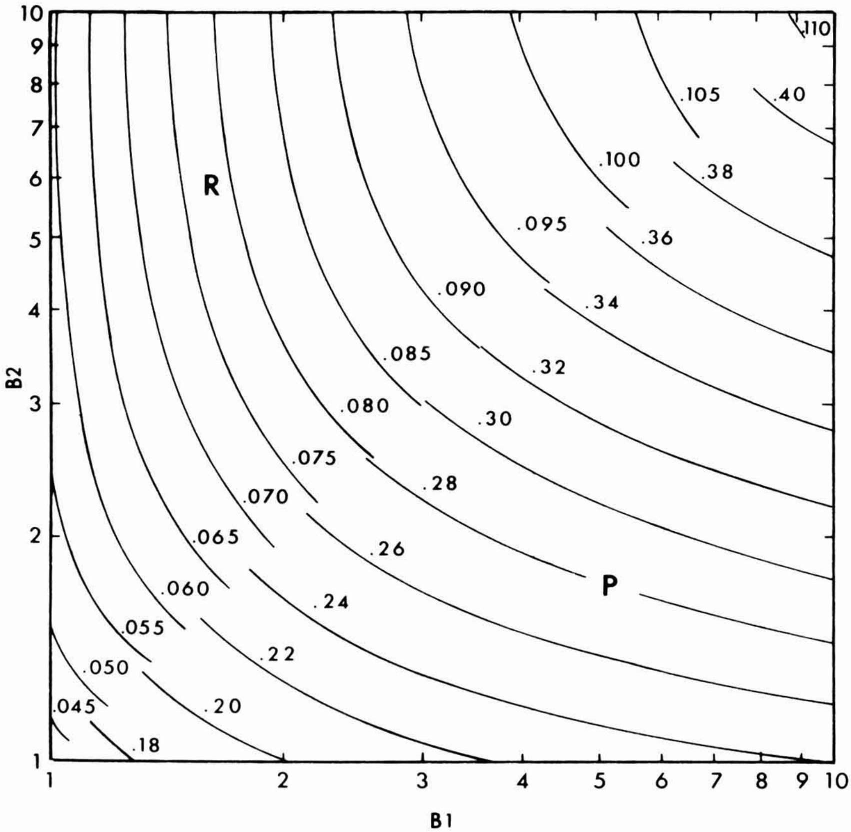

FIG. 2. CHART FOR OBTAINING P AND R FOR A BRICK (ADAPTED FROM EDE (1949)).

Nagaoka Modification. Nagaoka *et al.* (1955) modified Plank's equation as follows to predict the freezing times of fresh fish in an air blast freezer (Eq. 8):

$$t = [1 + 0.008\ (Ti)]\ \frac{Q \cdot p'}{(Tf - Ta)} \left[\frac{P\ d}{h} + \frac{R\ d^2}{k'} \right] \qquad (8)$$

where Q is the heat to be removed from a unit mass of the material in the precooling, phase change and tempering periods as given by (Eq. 9):

$$Q = C(Ti-Tf) + L + C'(Tf-Tc) \quad (9)$$

Levy Modification. Levy (1958) used a slightly different form of Nagaoka model to calculate freezing time and rates of fish as influenced by air flow rate in an air blast freezer (Eq. 10):

$$t = [1 + 0.008(Ti-Tf)] \frac{Q \cdot p'}{(Tf-Ta)} \left[\frac{P\,d}{h} + \frac{R\,d^2}{k'} \right] \quad (10)$$

The multiplication factor [1 +0.008 (Ti−Tf)] in Eq. 10 should be changed to [1 +0.00445 (Ti−Tf)] to suit working in British units.

I.I.R. Modification. The International Institute of Refrigeration (1972) modification is similar to the above but with an ethalpy factor Q* between Tf and Tc [Q as in Eq. 9 minus C(Ti−Tf)] and without the additional multiplication factor (Eq. 11):

$$t = \frac{Q^{*} \cdot p'}{(Tf-Ta)} \left[\frac{P\,d}{h} + \frac{R\,d^2}{k'} \right] \quad (11)$$

Mellor Modification. Mellor (1976) suggested inclusion of only one-half of the sensible heat in the precooling period and tempering period plus the latent heat in the calculation of Q (Eq. 12):

$$t = [0.5C(Ti-Tf) + L + 0.5C'(Tf-Tc)] \frac{p'}{(Tf-Ta)} \left[\frac{P\,d}{h} + \frac{R\,d^2}{k'} \right] \quad (12)$$

Cowell's Method. Cowell (1967) described Plank's equation in a dimensionless form as follows (Eq. 13):

$$\frac{Fo}{Ko} = F(G + 1/Bi) \quad (13)$$

where Fo is the Fourier number (Dt/a^2); Ko is the Kossovitch number [L/{C′(Tf−Ta)}]; Bi is the Biot number (ha/k′) associated with the frozen phase, and F and G are constants depending on the geometric shape of the

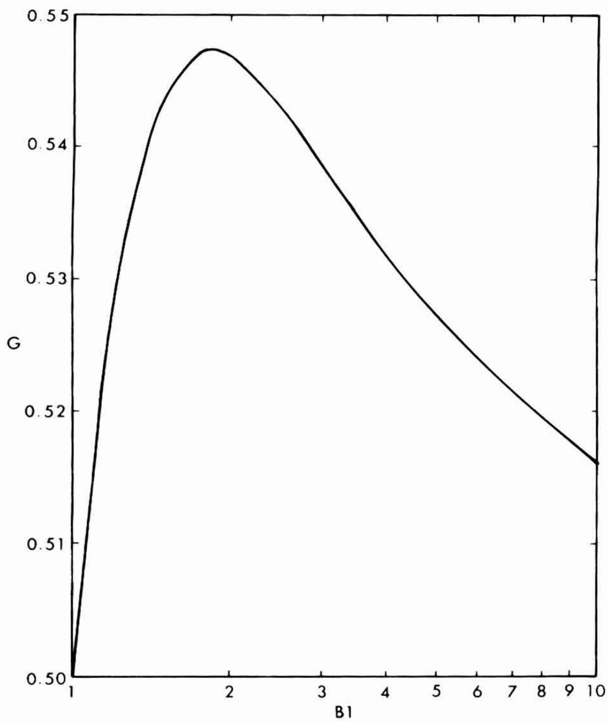

FIG. 3. G VALUES FOR AN INFINITE RECTANGULAR ROD, d×dBI (ADAPTED FROM COWELL (1967)).

material. The value of F is 1.0 for an infinite slab, 0.5 for an infinite cylinder and 0.33 for a sphere. The G value is 0.5 for all three geometric shapes. Cowell (1967) also presented charts for determining these constants for infinite rectangular rods and brick-shaped objects.

Mott's Procedure. Mott (1964) developed a number of tables to organize the thermo-physical data needed for use in Plank's equation. In his procedure, a functional relationship was utilized among three dimensionless numbers (Eq. 14, 15 and 16):

$$S = [(Bi+1)/G'] = A(d/V) \quad (14)$$

$$Bi = [hd/(2k')] \quad (15)$$

$$G' = [\{th(Tf-Ta)\}/(p'Qd)] \quad (16)$$

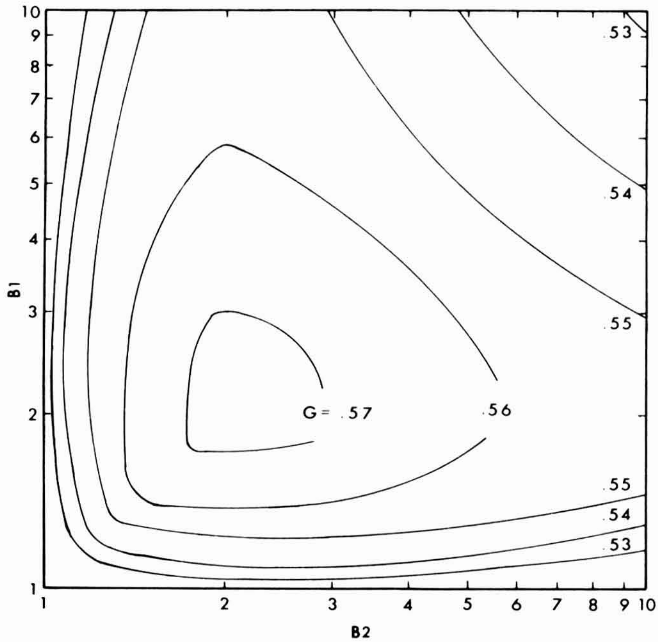

FIG. 4. G VALUES FOR A BRICK SHAPED BODY, d×dB1×dB2 (ADAPTED FROM COWELL (1967)).

By rearranging the above three relationships, an equation similar to Plank's can be obtained (Eq. 17):

$$t = \frac{Q \cdot p'}{(Tf - Ta)} \frac{V}{A} \left[\frac{1}{h} + \frac{d}{2k'} \right] \qquad (17)$$

Tables for obtaining the shape factor, S, and the thermo-physical properties, p′, k′, Tf, h and Q can be found in several publications (Mott 1964; Bakal and Hayakawa 1972, 1973, Heldman and Singh 1981).

Gutschmidt (1964) suggested the use of a relationship similar to Eq. 17 to predict freezing times of products of irregular shape. For other geometries such as the parallelepiped and right circular cone, models have been developed by Lorentzen and Rosvik (1960), and Tanaka and Nishimoto (1959, 1960, 1964). These equations are long, complicated and not often used (Bakal and Hayakawa 1972), and hence, they are not listed here.

Cleland and Earle Modifications. Cleland and Earle (1976b, 1977a, 1979a,b) carried out in-depth analyses of freezing time computations and experiental verification using a methylcellulose gel material molded to different shapes and subjected to a wide range of freezing conditions. They recommended a number of significant modifications to Plank's equation. Cleland and Earle (1976b) expressed Plank's equation in a dimensionless form as follows (Eq. 18):

$$Fo = \frac{P}{Bi \cdot Ste} + \frac{R}{Ste} \quad (18)$$

where Ste is the Stefan number [C′(Tf − Ta)/Q*, Q* being the enthalpy difference between Tf and Tc]. They accounted for variations in the precooling period by introducing a new dimensionless number, Plank's number [Pk = C(Ti − Tf)/Q*]. Through experimental investigations, Cleland and Earle (1976b) obtained the following empirical relationships, involving the dimensionless numbers, for an infinite slab (Eq. 19 and 20):

$$P^* = 0.5072 + 0.2018Pk + Ste[0.3224Pk + (0.0105/Bi) + 0.0681] \quad (19)$$

$$R^* = 0.1684 + Ste(0.2740Pk + 0.0135) \quad (20)$$

These values of P* and R* were then substituted in Plank's equation with the I.I.R.-type modification to calculate freezing time (Eq. 21):

$$t = \frac{Q^* \cdot p'}{(Tf - Ta)} \left[\frac{P^* d}{h} + \frac{R^* d^2}{k'} \right] \quad (21)$$

Correlations were reported to be accurate within ±3% for homogeneous products of slab geometry at moisture contents of 77%, and applicable for the following conditions: Ti < 40 °C; -15 < Ta < -40 °C; 10 < h < 500 W/m²C, and slab thickness up to 0.12 m. Cleland and Earle (1979b) presented relationships for infinite cylinders as follows (Eq. 22 and 23):

$$P^* = 0.3751 + 0.0999Pk + Ste[0.4008Pk + (0.0710/Bi) - 0.5865] \quad (22)$$

$$R^* = 0.0133 + Ste[0.0415Pk + 0.3957] \quad (23)$$

and for spheres (Eq. 24 and 25):

$$P^*=0.1084+0.0924Pk+Ste[0.2310Pk-(0.3114/Bi)+0.6739] \quad (24)$$

$$R^*=0.0784 + Ste[0.0386Pk - 0.1694] \quad (25)$$

The accuracy of these relationships for freezing time predictions were reported to be within $\pm 5.2\%$ for infinite cylinders and $\pm 3.8\%$ for spheres. The ranges of applicability were: $0.155 < \mathrm{Ste} < 0.345$, $0.5 < \mathrm{Bi} < 4.5$, and $0 < \mathrm{Pk} < 0.55$. Although these ranges cover most practical situations, it should be noted that these models were tested only at a moisture content of 77%, using a methylcellulose gel material. Ramaswamy and Tung (1980) observed that the modification suggested for infinite cylinders resulted in large errors in freezing time prediction of apple tissue in end-insulated tinplate cans. Presence of void spaces in the apple tissue and the nonhomogeneous nature of the apple pack could possibly explain part of the associated error.

Cleland and Earle (1979a) also arrived at several general relationships for the geometric factors as shown below (Eq. 26 and 27):

$$P'=P[1.026+0.5808Pk+Ste\{0.2296Pk+(0.0182/Bi)+0.1050\}] \quad (26)$$

$$R'=R[1.202+Ste(3.410Pk + 0.7366)] \quad (27)$$

where P' and R' are intermediate values of the modified geometric factors and P and R are the factors originally suggested by Plank (1941). These were further modified for different shapes as shown below:

infinite slab (Eq. 28 and 29):

$$P''=P' \quad (28)$$

$$R''=R' \quad (29)$$

infinite cylinder or sphere (Eq. 30 and 31):

$$P''=P'+ 0.1278P \quad (30)$$

$$R''=R'+ 0.1888R \quad (31)$$

rectangular brick (Eq. 32 and 33):

$$P''=P'+ P[0.1136+Ste(5.766P-1.242)] \quad (32)$$

$$R''=R'+ R[0.7344+Ste(49.49R-2.900)] \quad (33)$$

and the modified model was (Eq. 34):

$$t = \frac{Q^* \cdot p'}{(Tf - Ta)} \left[\frac{P''d}{h} + \frac{R''d^2}{k'} \right] \tag{34}$$

These modifications were reported to be accurate within ±5% for infinite slabs, ±7% for infinite cylinders and spheres and ±10% for rectangular bricks.

Loeffen *et al.* (1981) extended the above studies to include time-variable boundary conditions. Starting from Plank's original equation, they developed two simple methods for predicting freezing times of slabs, cylinders, spheres and rectangular bricks in situations where boundary conditions change with time. The first method was based on integrating the differential equation [re-arranged form of Eq. 5] used in deriving Plank's model with the assumption that Ta and h were time dependent. The differential equation was modified to accommodate the geometric factors R″ and P″ with Q as suggested by Cleland and Earle (1979a) and then solved numerically between $x=0$ and $x=a$. In the second method, the final form of Plank's modified equation (Eq. 34) was used assuming Ta and h to be constants over narrow time intervals. By selecting a small time interval (Δt) and calculating the corresponding freezing time by using Eq. 34, they evaluated the fraction $\Delta t/t$ over a series of time intervals. When freezing was complete, the summation of the above fraction from start to finish was equal to unity and the sum of the corresponding time intervals gave the freezing time. By comparing these methods with a three time level finite difference scheme, the authors reported that the agreement was generally good (difference < 10%).

Ramaswamy and Tung Modification. Ramaswamy (1979) and Ramaswamy and Tung (1980) compared the different models for predicting the freezing times of apples packed in end-insulated cylindrical containers for a range of air, liquid immersion and cryogenic freezing conditions and reported that the prediction errors as compared to experimental freezing times were markedly different for the different models. They found absolute mean error magnitudes of 18.2% (Plank 1941), 18.8% (Nagaoka *et al.* 1955), 12.8% (I.I.R. 1972) and 13.9% (Mellor 1976). Replacing the enthalpy factor Q* in Eq. 11 by Q (Eq. 9) reduced the mean error magnitude of the I.I.R. Model to 9.0%. The errors were also reported to depend significantly on the length of the precooling and tempering periods, with longer precooling periods resulting in over-estimation and longer tempering periods causing under-estimation of the freezing time when using Eq. 9 for calculating the enthalpy difference in the

I.I.R. model. By a multiple regression analysis of C(Ti−Tf) and C′(Tf−Tc) (heat load factors in precooling and tempering periods, respectively) with the expected values of their sums from the experimental results (Q*, calculated from Eq. 11 using experimental t, minus L), Ramaswamy (1979) suggested the following model (Eq. 35):

$$t=[0.3022C(Ti-Tf)+L+2.428C'(Tf-Tc)]\frac{p'}{(Tf-Ta)}\left[\frac{P\ d}{h}+\frac{R\ d^2}{k'}\right] \qquad (35)$$

The absolute mean error associated with this modification under a wide range of freezing conditions (Ti=1 to 25°C; Tc=-10 and -18°C; Ta=-18 to -178°C, and h=13.9 to 68.4 W/m²C) was reported to be 6.6%.

Luikov's Solutions. Luikov (1968) gave approximate solutions for predicting freezing times in objects of different geometric configurations. One of the conditions imposed was that the surface of the object reached the medium temperature instantaneously, which assumed there was no surface resistance to heat transfer. The solutions were reported as follows:

infinite cylinder (Eq. 36):

$$t = \frac{p\ L\ a^2}{4k'(Tf-Ta)} \qquad (36)$$

sphere (Eq. 37):

$$t = \frac{p\ L\ a^2}{6k'(Tf-Ta)} \qquad (37)$$

infinite slab (Eq. 38):

$$t = \frac{a^2[pL+0.4444C(Ti-Tf)p+0.5C'(Tf-Ta)p']}{2k'(Tf-Ta)} \qquad (38)$$

Bakal and Hayakawa Approach. Bakal and Hayakawa (1970), and Hayakawa and Bakal (1973) obtained a series of solutions for freezing time prediction problems for the case of an infinite slab under linear heat transfer

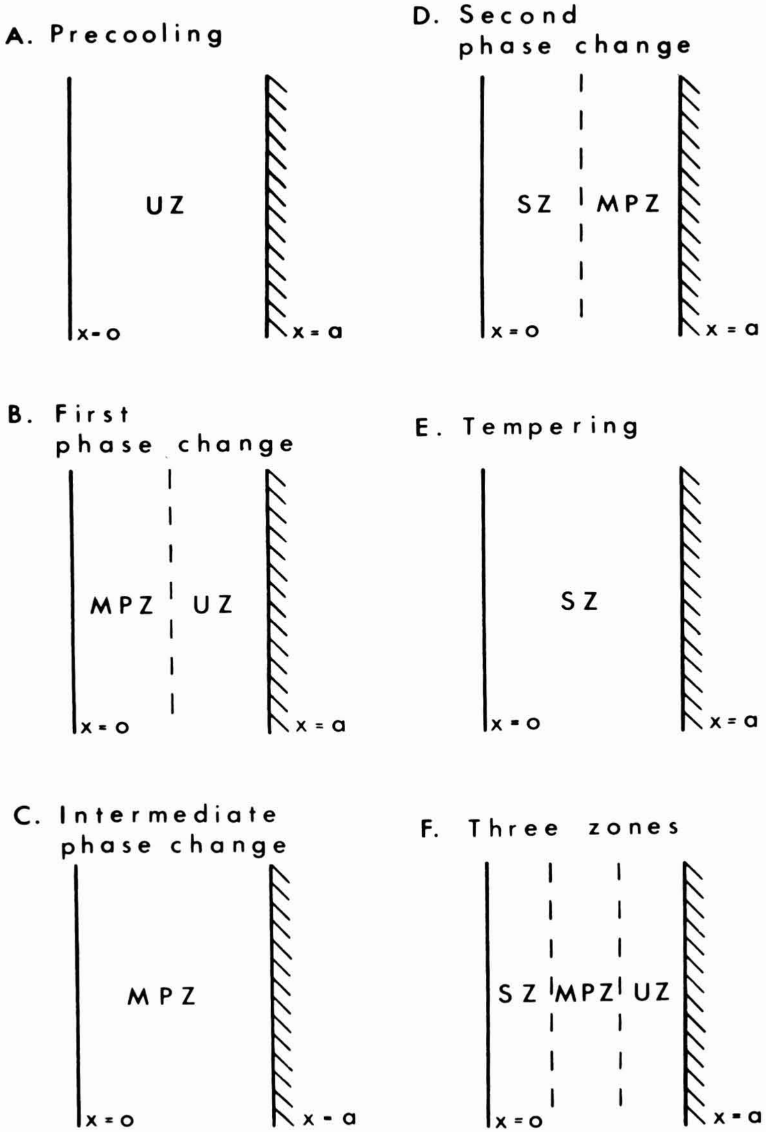

FIG. 5. FREEZING PROCESS: BAKAL AND HAYAKAWA APPROACH—MPZ, MIXED PHASE ZONE; SZ, SOLID (FROZEN) ZONE; UZ, UNFROZEN ZONE (ADAPTED FROM BAKAL AND HAYAKAWA (1973)).

boundary conditions. Their approach was based on a model developed by Tien and Geiger (1967) and Tien and Koump (1968) for solidification of alloys. They considered the freezing process to consist of six phases; precooling, first phase change, intermediate phase change, second phase change, tempering and three zone periods. They derived formulas for each of the six phases based on Goodman's integral technique (Goodman 1964) and found good agreement between the experimental and predicted values in at least four of the six phases (Bakal and Hayakawa 1973). It was further pointed out that the correlation between the predicted and experimental values was product dependent, being better for ground meat as compared with orange juice concentrate. Bakal and Hayakawa (1972, 1973) have also published reviews on the calculations of freezing times and the heat transfer rates during freezing and thawing of foods.

Plank's New Model. Plank (1963) proposed a modification of his own earlier model to take into account various initial and final temperatures. The proposed equation for a slab is shown below as cited by Mascheroni and Calvelo (1982) (Eq. 39):

$$t = \frac{p'a^2Q'}{(Tf-Ta)k'}\left[\frac{1}{Bi}+\frac{1}{2}\right][(1+0.0053(Ti-Tf)] + t' \qquad (39)$$

where Bi=ha/k', p'=1, Q' is the enthalpy change between Tf and -12 °C, k' is the thermal conductivity at -12 °C and t' is given by (Eq. 40):

$$t' = \frac{1.886\ a^2\ n\ p'\ C''}{k'}\left[\log\left[\frac{Tf-Ta}{Tc-Ta}\right]-0.0913\right]\left[\frac{1}{Bi}+\frac{1}{2}\right] \qquad (40)$$

where n is a function of Bi (values of Bi and n are 0.25, 1.210; 0.5, 1.118; 1.0, 1.156; 2.0, 1.112; 4.0, 1.065; 10.0, 1.020; 20.0, 1.008, and ∞, 1.00, respectively) and C'' is the change in enthalpy, between -4 °C and Tc, divided by (-4 − Tc). Mascheroni and Calvelo (1982) reported this model to predict the freezing times of beef with errors of less than 10%.

Mascheroni, Calvelo and De Michelis Modifications. A prediction model which combines precooling, phase change and tempering periods independently was proposed by Mascheroni and Calvelo (1982). The precooling period was defined as the time that elapses between the beginning of the cooling until the temperature Tf is reached at a point midway between the center and the surface of an infinite slab. Phase change was assumed to occur at the freezing point, Tf, with the subsequent tempering period from a uniform Tf to a final temperature of Tc at the center. The model for the phase change period is as follows (Eq. 41):

$$t = \frac{p\ M\ L''\ c'\ a^2}{(Tf - Ta)\ k''} \left[\frac{1}{Bi} + \frac{1}{2} \right] \qquad (41)$$

where p = density above the freezing point, M = moisture content (%, wet basis), L″ = latent heat of pure water, c′ = average ice content between Tf and Tc, k″ = thermal conductivity at (Tf + Ta)/2 and Bi = ha/k″. The precooling and tempering periods were to be determined using charts provided for the purpose using modified thermal property values. Similar charts for obtaining center and average temperatures in infinite slabs can be found in food engineering textbooks (Charm 1978; Heldman and Singh 1981, etc.) The authors (Mascheroni and Calvelo 1982) reported that this model predicted the freezing times of beef under a wide range of conditions with an average absolute error of 3.6%.

De Michelis and Calvelo (1983) extended the above model to cover brick and cylindrical-shaped foods. For calculating precooling and tempering periods, they employed the methodology provided by Cleland and Earle (1982) using the equivalent heat transfer dimensions (EHTD) concept. They reported that freezing time predictions showed a maximum of 10% difference with respect to experimental freezing times of meat samples in brick or cylindrical shapes.

De Michelis and Calvelo (1982) further extended the model for nonsymmetric freezing of beef. They used a microscopic balance with simultaneous phase change together with equations for predicting the thermal properties as a function of ice content and a cryoscopic descent model to simulate the nonsymmetric freezing of a beef slab. By solving the equations using numerical methods, they found the location of the thermal center to vary throughout the freezing process. Providing charts for predicting the thermal center location, they suggested a relationship similar to Eq. 41 for calculating the phase change period, with an average length dimension replacing a. They experimentally verified their model to predict various final temperatures in the thermal center with errors less than 9% within a wide range of operating conditions ($5 < Ti < 25\,°C$; $-25 < Ta\ -45\,°C$; $0.9 < Bi < 100$).

Hung and Thompson Modification. Hung and Thompson (1983) incorporated a total enthalpy difference, taking into account the amount of water that remains unfrozen at the end of the tempering period, to replace the latent heat factor in the basic Plank's model. They replaced the temperature difference (Ti−Ta) by a weighted average temperature difference for the precooling, phase change and tempering periods. They also modified the geometric factors, P and R in Plank's equation, by a linear regression technique employing the dimensionless numbers, Bi, Pk and Ste. After verification of their model using experimental freezing time data for a 23% methylcellulose gel material in the shape of an infinite slab, they reported the accuracy of the model to predict freezing times of four different food materials to vary from -3.54 to +6.14%. For comparison, they also evaluated other models for freezing time prediction accuracy and found the following errors: -48.25 to -5.54% (Plank 1941), 5.82 to 77.50% (Nagaoka *et al.* 1955), -59.38 to -12.73% (Mott 1964) and -24.79 to +8.35% (Cleland and Earle 1976b).

General Remarks on Simple Models

The foregoing section has attempted to review most of the relatively simple models used to predict freezing times of foods. For the most part, they are based on Plank's (1913) model which does not accommodate the precooling and tempering periods commonly associated with freezing processes. Modification of Plank's model were aimed mainly at substituting for the latent heat factor in Plank's equation.

Cleland and Earle (1977a, 1979a,b) suggested modifying the geometric factors P and R on the basis of three dimensionless numbers (Bi, Ste and Pk). When the simple models are evaluated for accuracy by comparing predicted freezing times with experimental results for a variety of foodstuffs, the large discrepancies found (Cleland and Earle 1977a, 1979a,b; Hung and Thompson 1983; Ramaswamy 1979) indicate that no simple model can be applied to a wide range of situations. These models tend to rely more on the properties of the frozen material even when extending to large precooling situations. It appears, therefore, that the thermal properties of the material in both unfrozen and frozen states and the nature of the material itself (uniformity, porosity, etc.) should be considered. The model proposed by Mascheroni and Calvelo (1982) is based on this approach, although it depends on the use of charts for precooling and tempering periods which would, perhaps, reduce the accuracy of estimation. The computation procedure in their model also appears to be fairly complicated.

Further, most of the simple Plank-type models described, except the models proposed by De Michelis and Calvelo (1982, 1983), Plank (1963), Mascheroni and Calvelo (1982) and Ramaswamy and Tung (1980), were developed to estimate freezing time from an initial temperature to a final temperature of -10 °C. Thus, they take into account variations in the precooling period, but not in the tempering period. The enthalpy factor (Q) used in these models accounts, to some extent, for the variations in the tempering periods. However, the use of "Tf−Ta" in the enthalpy calculation in Mellor's model and the use of Stefan's number in the Cleland and Earle models tend to over-estimate the freezing times during cryogenic freezing (Ramaswamy 1979). Perhaps this effect could be minimized by using "Tf−Tc" instead of "Tf−Ta". The models developed by De Michelis and Calvelo (1982, 1983), Plank (1963), Mascheroni and Calvelo (1982) and Ramaswamy and Tung (1980) have been examined under more than one tempering period.

Nagaoka *et al.* (1955) and Levy (1958) modifications have added multiplication factors with dimensional variables [{1+0.008 (Ti)} and {1+0.008 (Ti−Tf)} in Eq. 8 and 10, respectively, for temperatures expressed in Celsius degrees]. These factors should be modified to suit working in other units of temperature. This point is stressed because there is a possibility for the same coefficient to be employed when in °C or °F. Mott's procedure (Mott 1964) assumes conditions similar to Plank's model and, hence, suffers from the same limitations. Luikov's solution (Luikov 1968) deviates from actual test situations because surface resistance is assumed to be negligible. It is therefore important to take notice of the assumptions made in arriving at a particular model before using it for prediction of freezing times.

Fourier Models

A different approach in solving the freezing time prediction problem is to obtain solutions to Fourier's heat conduction equations under appropriate boundary conditions. The validity of Fourier models have been proven and extensively used in engineering applications; however, the solutions are rather complicated and few are available in the published literature. Carslaw and Jaeger (1959) and Muehlbauer and Sunderland (1965) have discussed eloquently the theories and mathematical modelling of various conduction heat transfer problems.

Newmann Solution. Newmann's solution given by Carslaw and Jaeger (1959) utilizes unidirectional heat transfer in a semi-infinite solid. The assumptions made in deriving Plank's equation are also valid here. The partial differential equations representing the temperature distribution in the unfrozen and frozen regions are represented as follows (Eq. 42 and 43):

Unfrozen region;

$$\frac{\partial^2 Ti}{\partial x^2} = \frac{1}{D} \frac{\partial Ti}{\partial t} \qquad (42)$$

Frozen region;

$$\frac{\partial^2 Tc}{\partial x^2} = \frac{1}{D'} \frac{\partial Tf}{\partial t} \qquad (43)$$

The equation expressing the heat flux between frozen and unfrozen regions, which must be equal to the latent heat liberated at the freezing point, is represented as (Eq. 44):

$$k' \frac{\partial Tc}{\partial x} - k \frac{\partial Ti}{\partial x} = p'L \frac{dx}{dt} \qquad (44)$$

The boundary conditions employed for solving these differential equations are (Eq. 45, 46, 47 and 48):

$$Ti(x,0) = Ti \qquad (45)$$

$$Ti(0,t) = Ts(t) \qquad (46)$$

$$Ti(x,t) = Tf(x,t) = Tf \qquad (47)$$

$$\frac{\partial Ti[\,d/2\,,\ t\,]}{\partial x} = 0 \qquad (48)$$

Imposing these boundary conditions, Newmann derived a solution for the time-temperature relationship in an infinite slab as (Eq. 49):

$$Tc = \frac{Tf}{erf(v)}\ erf \left[\frac{x}{2\{D't\}^{1/2}} \right] \qquad (49)$$

where v may be obtained from the following relationship (Eq. 50):

$$\frac{\exp(-v^2)}{\mathrm{erf}(v)} - \frac{k}{k'}\left[\frac{D'}{D}\right]^{1/2} \frac{(Ti-Tf)\exp(-D'\cdot v^2/D)}{Tf\ \mathrm{erfc}[v\{D'/D\}^{1/2}]} = \frac{Lv^{1/2}}{C'\ Tf} \qquad (50)$$

When Tc=Tf=Ti, and Eq. 47 reduces to (Eq. 51):

$$x = 2\ v\ [D'\ t]^{1/2} \qquad (51)$$

Equation 51 suggests that the location of the freezing front is a linear function of freezing time on a logarithmic plot with slope = 1/2, and that v can be calculated from the intercept (Bakal and Hayakawa 1970).

Charm and Slavin (1962) used Eq. 49 to predict the freezing times of cod fillets by using a modified thickness equal to [(d/2)+(k'/h)]. However, Cowell (1967) reported that this method resulted in over-estimating freezing times when the Biot number was less than 1.0.

Albin *et al.* (1976) employed Goodman's integral technique (Goodman 1964) to solve Fourier's differential equations using a number of dimensionless parameters. They presented an analysis for predicting the freezing characteristics of lamb, veal and fish slices in rectangular packages in a plate freezer. By the use of four dimensionless numbers, they also accounted for the variations in the plate (surface) temperature.

Chung and Yeh (1975) assumed simultaneous convection and radiation heat exchange between the cooling medium and the surface of a semi-infinite body and reduced Fourier's partial differential equations to separable first order ordinary differential equations by using Goodman's integral technique. Although these resultant equations are not suitable for arriving at simple analytical solutions, they may be easily solved by numerical methods.

Rathjen and Jiji (1970) derived approximate analytical formulas for the estimation of transient heat transfer and the location of the freezing front in a two dimensional corner. They also provided charts for predicting the location of the ice front and reported that the results were in good agreement with the solution of the original heat conduction equations by a finite difference technique.

Tao's Charts. Tao (1967) developed several charts for estimating freezing times in infinite slabs, infinite cylinders and spheres by numerically solving Fourier heat conduction equations under convective heat transfer at the surface. As in Plank's model, these charts were based on the material temperature being maintained at the freezing point throughout the process, and hence do not take into account the precooling or the tempering periods. The charts were based on three dimensionless groups as shown below (Eq. 52, 53 and 54):

$$t^* = tk'(Tf-Ta)/(Lp'a^2) \tag{52}$$

$$B^* = k'/(ha) \tag{53}$$

$$r^* = C'(Tf-Ta)/L \tag{54}$$

In order to calculate the freezing time (t), B* and r* are first evaluated with Eq. 53 and 54 and used in the appropriate chart to obtain t* which is then used in Eq. 52. Tao's charts can be found in Tao (1967), Bakal and Hayakawa (1973) and Heldman and Singh (1981).

Numerical Methods

The different methods discussed up to this point assume constant thermal properties for the material. In order to provide for variations in thermal properties during the freezing process, it should be possible to use an equation of the type (Eq. 55):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[D(T)\,\frac{\partial T}{\partial x}\right] \tag{55}$$

which is a partial differential equation for one dimensional heat conduction with thermal diffusivity as a function of temperature. A more general way of expressing the relationship is as follows (Eq. 56 and 57):

infinite slab,

$$p(T)\ C(T)\ \frac{\partial T}{\partial t} = k(T)\ \frac{\partial^2 T}{\partial x^2} \tag{56}$$

infinite cylinder (b=1) or sphere (b=2),

$$p(T)\ C(T)\ \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left[k(T)\frac{\partial T}{\partial r} + \frac{bk(T)}{r}\ \frac{\partial T}{\partial r}\right] \tag{57}$$

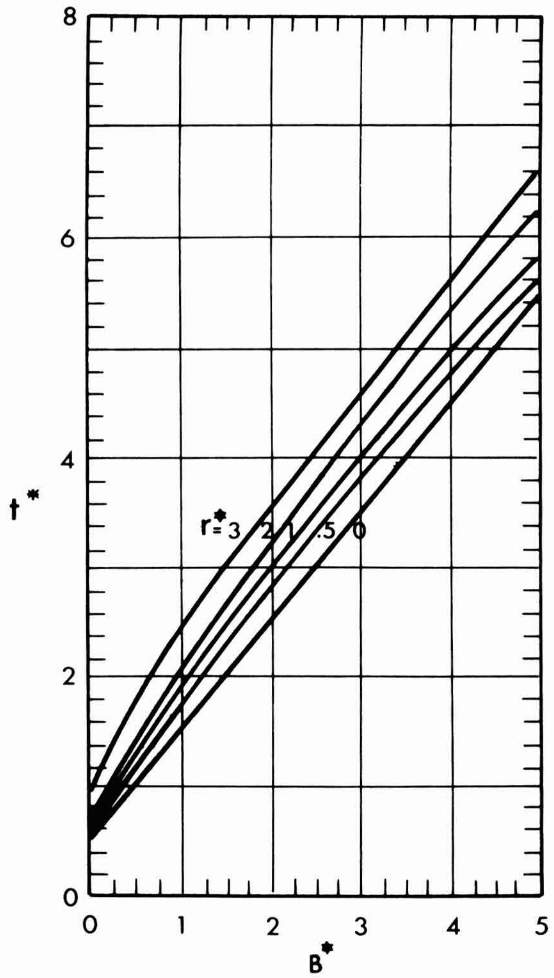

FIG. 6. TAO'S CHART FOR ESTIMATING FREEZING OR THAWING TIME OF AN INFINITE SLAB (ADAPTED FROM BAKAL AND HAYAKAWA (1973)).

These relationships as such do not account for the boundary conditions. The most common boundary condition in freezing studies is the one with a finite convective surface heat transfer coefficient referred to as the third kind of boundary condition. These have been described by Cleland and Earle (1977b)

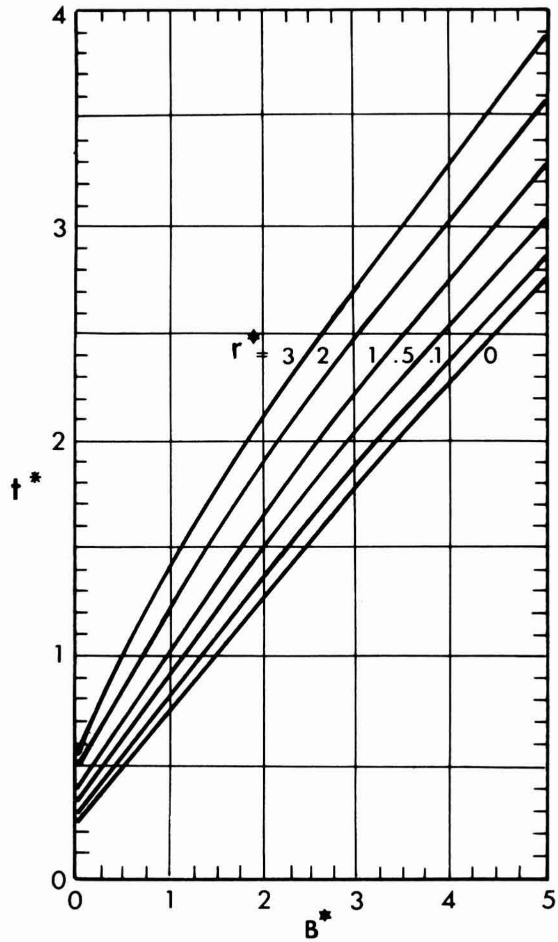

FIG. 7. TAO'S CHART FOR ESTIMATING FREEZING OR THAWING TIME OF AN INFINITE CYLINDER (ADAPTED FROM BAKAL AND HAYAKAWA (1973)).

and Hayakawa (1977) and are represented by the following relationships (applicable to the surface) (Eq. 58 and 59):

infinite slab,

$$h(Ta-Ts) = -k(T)\ [\ \partial T/\partial x\ ] \qquad (58)$$

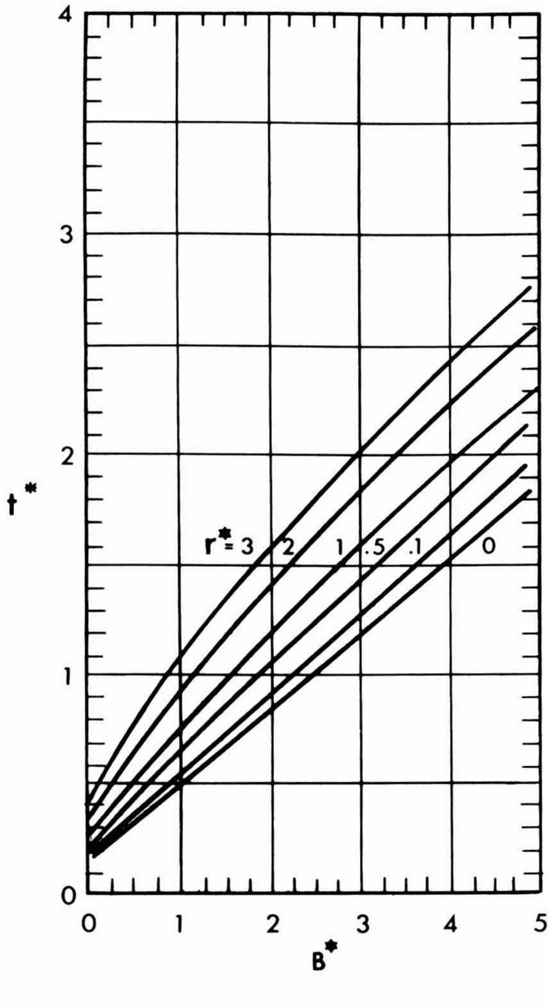

FIG. 8. TAO'S CHART FOR ESTIMATING FREEZING OR THAWING TIME OF A SPHERE (ADAPTED FROM BAKAL AND HAYAKAWA (1973)).

infinite cylinder or sphere,

$$h(Ta-Ts) = -k(T)\ [\ \partial T/\partial r\ ] \tag{59}$$

These differential equations are difficult to solve without the use of numerical methods. The numerical methods are versatile and can accommodate a wide variety of boundary conditions, but also involve extensive computations and, therefore, require the use of a computer.

There have been two general approaches in using these numerical methods. In one approach, the latent heat was assumed to be released at a fixed freezing point (Charm *et al.* 1972). Since foods do not exhibit sharp melting points, the solutions of this type depart from the actual situation. Charm (1978) has given a computer program and also provided a table for predicting the freezing times of foods under a wide range of conditions. The second approach takes into consideration the variations of apparent specific heat and thermal conductivity as a function of temperature and, hence, does not require a latent heat factor. This approach has been more widely used (Bonacina and Comini 1973; Bonacina *et al.* 1973; Cleland and Earle 1977a, 1979a,b; Fleming 1971; Heldman 1974b, Heldman and Gorby 1975b; Hohner and Heldman 1970; Purwaderia 1980; Reballato *et al.* 1978; Schwartzberg 1977; Schwartzberg *et al.* 1977).

Two types of numerical methods are commonly used: the finite difference method and the finite element method. The finite element methods have been used by Bonacina and Comini (1973) and Rebellato *et al.* (1978). These methods are complex and versatile; however, for unidirectional heat transfer problems, finite element methods offer no distinct advantage over finite difference methods (Cleland and Earle 1979b).

THERMO-PHYSICAL PROPERTIES OF IMPORTANCE

Freezing time prediction models require a thorough knowledge of the thermo-physical properties of the material to be frozen and the ambient conditions. The properties of major interest are; specific heat capacity, thermal conductivity and density in both unfrozen and frozen states, latent heat, surface heat transfer coefficient and the conditions of freezing. Extensive reviews and tabulated data are available on thermal conductivity and specific heats of food and agricultural materials (Dickerson 1968; Mohsenin 1980; Polley *et al.* 1980).

Density variations within the unfrozen or frozen state are not very significant and, hence, can be considered constant without much loss in accuracy. The temperature dependence of thermal conductivity and apparent specific heat has been observed to be significant (Choi and Okos 1980; Dickerson and Read 1975; Heldman, 1974a, 1982; Heldman and Gorby 1975a; Heldman and Singh 1981; Hsieh *et al.* 1977; Ramaswamy 1979; Ramaswamy and Tung 1980, 1981). Attempts have been made to establish models for the temperature dependence of thermal conductivity, apparent specific heat, density and thermal diffusivity (Bonacina *et al.* 1974; Heldman 1974a). This aspect has been discussed in detail by Heldman and Singh (1981).

The determination of surface heat transfer coefficients is another problem of great importance in freezing time predictions. Although typical average surface heat transfer coefficients are available in the literature (Heldman and Singh 1981), these values do not account for the complexities of typical food freezing situations. Various methods have been suggested for the evaluation of the heat transfer coefficients associated with test situations (Charm 1978; Cleland and Earle 1976a; Cowel and Namor 1974; Earle 1971). All of these methods estimate an average heat transfer coefficient for the test situation. Chavaria (1978) reported that estimation of the local coefficients on the surface of the product during exposure to the freezing environment should lead to improved freezing time predictions since average coefficients may not represent the true test situation. However, such local coefficients could only be accommodated by the numerical methods.

CONCLUSIONS

An attempt has been made to review pertinent information available on the prediction of freezing times of foods. The emphasis has been focused on the simpler Plank-type models which can be solved without the use of computers. A brief discussion of other methods has also been included for reference. Several modifications have been suggested to overcome the basic limitations of Plank's original equation, but with limited success. Further refinement of the model appears to be necessary for accurate prediction of freezing times under the wide range of practical freezing conditions. The numerical methods are potentially more promising and can take into account variations in boundary conditions and product properties. These methods, however, will require access to a computer.

LIST OF SYMBOLS

A	Cross sectional area perpendicular to heat flow
a	Radius of a of an infinite cylinder or sphere or half-thickness of an infinite slab
Bi	Biot number
B*	Reciprocal of Biot number
B1,B2	Factors for the dimensions of a rod or brick

C	Specific heat capacity above freezing point
C′	Specific heat capacity below freezing point
C″	Enthalpy change between -4 °C and Tc divided by (-4 − Tc)
C(T)	Specific heat capacity as a function of temperature
c′	Average ice content between Tf and Tc
D	Thermal diffusivity above freezing point
D′	Thermal diffusivity below freezing point
D(T)	Thermal diffusivity as a function of temperature
d	Diameter of infinite cylinder or sphere, or thickness of an infinite slab
dx/dt	Velocity of the frozen front
ΔT	Temperature difference
Δt	Time interval
erf	Error function
erfc	Coerror function
F	Factor in Eq. 13
Fo	Fourier number
G	Factor in Eq. 13
G′	Dimensionless time, Eq. 16
h	Heat transfer coefficient
Ko	Kossovitch number
k	Thermal conductivity above freezing point
k′	Thermal conductivity below freezing point
k″	Thermal conductivity at (Tf+Ta)/2
k(T)	Thermal conductivity as a function of temperature
L	Latent heat of fusion
L″	Latent heat of water at 0 °C
M	Moisture content
n	A function of Biot number
P,P*,P′,P″	Geometric factors in Plank-type equations
Pk	Plank's number
p	Density above freezing point
p′	Density below freezing point
p(T)	Density as a function of temperature
Q	Enthalpy change between Ti and Tc
Q*	Enthalpy change between Tf and Tc
Q′	Enthalpy change between Tf and -12 °C
q	Rate of heat flow
R,R*,R′,R″	Geometric factors in Plank-type equations
r	Radius of a cylinder or sphere

r^*	Modified Stefan's number Eq. 54
Ste	Stefan's number
T	Temperature
Ta	Ambient temperature
Tc	Final temperature
Tf	Freezing point
Ti	Initial temperature
Ts	Surface temperature
t	Freezing time
t'	Time, Eq. 40
t^*	Dimensionless time, Eq. 52
V	Volume
v	Factor determined by Eq. 50 or 51
$\underline{w}$	Average freezing rate
x	Thickness of the icefront

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MODELING HEAT AND MASS TRANSFER DURING THE OVEN ROASTING OF MEAT

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ABSTRACT

The roasting (baking) of meat involves both heat and mass transfer. A mathematical model which describes the roasting process as it occurs in a conventional oven is presented. Numerical solutions are presented for several different roasting conditions and the results are compared to available experimental results. A significant fraction of the energy required for roasting is associated with the evaporation of water and this needs to be considered in modeling the roasting process. Water losses due to mass transfer from the product depend on oven humidity and temperature. The mathematical model considers the variation of oven humidity with time during roasting. The implicit alternating direction finite difference method is used to obtain the numerical solutions.

INTRODUCTION

The roasting of meat involves both heat and mass transfer. The evaporation of water during the roasting process needs to be considered in modeling the roasting process. In this work, a mathematical model is presented which includes both heat and mass transfer. The model is used with finite difference methods to obtain simulated results which are compared to the experimental results of Bengtsson *et al.* (1976).

Considerable research on the roasting of meat has already been reported in the literature. The work most closely related to this work is that of Godsalve (1976), Godsalve *et al.* (1977a, 1977b), Bengtsson *et al.* (1976), Skjoldebrand and Hallstrom (1980), Skjoldebrand (1980), Bimbenet *et al.* (1971), Dagerskog (1976), Hung *et al.* (1978), and Baerdemaeker *et al.* (1977). Bengtsson *et al.* (1976) has modeled the roasting process and compared the results with experimental measurements. In a conventional oven, the partial

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pressure of water vapor varies during the roasting process because of evaporation. This variation is considered in the present work.

The thermal conductivity of beef is an important physical property parameter in this work. Khandon and Okos (1981), Polley *et al.* (1980), Hill *et al.* (1967), Lentz (1960), Woodams and Nowrey (1968), and Kopelman (1966) have reported results on the thermal conductivity of heat flow relative to the direction of muscle fibers (Hill *et al.* 1967; Lentz 1960; Kopelman 1966). The thermal conductivity also varies with the moisture content of the meat.

MATHEMATICAL MODEL

In the process of roasting meat, the water at the surface of the meat behaves like free or unbound water as long as sufficient water is available at the surface. The model does not consider the internal movement of water due to convective flow and diffusion. Thus, the model within the meat considers heat transfer and meat temperature while the loss of water is modeled at the surface of the meat and in the gas phase in the oven. Heat transfer within the meat can be given by Fourier's law (Eq. 1):

$$\frac{\partial T}{\partial t} = \alpha_x \frac{\partial^2 T}{\partial X^2} + \alpha_y \frac{\partial^2 T}{\partial Y^2} + \alpha_z \frac{\partial^2 T}{\partial Z^2} \qquad (1)$$

where t is time, X, Y, and Z are the three space dimensions, T is temperature, $\alpha = k/\rho c_p$ is the thermal diffusivity of the meat, and the subscripts x, y, and z allow the directional variation of thermal conductivity to be incorporated into the model. Consider a rectangular slab of meat with dimensions 2a, 2b, and 2c with the origin at the geometric center of the meat. Because of internal symmetry, only the segment, where X, Y, and Z are all positive, is considered. The boundary conditions include the initial temperature of the meat as (Eq. 2):

$$t = 0,\ T = T_o,\ 0 \le X \le a, \qquad 0 \le Y \le b,\ 0 \le Z \le c \qquad (2)$$

At the surface of the meat, the heat transfer to the meat, the heat to evaporate water and conduction into the meat are considered. For example, at X = a (Eq. 3):

$$h(T_a - T) = \lambda k_p (P_s - P_a) + k_x \left.\frac{\partial T}{\partial X}\right|_{X=a} \qquad (3)$$

where h is the heat transfer coefficient at the surface, λ is the latent heat of vaporization of water, k_p is the mass transfer coefficient at the meat surface, T_a is the oven temperature, P_s is the vapor pressure of water at the meat surface temperature, T_s, and P_a is the partial pressure of water vapor in the oven. Similar boundary conditions may be written for the other surfaces of the meat. The boundary conditions associated with internal positions due to symmetry considerations are that heat is not conducted across these boundaries. For example, at (Eq. 4)

$$X = 0 \,, \quad \frac{\partial T}{\partial X} = 0 \qquad (4)$$

where the plane $X=0$ passes through the geometric center of the meat.

The mathematical model for the water vapor in the oven is for an oven which is vented such that the oven pressure remains constant. For constant oven temperature and pressure, the total moles in the gas phase remain constant. However, as roasting progresses, the moles of water vapor increase. The model presented here assumes complete mixing of the gas in the oven. The moles of gas flowing from the oven is equal to the molar rate of evaporation. The water vapor balance is (Eq. 5)

$$\frac{dM_w}{dt} = N_w - N_w y_w \qquad (5)$$

where M_w is the moles of water vapor in the gas phase in the oven, N_w is the molar rate of evaporation from the meat, and $N_w y_w$ is the molar flow rate of water from the oven. The mole fraction of water vapor in the oven, y_w, is given by (Eq. 6)

$$y_w = \frac{M_w}{M_t} \qquad (6)$$

where M_t is the total number of moles in the gas phase in the oven. The rate of evaporation from the meat surface, N_w, depends on the mass transfer term $k_p(P_s - P_a)$ in Eq. 3 which should be integrated over the external surface area of the meat.

The relationship between vapor pressure and temperature for water is tabulated in steam tables and in handbooks; the Antoine equation provides a nonlinear analytical relationship. Over short ranges of temperature, an approximate linear relationship may be used. The expression (Eq. 7)

$$P_s = A + BT \qquad (7)$$

is used in this work for 20 °C temperature increments in order to simplify the numerical solution procedure. The partial pressure of water vapor P_a is given by (Eq. 8)

$$P_a = y_w P \tag{8}$$

where P is total pressure.

The surface temperature and the corresponding water vapor pressure will vary with position. For the numerical methods that are commonly employed, this variation with position may be included when summing or integrating over the surface area to obtain N_w.

The initial condition for Eq. 5 specifies the quantity of water vapor in the oven at the start of the roasting process. This may be taken as zero.

METHODS OF SOLUTION

No analytical solutions to this problem have been found. The two most common methods of numerical solution are finite difference methods and finite element methods. Baerdemaeker *et al.* (1977) have shown how heat transfer problems may be solved using finite element methods. Heat transfer in chicken and beef is considered in their work. An advantage of the finite element method is that irregular shapes may be considered. The implicit alternating direction (I.A.D.) finite difference method is used in this work to obtain numerical solutions (Rosenberg 1969; Carnahan *et al.* 1969). The details of the method are presented in the Appendix. The I.A.D. method is very stable and relatively large step sizes may be used.

RESULTS AND DISCUSSION

Computer simulations were carried out for two different oven temperatures, 175 °C and 225 °C. The values of the physical properties were obtained from the literature. The thermal conductivity of the beef was taken to 0.4 watts/m °C (Hill *et al.* 1967; Khandon and Okos 1981), and the density and specific heat were taken to be 879 kg/m³ and 2510 J/kg °C, respectively (Khandon and Okos 1981; Polley *et al.* 1980). These values were combined to obtain a constant value of $1.8 \times 10^{-7} m^2/s$ for the thermal diffusivity, α which was used throughout the roasting process. The dimensions of the meat were taken to be the same as in the work of Bengtsson *et al.* (1976) (15×8×5.5 cm). A two dimensional approximation was used with heat transfer in the direction of greatest length being neglected. The heat transfer coefficient was taken to be 5 watts/m^2 °C. The value of the mass transfer coefficient, k_p, was obtained from the relationship between heat and mass transfer coefficients during drying which is (Eq. 9) (Bimbenet *et al.* 1971)

$$\frac{h}{k_p \lambda} = 64.7 \ kg/m(^oC)(s^2) \quad (9)$$

Figures 1 and 2 show how the wet bulb temperature, T_w, the corner surface temperature, T_s, and the center temperature of the meat, T_c vary with time during the roasting process. Figure 1 is for roasting at an oven temperature of 175 °C with an initial meat temperature of 5 °C. In Fig. 2, an oven temperature of 225 °C is used with the same heat transfer coefficient as in Fig. 1 (5 watts/m^2 °C). The surface temperature which is shown in Fig. 1 and 2 is the temperature at an exposed corner of the cross section; that is, it is the warmest point of the cross section which passes through the geometric center of the meat. The surface temperature is below the wet bulb temperature because part of the heat is conducted into the meat while the other part is used for evaporation. The wet bulb temperature and the meat surface temperature should be equal when there is no heat transfer due to conduction into the meat. Since the oven pressure is one atmosphere, the surface temperature should not exceed 100 °C as long as unbound water is available at the meat surface. The model assumes sufficient moisture is present at the surface.

The variation of moisture loss with time for roasting with h=5 watts/m^2 °C and T_a=175 °C and 225 °C is shown in Fig. 3. Increasing the oven temperature from 175 °C to 225 °C causes a 15% reduction in cooking time but doubles the moisture loss. For an oven temperature of 225 °C and h=5 watts/m^2 °C, 21.8 g of moisture (per 600 g of meat) are evaporated from the meat surface during the roasting time required for the center temperature to reach 70 °C. The energy required for evaporating this water is approximately 53,000 J, which is about 30% of the total energy required for cooking. It is clear that the energy required for evaporation is significant and should be considered in modeling the roasting process.

The energy required to melt fat during the roasting process is a relatively small part of the total energy required. For the meat samples of Bengtsson *et al.* (1976) which contained about 4% fat, the amount of energy required to melt all of the fat would be only about 3% of the total energy required for the meat to be cooked to 70 °C. Since only a portion of the fat melts, the melting of the fat may be neglected in modeling heat transfer.

In Fig. 1 and 2 and Table 1, the simulation results are compared with the experimental results of Bengtsson *et al.* (1976). The center temperatures are

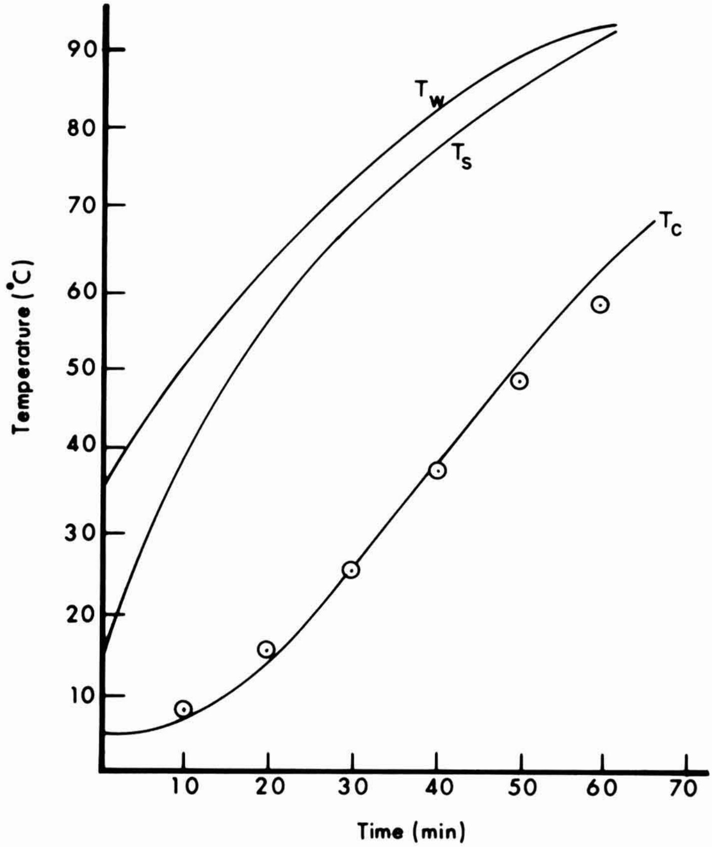

FIG. 1. SIMULATION RESULTS FOR THE ROASTING OF BEEF AT AN OVEN TEMPERATURE OF 175 °C, FOR h=5 WATTS/m² °C. THE CENTER TEMPERATURE (T_c) IS COMPARED WITH THE MEASURED VALUES OF BERGTSSON *ET. AL.* (1976). T_w IS WET BULB TEMPERATURE AND T_s IS THE CORNER SURFACE TEMPERATURE.

in relatively good agreement, especially during the early period of roasting. During the later period of roasting, the simulation results predict higher center temperatures than those obtained experimentally. However, the experimentally observed rates of evaporation exceed the simulated rates because of the experimental equipment that was used. Bengtsson *et al.* (1976) employed a small oven (24×25×32 cm) within a forced convection oven. Analysis of their experimental results and comparison with the simulated moisture loss suggests that air from the forced convection oven entered their small rectangular oven

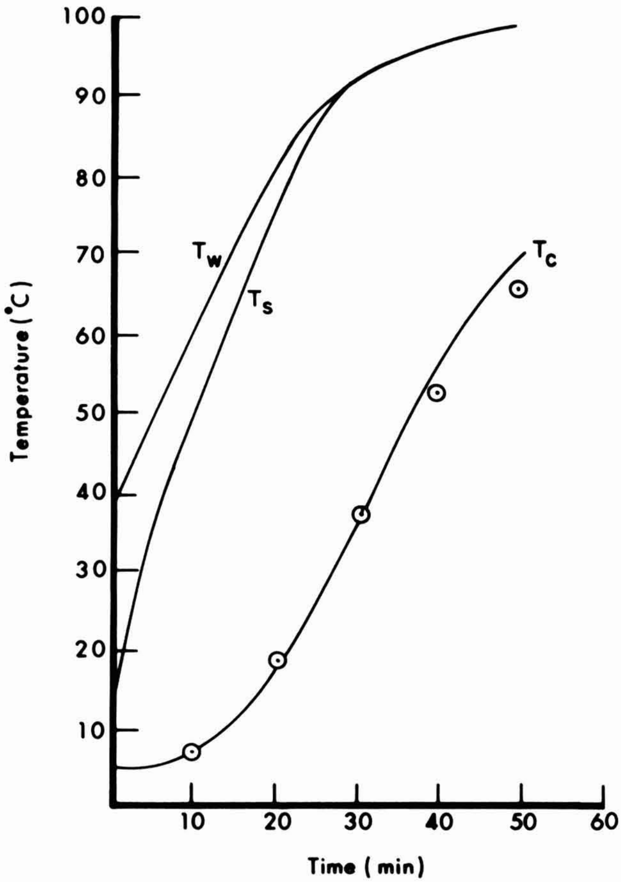

FIG. 2. SIMULATION RESULTS FOR THE ROASTING OF BEEF AT AN OVEN TEMPERATURE OF 225°C, FOR h=5 WATTS/m²°C. THE CENTER TEMPERATURE (T_c) IS COMPARED WITH THE MEASURED VALUES OF BENGTSSON *ET. AL.* (1976)

to reduce the partial pressure of water vapor in the air and to increase the evaporation rate. This phenomena could easily be included in the model of the gas phase in the oven; that is, Eq. 5 may be written in the form (Eq. 10)

$$\frac{dM_W}{dt} = Fy_o + N_W - (F + N_W)\, y_W \tag{10}$$

where F is the molar flow rate of air into the oven and y_o is the mole fraction of water in the entering air.

Table 1. Comparison of calculated and experimental cooking time for oven temperatures of 175°C and 225°C

Oven Temp. (°C)	Initial Temp. (°C)	Final Center Temp. (°C)	Experimental* Cooking time (min)	Calculated Cooking time (min)
175.0	5.0	40.0	39.0	41.0
		70.0	80.0	70.0
225.0	5.0	40.0	32.0	32.5
		70.0	57.0	50.0

* Bengtsson *et al.* 1976.

A second factor which is not considered in the computer simulation is the variation of thermal diffusivity with temperature and moisture content. As the meat dries and crust forms on the meat surface, the thermal conductivity will decrease (Khandon and Okos 1981). This factor would also contribute to the experimental cooking time being longer than the simulated time.

A third factor which was not considered was the variation of the heat transfer coefficient during the roasting process. Bengtsson *et al.* (1976) obtained a good fit of their data by decreasing the heat transfer coefficient as the roasting process progressed.

The general shape of the curves shown in Fig. 1 and 3 is similar to the corresponding experimental curves shown in Fig. 3 of Bengtsson *et al.* (1976). Based on the measured evaporation losses of Bengtsson and the fact that their evaporation loss curve is very similar in shape to the one in Fig. 3 for an oven temperature of 175 °C, it appears that sufficient unbound water is present at the meat surface and that the availability of water does not limit the rate of evaporation. Their results also show that more than 1.5 g of water per g of fat free dry solids was present at the surface of the meat when the center temperature reached 70 °C for oven temperatures of 175 °C and 225 °C. Thus, the evidence in their work indicates that unbound water was present at the surface of the meat throughout the roasting process.

The work of Skjoldebrand (1980) indicates that, in forced convection ovens where the values of the heat and mass transfer coefficients are larger, conditions are frequently reached where the falling rate period of drying is encountered; that is, where there is not sufficient unbound water at the meat surface to maintain the evaporation rate at the rate predicted by the model employed in the present work.

Computer simulation allows investigation of the effects of changes in roasting conditions on the meat temperature and evaporation losses. Figure 4 shows

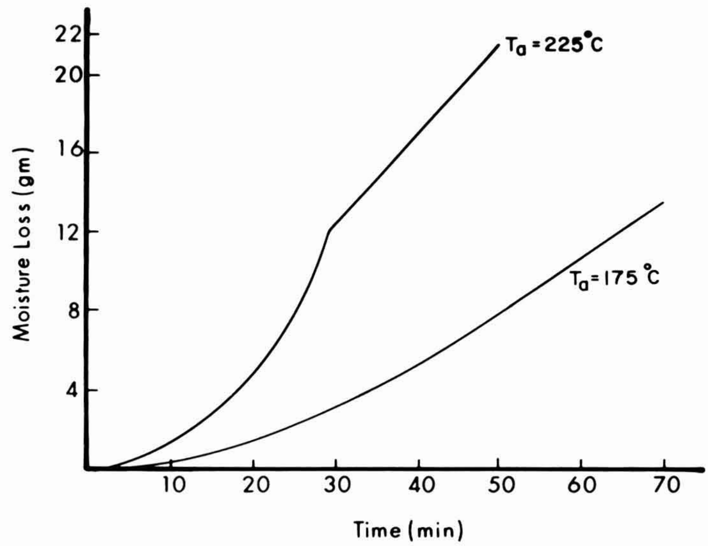

FIG. 3. SIMULATION RESULTS SHOWING THE MOISTURE LOSS DUE TO EVAPORATION FOR OVEN TEMPERATURES (T_a) OF 175° AND 225° FOR h=5 WATTS/m² °C.

how the center temperature varies with time for different values of the heat transfer coefficient. Figure 5 shows the position of the 70 °C temperature profile after various periods of roasting at 175 °C. Figure 6 shows several lines of constant temperature after 30 minutes of roasting at 175 °C. In Fig. 5 and 6, the isotherms are shown for only one quadrant of the meat cross section because the other quadrants are symmetrical to the one which is shown. The center of the piece of meat is the origin in Fig. 5 and 6. Additional simulation results are presented elsewhere (Singh 1983).

CONCLUSIONS

A mathematical model is presented for the period of roasting where unbound water is present at the meat surface and evaporation is limited by the rate of mass transfer in the vapor phase. The model is used to show the effects of oven temperature and heat transfer coefficients on the center temperature and surface temperature of the meat, the wet bulb temperature and the evaporation of water from the meat.

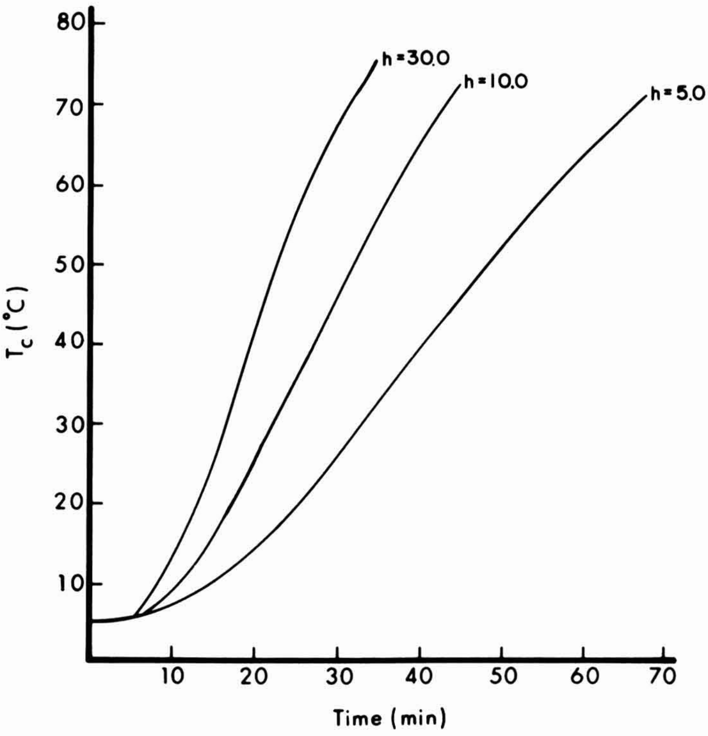

FIG. 4. EFFECT OF HEAT TRANSFER COEFFICIENT (h) ON THE CENTER TEMPERATURE FOR AN OVEN TEMPERATURE OF 175 °C.

Loss of moisture is an important factor in the cooking of meat. A major part of the energy required for cooking is used in evaporating water from the meat. Moisture loss is greater when meat is roasted at higher oven temperatures but total cooking time is decreased. Evaporative losses can be reduced by raising the relative humidity inside the oven and by lowering the oven temperature.

When meat is cooked in a closed oven with a vent, the humidity and the wet bulb temperature in the oven increase as the meat cooks because water evaporates from the meat surface. Since the drying rate and the heat transfer rate are dependent on the humidity and wet bulb temperature, these factors need to be included in modeling the roasting process.

Only a small fraction of the energy required for cooking is used for melting the fat contained in the meat. Melting of fat is not very critical in modeling the heat transfer associated with the roasting process.

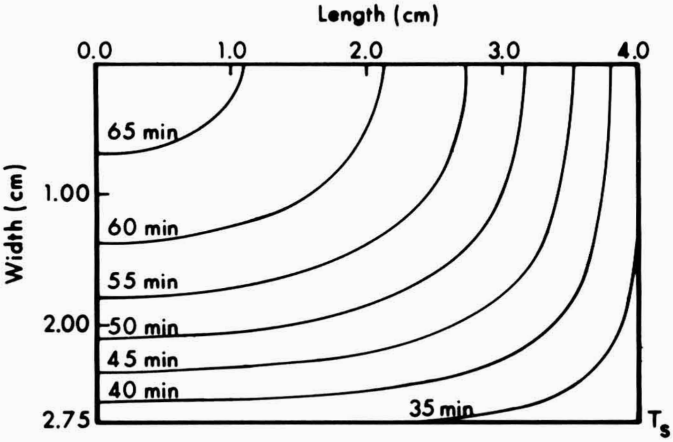

FIG. 5. SIMULATION RESULTS WHICH SHOW THE POSITION OF THE 70 °C TEMPERATURE PROFILE AT SEVERAL COOKING TIMES. THE ORIGIN REPRESENTS THE CENTER OF THE MEAT PIECE.

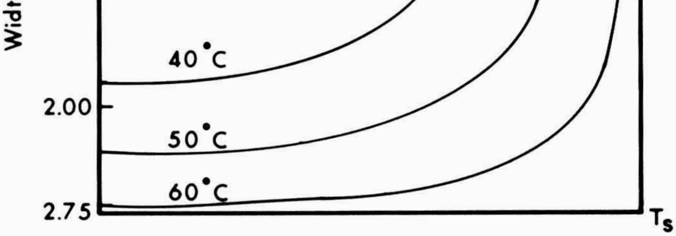

FIG. 6. SIMULATION RESULTS WHICH SHOW SEVERAL TEMPERATURE PROFILES AFTER 30 MIN. OF ROASTING AT AN OVEN TEMPERATURE OF 175 °C. THE ORIGIN REPRESENTS THE CENTER OF THE MEAT PIECE.

APPENDIX

NUMERICAL SOLUTION USING FINITE DIFFERENCE METHODS

The numerical solutions were obtained for two space dimensions, X and Y. The point X=0, Y=O was taken to be the geometric center of the meat piece. The values of the constants A and B in Eq. 7 which were used are given in Table A1.

Table A1. Least Square Estimates of the parameters A and B in Equation (7) for the different temperature ranges.

Temperature Range (°C)	A (Pascals)	B Pascals/°C
$0 < T \leq 30.0$	-126.35	140.85
$30 < T \leq 50.0$	-8,357.00	412.21
$50 < T \leq 70.0$	-36,001.81	958.89
$70 < T$	-108,230.00	1,983.65

Equation 1 and its boundary conditions may be written in dimensionless form for two space dimensions by introducing the dimensionless variables

$$x = \frac{X}{a}$$

$$y = \frac{Y}{a}$$

$$\theta = \frac{T - T_o}{T_a - T_o}$$

and

$$\tau = \alpha t/a^2$$

On substituting these dimensionless variables, Eq. 1 and its boundary conditions have the following form (Eq. A1)

$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} \tag{A1}$$

At $\tau=0$, $\theta=0$ for $0\leq x\leq 1$ and $0\leq y\leq b/a$. At $x=0$ (Eq. A2),

$$\left.\frac{\partial\theta}{\partial x}\right|_{x=0} = 0, \quad 0 \leq y \leq b/a \tag{A2}$$

At $x=1$ (Eq. A3),

$$\left.\frac{\partial\theta}{\partial x}\right|_{x=1} = \frac{ah}{k}(1-\theta) - \frac{a\lambda k_p}{k}\left[\frac{A - P_a + BT_o}{T_a - T_o} + B\theta\right] \tag{A3}$$

Similar dimensionless equations may be written for $y=0$ and $y=b/a$. Since the heat transfer is perpendicular to the muscle fibers in both the x and the y directions, the same numerical value of thermal conductivity was used in both directions.

As shown in Fig. 5 and 6, the numerical solutions were obtained for one quadrant of the meat cross section. The x and y dimensions were divided into equal length segments with $\Delta x=1/n$, $\Delta y=\Delta x$, and $m=nb/a$ where the y direction is divided into m equal length segments. The Implicit Alternating Direction (I.A.D.) finite difference method (Rosenberg 1969; Carnahan *et al.* 1969) was used to obtain numerical solutions. In this method, for the two dimensional case, two difference equations which are used over two successive time steps of duration $\Delta\tau/2$ are employed. The first equation is implicit only in the x direction and the second is implicit only in the y direction. The first equation contains the finite difference analog for $\partial^2\theta/\partial x^2$ written for time $\tau_k+\Delta\tau/2$ (abbreviated as *) and the analog for $\partial^2\theta/\partial y^2$ at time τ_k; that is Eq. A1 may be written in finite difference form where i denotes a position along the x axis, j for the y axis, and k for the time axis (Eq. A4).

$$\frac{\overset{*}{\theta}_{i+1,j} - 2\overset{*}{\theta}_{i,j} + \overset{*}{\theta}_{i-1,j}}{(\Delta x)^2} + \frac{\theta_{i,j+1,k} - 2\theta_{i,j,k} + \theta_{i,j-1,k}}{(\Delta y)^2} = \frac{\overset{*}{\theta}_{i,j} - \theta_{i,j,k}}{\Delta\tau/2} \tag{A4}$$

The second equation of the I.A.D. method is analogous to Eq. A4 except that $\partial^2\theta/\partial y^2$ is written for the time level $\tau_k+\Delta\tau=\tau_{k+1}$. Equations similar to Eq.

A4 are written for each position $i=1, \ldots, n$ and then solved simultaneously for each value of j. Then, an analogous procedure is used at τ_{k+1} to find values of $\theta_{i,j,k+1}$. In this case the equations for $j=1,2, \ldots, m$ are solved simultaneously for each value of i.

The boundary conditions must be used to obtain appropriate finite difference equations at $i=1$ and $i=n$, for the x direction, for example. Since $\theta^*_{0,j}=\theta^*_{2,j}$ because of symmetry, Eq. A4 for $i=1$ may be written in terms of the unknowns $\theta^*_{1,j}$ and $\theta^*_{2,j}$. An expression relating $\theta^*_{n,j}$ and $\theta^*_{n+1,j}$ for substitution into Eq. A4 for $i=n$ to eliminate $\theta^*_{n+1,j}$ as an unknown is also needed. This is obtained by writing a Taylor series expansion for $\theta^*_{n,j}$ about the boundary point $(n+1, j)$ and neglecting third order and higher order terms. The value of $(\partial\theta^*/\partial x)$ at $n+1$, j is obtained from the boundary condition, Eq. A3. The value of $\partial^2\theta/\partial x^2$ at $n+1$, j is eliminated by solving the Taylor series expansion for that term and substituting it into Eq. A1 with the other two terms in Eq. A1 written in finite difference form. The resulting equation is (Eq. 5)

$$\theta^*_{n+1,j} = \frac{R\theta^*_{n,j} + E}{1 + R(1 + G_1 + G_2)} \quad \text{(A5)}$$

where (Eq. A6)

$$E = \frac{R}{2}\left[\theta_{n+1,j+1} + \theta_{n+1,j-1} - 2\theta_{n+1,j} + 2G_1 - \frac{2G_2}{B}\left(\frac{A - P_a + BT_o}{T_a - T_o}\right)\right] + \theta_{n+1,j} \quad \text{(A6)}$$

$$G_1 = \frac{ah\Delta x}{k} \quad \text{(A7)}$$

$$G_2 = \frac{a\lambda k_p B\Delta x}{k} \quad \text{(A8)}$$

$$R = \frac{\Delta\tau}{(\Delta x)^2} \quad \text{(A9)}$$

The values of θ in Eq. A6 are those at time, τ_k; thus, these are known from the previous time step.

Equation A5 may be substituted into Eq. A4 for $i=n$ to eliminate $\theta^*_{n+1,j}$. The resulting set of equations for $i=1,2, \ldots, n$ is such that the first and last equations each have only two unknowns. The set of equations is commonly written in the form of a tridiagonal matrix equation. Algorithms to obtain numerical solutions with this set of equations are readily available. For additional details, please refer to Singh (1983) or Carnahan *et al.* (1969).

NOMENCLATURE

a = width of the meat piece (m)
A,B = constants of Eq. 7 (Pascals and Pascals/°C)
c_p = heat capacity of meat at constant pressure (J/kg °C)
h = heat transfer coefficient between air and meat (J/m²s °C)
k = thermal conductivity in the meat (J/ms °C)
k_p = mass transfer coefficient between air and meat (kg/m² Pascals s = s/m)
M_t = total moles of air and water vapor in the oven (kg-moles)
M_w = moles of water vapor in the oven (kg-moles)
N_w = molar rate of evaporation from the meat (kg moles/s)
P = total pressure in the oven (Pascals)
P_a = partial pressure of water vapor in air (Pascals)
P_s = water vapor pressure at the meat surface temperature (Pascals)
t = time (s)
T = temperature (°C)
T_a = oven temperature (°C)
T_c = center temperature of the meat piece (°C)
T_o = initial temperature of the meat piece (°C)
T_w = wet bulb temperature of the meat piece (°C)
T_s = corner surface temperature of the meat piece (°C)
Y_w = mole fraction water vapor in the gas phase in the oven
x,y,z = dimensionless space variables
X,Y,Z = space variables (m)
α = thermal diffusivity in the meat (m²/s)
Δx = dimensionless increment in the x direction
Δy = dimensionless increment in the y direction
Δt = time increment (s)
τ = dimensionless time
$\Delta\tau$ = dimensionless time increment
λ = latent heat of vaporization of water (J/kg)
ρ = density of meat (kg/m³)
θ = dimensionless temperature

Subscripts

i = represents position on the x axis
j = represents position on the y axis
k = represents position in time

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LITERATURE ABSTRACTS

TRANSACTIONS FROM THE ASAE

Factors Affecting Beef Carcass Chilling Rates. K. C. Schneider, V. E. Sweat, J. A. Arce, T. R. Dutson, P. F. Dahm. Trans. ASAE. 498.

Experimental data for chilling rates of beef carcasses were obtained in a carcass chill cooler. The chilling rates were modeled as a function of carcass weight, thickness of fat covering on the carcass, and location of the carcass within the cooler.

Criteria for Energy-efficient Packaging and Freezing of Boxed Beef. W. Moleeratanond, B. H. Ashby, A. Kramer, W. A. Bailey. Trans. ASAE. 502.

More than 70 percent of U.S. beef is distributed in corrugated boxes which act as insulation and slow the freezing rate of beef frozen after boxing. Ground beef was blast frozen at varying air temperatures and velocities in two different styles and sizes of corrugated fiberboard boxes. Maximum energy efficiency was attained when the beef was frozen at −29 °C with air velocity a 3 mps in a 508- by 406- by 127-mm full-telescope style box. Energy savings up to 48 percent were obtained by using the optimal combination of box style, freezing air temperature, and air velocity. Overall energy efficiency was increased by 7 percent when freezing meat in the full-telescope style boxes, compared to the overlap-slotted container style. Addition of handholes in the boxes decreased energy consumption for freezing the meat by 6 percent. Nomographs were developed for predicting the freezing time for ground beef under different box styles and blast freezer conditions.

Prediction of Cooling Characteristics During Air Cooling and Cylindrical Food Products with a Flowing Film of Cold Water at the Surface (Air-Film Cooling). P. M. Abdul Majeed. Trans. ASAE. 508.

Air-film cooling of perishable food products is expected to incorporate the advantages of both air cooling and hydrocooling processes. This technique consists of passing cold air over product which is continuously wetted by a spray of chilled water. An analysis which yields the time-temperature histories during cooling of cylindrical food products is presented. The ranges of parameters in which the process is most effective are identified. The cooling speed and the governing parameters are correlated.

Solvent Extraction of Carotenoids from Alfalfa. D. M. O'Day, J. R. Rosenau. Trans. ASAE. 515.

Three organic solvents are evaluated in terms of their ability to selectively extract carotenoids from alfalfa while maintaining the protein within the fiber. Extraction performance is a function of solvent polarity as it influences solvent concentration limits within the water layer of the cells and solubility of lipoidal material.

Computer-aided Selection of Dimensionless Numbers. C. Heatwole, L. A. Stauffer, M. E. Wright. Trans. ASAE. 525.

For a set of n pertinent quantities with m fundamental dimensions, of which the rank of the dimensional matrix is $r=m$, there are an infinite number of possible *sets* of dimensionless numbers (π-terms) with n-m π-terms in each set. If each π-term within each set contains a unique pertinent quantity, linear independence of the π-terms is assured and the total number of sets of π-terms is reduced to $n!/\{m!\ (n-m)!\}$. A systematic approach for determining all possible such sets of dimensionless numbers with the aid of a computer program is described. The output from the computer program allows the investigator to review these sets without making exhaustive calculations and then to choose one that best fits his experimental capabilities.

Characteristics of the Thin Rice Kernels before and after Parboiling. J. Matthews, J. I. Wadsworth, J. J. Spadaro. Trans. ASAE. 818.

Rice separated by thickness yields a thin fraction that is subject to large endosperm losses in the bran and high breakage when milled as raw rice. Parboiling this fraction improves the quality of the rice: breakage, chalkiness, and losses in the bran are eliminated. However, the thin fraction contains a high percentage of pecky (discolored) kernels. For the rice lots examined the average loss from pecky kernels approximated the average losses found in raw milling. In general, an increase in edible rice would not be obtained by parboiling the thin fraction.

Conversion of Tomato, Peach and Honeydew Solid Waste into Methane Gas. D. J. Hills, D. W. Roberts. Trans. ASAE. 820.

Methane production by anaerobic digestion of tomato, honeydew and peach solid wastes was investigated. Results from a two-year laboratory investigation and seasonal operation of a pilot plant size digester are presented. For 4L laboratory digesters operating at 35 °C the following loading rates and retention times were found to be optimal for tomato, honeydew and peach residues, respectively: 5, 3, and 1 kg VS/$m^3 \cdot d$ and 25, 20, and 15 d. Under these operating conditions 33 percent, 83 percent and 86 percent of the volatile solids were destroyed for tomato, honeydew and peach residues, respectively, and the corresponding gas productions, corrected to STP, were 0.43, 2.45, and 1.15 vol/digester vol/day. On a conversion efficiency basis these values relate to 0.14, 0.81, and 1.15 m^3/kg VS loaded, respectively. Operation of the 22 m^3 pilot plant generally confirmed the laboratory data for tomato solid waste.

A Finite Element Model for Prediction of Freezing Rates in Food Products with Anomalous Shapes. H. K. Purwadaria, D. R. Heldman. Trans. ASAE. 827.

A finite element simulation model to predict temperature histories for food products with elliptical and trapezoidal shapes has been developed. The validity of the model has been verified using experiemtnal freezing tests. The results illustrate improvements in agreement between predicted and experimental results achieved by using a variable local surface heat transfer coefficient in the prediction model.

Corn Dry Milling as Influenced by Harvest and Drying Conditions. A. J. Peplinski, R. A. Anderson, O. L. Brekke. Trans. ASAE. 827.

Sublots from a single variety of corn were harvested with moisture contents ranging from 17 to 32 percent, and with the picker-sheller set to yield shelled grain with high or low damage. Each sublot was then dried to 11 to 14 percent moisture at air temperatures ranging from -1 to 150 °C. Yields of prime products (low-fat grits and meal) from the dry milling of the lots increased and germ (source of corn oil) fraction yield decreased as corn drying temperatures were lowered. Fat content of prime products showed no trend, while fat in the germ increased with lowering drying temperatures. Harvest moisture content and picker-sheller damage had minimal effect on product yields or on fat content. Recoverable oil was lowered by drying at 150 °C. The variables studied produced minimal effects on the brewers extract determination, which is a guide to the amount of carbohydrate in the product available for enzymatic conversion to sugars. The data indicate that corn harvested at 25 percent or less moisture and dried at 82 °C or lower air temperatures will yield optimum dry milling results with respect to product recovery and quality.

This research is the first to show the effect of harvest moisture and sheller damage on the dry milling of corn, and it corroborates the effects of excessive drying temperatures on products obtained from dry milling.

The Thermal Conductivity of Beef as Affected by Temperature and Composition. M. S. Baghe-Khandan, M. R. Okos, V. E. Sweat. Trans. ASAE. 1118.

Thermal conductivity was determined for eleven beef samples ranging in composition from 43.9 to 77.5 percent moisture, 3.1 to 28.1 percent fat and 17.0 to 37.1 percent protein. The collected data was used to determine a mathematical correlation between beef thermal conductivity and product composition over the temperature range of 30 to 90 °C.

Telemetry System for Monitoring the Commercial Egg Industry. J. A. Dickens, R. E. Vaughn. Trans. ASAE. 1123.

An electronic egg was designed and built to monitor impact forces exerted on commercial eggs during handling operations. The egg consisted of a clear acrylic body with a miniature piezoelectric tranducer and a miniature radio transmitter. As the electronic egg moves through the handling equipment, all impact forces are monitored and recorded. Using the electronic egg, egg breakage could be significantly reduced; therefore increasing profits for the packer or producer and possible reducing the cost to the consumer.

Moisture Content Variation in Freshly Harvested Rice Associated with Kernel Thickness. J. I. Wadsworth, J. Matthews, J. J. Spadaro. Trans. ASAE. 1127.

Samples of freshly harvested rough rice were each separated into fractions according to the thickness of the kernels. Average moisture content decreased with increasing kernel thickness and the greatest moisture content variation was associated with the thinner kernels that comprised 5 to 10 percent of the sample. Rice grown with higher nitrogen (N) application rates had higher percentages of thin kernels, higher average moisture contents, and greater variations in moisture content than rice grown with lower N levels. During a heavy rain thick kernels absorbed more moisture than thin ones. Mechanical separation by kernel thickness was an effective means of dividing a mass of freshly harvested rice into fractions with different moisture contents.

Thermal Conductivity of Defatted Soy Flour. K. Wallapapan, V. E. Sweat. Trans. ASAE. 1440.

Thermal conductivity of defatted soy flour was measured with a line heat source probe at room temperature for moisture contents ranging from 4 to 32 percent and bulk mass density from 330 to 710 kg/m^3. Thermal conductivity varied from 0.03 to 0.09 W/m-°C.

Agitating Processes of Canned Citrus Slices. H. W. Adams. Trans. ASAE. 1445.

Cans containing grapefruit sections and orange slices in syrup were processed in rotary pressure cooker. Heat penetration data collected enabled a short process to be run. Innoculated packs need to be run to verify processes.

Cleaning Poultry Fat from Stainless Steel Flat Plates. W. L. Shupe, J. S. Bailey, W. K. Whitehead, J. E. Thomson. Trans. ASAE. 1446.

A fixture used to test cleaning of flat stainless steel plates with spray nozzles was constructed. Tests run included: (a) nozzle impact force measurements, (b) microbiological cleaning, and (c) gravimetric determination of fat removal. Bacteria counts on stainless steel plates were not significantly different when washing pressure was at 690, 2068 or 4137 kPa. Washing with 50 or 70 °C water removed significantly more bacteria than washing with 20 °C water, with or without detergent. Fat removal was not significantly different at various water pressures or temperatures when detergent was used. When detergent was not applied, fat removal was signifcatnly lower with 690 kPa than either 2068 or 4137 kPa and lower with 20 °C water than either 50 or 70 °C.

Parboiled Rice Quality as Affected by the Level and Distribution of Moisture after the Soaking Process. Trans. ASAE. 1450.

A study of the soaking process in rice parboiling was conducted to evaluate the effects of level and distribution of moisture after soaking on grain quality. Saturn variety medium grain rice was subjected to different soaking times with and without pressure, steaming times, and periods of partial equilibration after soaking. The parboiled rice was processed and analyzed for yields, translucency and color. Photomicrographic examinations were also performed.

Grain moisture levels as low as 23.5 percent (wet basis) after soaking were found adequate to obtain high head yields. Pressure soaking considerably reduced soaking times, and the partial equilibration of the grains after the soaking stage was observed to improve the percent whole grain, grain translucency and decrease deformity, while increasing the color of the product. Photomicrographs illustrated the grain structure.

Citrus Evaporator Technology. C. S. Chen. Trans. ASAE. 1457.

The HTST evaporators account for 91% of the 1.6 million kg/h evaporating capacity in the citrus industry in Florida. The characteristics of various evaporators as they apply to citrus juices concentration are described. As much as 23 percent energy savings are demonstrated for an efficient design.

A Comparison of Microwave, Air Oven and Moisture Meters with the Standard Method for Rough Rice Moisture Determination. Trans. ASAE. 1464.

A comparative study of moisture of rough rice using a microwave oven, air oven and four electrical meters was conducted with reference to the standard AOAC method. Four electrical moisture meters were included in this study. Two were of resitance type and the other two of capacitance type. In the microwave and air oven methods, whole grain as well as ground samples were tested. The range of moisture for the long grain Labelle variety of rice used in the study was 10 to 18 percent (w.b.) The results showed that the microwave method of moisture measurement (for ground samples) agreed closely with the standard AOAC technique, the air oven method (for whole grain sample) showed the most deviation.

Models for the Rheology and Statistical Strength of Uniformly Stressed Vegetative Tissue. Trans. ASAE. 1776.

The first part of this paper is a literature review of the important features of plant vegetative tissue that relate to its rheological and strength properties. Several internal mechanisms by which an applied load is resisted are described, and two internal mechanisms of failure initiation are discussed. Second, a simple elastic mechanics model is developed for the cellular structure under a uniform load, and results are obtained which give a qualitative relation between applied external stresses and strains, cell wall stresses, and cell turgidity. Third, a description of the statistical failure process in uniformly stressed samples is postulated, and a probability model is developed for the initiation of this failure process. The theoretical development leads to the use of the Weibull distribution to describe the yield strength of tissues exhibiting a sharp reduction in stress at yielding. Experimental data for apple and potato samples show the Weibull model to be adequate statistically. The Weibull model is a useful tool for predicting the amount of damaged tissue under a known applied stress.

Vibration Sorting of Simulated Small Fruit. J. G. Montegano-Gaitan, D. D. Hamann, F. G. Giesbrecht. Trans. ASAE. 1785.

Small spheres and/or flat belts were formed from 16 polymer materials. The spheres were sorted by being carried on a flat belt over a vibrating metal surface so the vibration passed through the belt to the spheres causing them to bounce over a barrier. It was concluded that specifying the Young's modulus and loss tangent (energy damping) of the vibrating surface (belt) was an effective means of improving sorting compared to using the same specifications for all applications.

Rheological, Chemical and Textural Characteristics of Sweet Potato Flakes. V. N. M. Rao, L. R. Graham. Trans. ASAE. 1792.

Cultivars of sweet potatoes were pureed and subjected to rheological and chemical testing and the bulk of each batch was dehydrated using a double drum dryer. Rehydrated flakes were evaluated by a taste panel. Taste panel descriptors were significantly correlated to rheological parameters and acid detergent fiber of the puree before dehydration.

Raoult's Law, Water Activity and Moisture Availability in Solutions. (1983) M. Caurie. J. Food Sci. *48,* 648–649.

A rationalization of Raoult's law has led to the conclusion that water activity (a_w) is a joint solution property of vapor pressure solute and solvent concentrations. It is shown from this that a_w is not a measure of the absolute value of the mole fraction of water as indicated by Raoult's law but a measure of only a fraction of the mole fraction of water remaining free in solution available and unbound to solute molecules. The law is shown to overestimate this water activity (a_w) at all dilutions by an amount equal to the product of the mole fraction of solute and the lowered relative vapor pressure the solute generates in solution.

Thermal Properties of Beef Loaf Produced in Foodservice Systems. L. M. McProud, D. B. Lund. (1983) J. Food Sci. *48,* 677–680.

There is a lack of information on thermal and other properties of foods, especially food mixtures. Physical properties of beef loaf prepared following formula and procedures used in alternate foodservice systems were determined: heat capacity (0.88 cal/g °C uncooked, 0.91 heated to 60 °C), moisture content (72.1% uncooked, 66.2% heated), thermal conductivity (0.40 w/cm °C uncooked, 0.47 heated), fat (17.6% uncooked, 13.0% heated) and density (1.00 g/cm^3 uncooked and 0.70 heated). The surface heat transfer coefficient for a forced convection oven was also determined (62 w/m^2 °C). Times to heat beef loaves to specified ending temperatures in a forced convection oven at 163° C and 176 °C were calculated. There was less than 1 min difference in calculated heating time required to reach the desired end temperature. The actual times to reach ending temperature show very good agreement with the calculated times.

Flow Characteristics of Soybean Constituents Controlled by Ratio of Total to Imbibed Water. (1983) G. E. Urbanski, L. S. Wei, A. J. Nelson, M. P. Steinberg. J. Food Sci. *48,* 691–694.

The objective was to quantify the relationship between water imbibing capacity of soybean components and their rheological characteristics in suspension. These components were: full fat soy flour, desludged full fat soy flour, defatted soy flour, soybean cell wall material and soybean sodium proteinate. It was found that the relationship between the ratio of the total to imbibed water (T/I) and consistency coefficient for all components at all concentrations could be expressed by a single curve. Flow behavior index vs T/I for all components also showed a single curve. A plot of apparent viscosity against T/I at the maximum shear rate showed that the data for all components at all concentrations fell on the same curve at a given shear rate.

Effect of Water Activity and Moisture Content on the Stability of Beet Powder Pigments. (1983) E. Chen, I. Saguy. J. Food Sci. *48,* 703–707.

The effect of water activity (''dry'' –0.84) and moisture content on the stability of beet pigments (betanine and vulgaxanthine I) was investigated in beet powder stored at 35 °C. Pigment deterioration followed a first order reaction. Water activity and moisture content had a pronounced exponential effect on pigment stability. A decrease of approximately one order of magnitude in pigment stability was observed when a_w was increased from 0.32 to 0.75. Storing the powder at a_w of 0.121 or below resulted in practically no deterioration of the pigments over a period of several months. Profound differences in pigment stability were attributed to sorption hysteresis and system composition.

Kinetics of Oxidation of Potato Chips Under Constant Temperature and Sine Wave Temperature Conditions. (1983) T. P. Labuza, S. Bergquist. J. Food Sci. *48,* 712–715 + 721.

Lipid oxidation in potato chips at 30, 37 and 45 °C followed zero order kinetics as measured by peroxide value (PV). An Arrhenius plot of log k versus $(T\,°K)^{-1}$ showed slight underprediction at low temperatures. Data from constant conditions were used to predict the extent of this free radical reaction under a sine wave temperature fluctuation (25/45 °C with a 24 hr period). Predictions of effective rate constant, temperature and extent were found to agree to within 3.5% of the actual results up to a PV of 7 where bimolecular oxidation occurred. The sine wave condition entered the bimolecular oxidation sooner than was observed under steady data for the same effective temperature.

Experimental Verification of a Heat Transfer Model for Simulated Liquid Foods Undergoing Flame Sterilization. (1983) LR. D. Peralta Rodriguez, R. L. Merson. J. Food Sci. *48,* 726–733.

Four silicone oils with viscosities ranging from 0.0023 Pa-s to 0.3385 Pa-s were used as model liquid foods to measure the heating rates in a specially-designed single-can flame sterilizer. A previously-developed mathematical heat transfer model was experimentally tested with respect to the effect of liquid viscosity, can rotation, combustion gases crossflow velocity, and can-burner separation. For all the cases studied, order of magnitude agreement was obtained between experimentally measured and predicted heating rates, with experimental values ranging from 0.16 °C/s to 0.52 °C/s.

Dynamic Optimization of Dehydration Processes: Minimizing Browning in Dehydration of Potatoes. (1983) M. Mishkin, I. Saguy, M. Karel. J. Food Sci. *48,* 1617–1621.

A simulation-optimization procedure based on the complex method was used to determine optimal drying schemes for minimizing browning during dehydration of white potatoes. Browning kinetics were obtained from the literature, and the heat and mass transfer characteristics in the potatoes were based on experimental data obtained previously. The optimal dryer temperature control path reduced the temperature while the sample disk moisture content was in the range 0.1-0.2 g/g-solids, where the browning rate is maximal. Excellent agreement was obtained between optimal dryer temperatures based on local moisture and those based on average moisture contents.

Clarification of Pear Juice by Hollow Fiber Ultrafiltration. (1983) D. E. Kirk, M. W. Montgomery, M. G. Kortekaas. J. Food Sci. *48,* 1663–1666.

Hollow fiber ultrafiltration was successfully applied to obtain a clear, amber-colored pear juice. For the three hollow fiber membrane cartridges tested (50,000, 30,000 and 10,000 dalton molecular weight cut-off), the proceess parameters were optimized and found to be similar. The permeate flux increased with increased transmembrane pressure and then declined. Flux reached a maximum at an average transmembrane pressure of 157 kPa with an average feed stream velocity of 0.25 meters/sec at 50 °C. Higher flux was obtained at higher temperatures within the temperature limitations of the membrane. Flux decreased linearly with the logarithm of the concentration.

Water Activity and Freezing Point Depression of Aqueous Solutions and Liquid Foods. (1983) C. R. Lerici, M. Piva, M. Dalla Rosa. J. Food Sci. *48,* 1667–1669.

Water activity (a_w) of binary aqueous solutions and liquid foods (skim milk, coffee beverages, peach and tomato juices) at different total solids concentration (by wt) was evaluated, measuring freezing point depression (FPD). The calculated values differed from those obtained by electric hygrometer by less than 0.01 a_w units. Water activity was also evaluated in model systems containing ethanol, for which a_w determination by conventional electric hygrometer is not possible.

Continuous Lactose Hydrolysis in Fixed-bed and Expanded-bed Reactors Containing Catalytic Resins. (1983) H. C. Chen, R. R. Zall. J. Food Sci. *48,* 1741–1744 + 1757.

Kinetics studies of lactose hyrolysis in a continuous fixed-bed column reactor containing catalytic resins showed that the reaction was first order. The Q_{10} value between 85 and 95 °C was 4.08 and estimated activation energy was 36.90 Kcal/mole. Operational difficulties occurred when deproteinated whey was used as the substrate for the above process. Therefore, an expanded-bed process was developed to hydrolyze deproteinated whey. Acid was also added to the deproteinated whey to enhance the functionality of catalytic resin. The modified process improved reaction rate and facilitated process operation. At 95 °C, 99% of the lactose in whey was hydrolyzed within 3 hr of residence time when the substrate was acidified with concentrated nitric acid to a final acid concentration of 0.6N.

Thermal Conductivity of Frozen Beef Liver. (1983) M. Barrera, N. E. Zaritzky. J. Food Sci. *48,* 1779–1782.

The thermal conductivity of frozen beef liver has been determined, using a transient method. Since phase change in liver takes place within a wide temperature range, there are limitations of the application of the probe method which has been developed for a system without phase change. For that reason, the experiments have been performed setting limited values for the operational parameters (maximum heating power and measurement time range) in order to minimize errors of measurements. Thermal conductivty data were expressed as a function of temperature and a mathematical model based on Maxwell Eucken's equation has been included for the interpretation of the results.

Effect of Locust Bean Gum and Selected Sweetening Agents on Ice Recrystallization Rates. (1983) E. K. Harper, C. F. Shoemaker. J. Food Sci. *48,* 1081–1803 + 1806.

A methodology has been devised to study the effects of sweeteners and a stabilizer on the rate of ice recrystallization. Aqueous solutions of sucrose, corn syrup (62 DE), and high fructose corn syrup with locust bean gum, and solutions of corn syrup with varying levels of locust bean gum were also studied. Microprocessor controlled time-temperature experiments were performed with each sample. Average ice crystal size was measured after each heating/cooling cycle. Effect of viscosity on ice recrystallization growth rates was also studied. This methodology is an improved technique for providing temperature control during fluctuating temperature studies. Concentration of locust bean gum showed no correlation to ice recrystallization rates. The choice of sweetener used in the aqueous solution was found to affect the rate of ice recrystallization.

F N P

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HASSON, E. P. and LATIES, G. G. 1976. Separation and characterization of potato lipid acylhydrolases. Plant Physiol. *57,* 142–147.

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