FOOD FREEZING TIMES AND HEAT TRANSFER COEFFICIENTS

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Abstract

The freezing of food is the most significant application of refrigeration. In order for freezing operations to be cost-effective, it is necessary to optimally design the refrigeration equipment. This requires estimation of the freezing times of foods and the corresponding refrigeration loads. These estimates, in turn, depend upon the surface heat transfer coefficient for the freezing operation.

This paper describes the thermodynamics of food freezing and reviews basic freezing time estimation methods. It also describes a study which was initiated to resolve deficiencies in heat transfer coefficient data for food freezing processes. Members of the food refrigeration industry were contacted to collect freezing curves and surface heat transfer data. A unique iterative algorithm was developed to estimate the surface heat transfer coefficients of foods based upon their freezing curves. Making use of this algorithm, heat transfer coefficients for various food items were calculated from the freezing curves collected during the industrial survey.

The algorithm described in this paper was developed and used in a recent ASHRAE research project to generate over 800 heat transfer coefficients which will appear in future additions of the ASHRAE Refrigeration Handbook. These heat transfer coefficients can then be used with the freezing time estimation methods mentioned in this paper and detailed in the ASHRAE Refrigeration Handbook to achieve efficient design of food freezing equipment.

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Nomenclature

A	surface area
A_n	n[th] term in heat transfer equation solution
Bi	Biot number
B_n	n[th] term in heat transfer equation solution
c	specific heat capacity
C	slope of cooling curve
C_l	volumetric heat capacity for the unfrozen phase
C_s	volumetric heat capacity for the frozen phase
d	smallest dimension
D	characteristic dimension
E	equivalent heat transfer dimensionality
f	cooling parameter
h	heat transfer coefficient
H	volumetric enthalpy
j	cooling parameter
k	thermal conductivity
k_m	thermal conductivity of cooling medium
k_s	thermal conductivity of frozen phase
L_f	volumetric latent heat of fusion
m	mass
Nu	Nusselt number
P	geometric factor
Pk	Plank number
q	heat transfer rate
R	geometric factor
Re	Reynolds number
Ste	Stefan number
t	temperature
t_1	temperature at time q_1
t_2	temperature at time q_2
t_i	initial temperature
t_f	initial freezing temperature
t_m	cooling/freezing medium temperature
t_s	surface temperature
U	cooling medium velocity
Y	fractional unaccomplished temperature difference
Z	characteristic dimension

DH_{10}	volumetric enthalpy difference
q	time
q_1	precooling time
q_2	phase change time
q_3	subcooling time
m_m	dynamic viscosity of the cooling medium
r	density
r_m	density of cooling medium
w	first root of transcendental Equation (17)

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Introduction

Preservation of food is one of the most significant applications of refrigeration. It is known that the freezing of food effectively reduces the activity of micro-organisms and enzymes, thus retarding deterioration. In addition, crystallization of water reduces the amount of liquid water in food items and inhibits microbial growth (Heldman, 1975).

In order for food freezing operations to be cost-effective, it is necessary to optimally design the refrigeration equipment to fit the specific requirements of the particular freezing application. The design of such refrigeration equipment requires estimation of the freezing times of foods, as well as the corresponding refrigeration loads.

Numerous methods for predicting food freezing times have been proposed. The designer is thus faced with the challenge of selecting an appropriate estimation method from the plethora of available methods. Therefore, this paper reviews basic freezing time estimation methods which are applicable to regularly shaped food items.

In addition, knowledge of the surface heat transfer coefficient is required in order to utilize these freezing time estimation methods. A small number of studies have been performed to measure or estimate the surface heat transfer coefficient during cooling, freezing or heating of food items for only a very limited number of food items and process conditions. Thus, there was clearly a need to expand upon the previous work by developing a comprehensive database of heat transfer coefficients for a wide range of food items and process conditions. Hence, a unique iterative algorithm was developed to estimate the surface heat transfer coefficients of foods based upon their freezing curves. Making use of this algorithm, heat transfer coefficients for various food items were calculated from the freezing curves collected during an industrial survey.

Thermodynamics of the Freezing Process

The freezing of food is a complex process. Prior to freezing, sensible heat must be removed from the food to decrease its temperature from the initial temperature to the initial freezing point of the food. This initial freezing point is somewhat lower than the freezing point of pure water due to dissolved substances in the moisture within the food. At the initial freezing point, a portion of the water within the food crystallizes and the remaining solution becomes more concentrated. Thus, the freezing point of the unfrozen portion of the food is further reduced. As the temperature continues to decrease, the formation of ice crystals increases the concentration of the solutes in solution and depresses the freezing point further. Thus, it is evident that during the freezing process, the ice and water fractions in the frozen food depend upon temperature. Since the thermophysical properties of ice and liquid water are quite different, the corresponding properties of the frozen food are temperature dependent. Therefore, due to these complexities, it is not possible to derive exact analytical solutions for the freezing times of foods.

Numerical estimates of food freezing times can be obtained using appropriate finite element or finite difference computer programs. However, the effort required to perform this task makes it impractical for the design engineer. In addition, two-dimensional and three-dimensional simulations require time consuming data preparation and significant computing time. Hence, the majority of the research effort to date has been in the development of semi-analytical/empirical food freezing time prediction methods which make use of simplifying assumptions.

These semi-analytical/empirical freezing time prediction methods fall into two main categories. Methods in the first category, discussed in this paper, are applicable to food items which have the following regular shapes:

1. Infinite Slabs.
2. Infinite Circular Cylinders.
3. Spheres.

Methods in the second category are applicable to food items which have irregular shapes. These methods require a two-step procedure in which the freezing time is first estimated by using one of the methods applicable to regularly shaped food items. Thus, freezing time estimation for both regularly and irregularly shaped food items requires the use of the methods described in this paper.

Freezing Time Estimation Methods

In the following discussion, the basic freezing time estimation method developed by Plank is discussed first, followed by a discussion of those methods which are based upon modifications of Plank's equation. The discussion then focuses upon those methods in which the freezing time is calculated as the sum of the precooling, phase change and subcooling times.

Plank's Equation

The most widely known basic method for estimating the freezing times of foods is that developed by Plank (1913, 1941). In this method, it is assumed that only convective heat transfer occurs between the food item and the surrounding cooling medium. In addition, it is assumed that the temperature of the food item is its initial freezing temperature and that this temperature is constant throughout the freezing process. Furthermore, a constant thermal conductivity for the frozen region is assumed. Plank's freezing time estimation method is given as follows:

$$q = \frac{L_f}{t_f - t_m}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right] \tag{1}$$

- q is the freezing time
- L_f is the volumetric latent heat of fusion
- t_f is the initial freezing temperature of the food
- t_m is the freezing medium temperature
- D is the thickness of the slab or the diameter of the sphere or infinite cylinder
- h is the surface heat transfer coefficient
- k_s is the thermal conductivity of the fully frozen food
- P and R are geometric factors

For the infinite slab, $P = ½$ and $R = 1/8$. For a sphere, P and R are 1/6 and 1/24, respectively, and for an infinite cylinder, $P = 1/4$ and $R = 1/16$.

The geometric factors, P and R, provide insight as to the effect of shape upon freezing time. Plank's shape factors indicate that an infinite slab of thickness D, an infinite cylinder of diameter D and a sphere of diameter D, if exposed to the same conditions, would have freezing times in the ratio of 6:3:2. Hence, a cylinder will freeze in half the time of a slab and a sphere will freeze in one-third the time of a slab.

Various researchers have noted that Plank's method does not accurately predict the freezing times of foods. This is due, in part, to the fact that Plank's method assumes that food freezing takes place at a constant temperature, and not over a range of temperatures as is the case in actual food freezing processes. In addition, the thermal conductivity of the frozen food is assumed to be constant, but in reality, the thermal conductivity varies greatly during freezing. Another limitation of Plank's equation is that it neglects the removal of sensible heat above the freezing point. However, Plank's method does have the advantage of being a simple model for predicting food freezing time. Subsequently, researchers have focused upon development of improved semi-analytical/empirical cooling and freezing time estimation methods which account for precooling and subcooling times, non-constant thermal properties, and phase change over a range of temperatures.

Modifications to Plank's Equation

Cleland and Earle (1977, 1979) improved upon Plank's model by incorporating corrections to account for the removal of sensible heat both above and below the initial freezing point of the food as well as temperature variation during freezing. Regression equations were developed to estimate the geometric parameters, P and R, for infinite slabs, infinite cylinders and spheres. In these regression equations, the effects of surface heat transfer, precooling and final subcooling are accounted for by means of the Biot number, Bi, the Plank number, Pk, and the Stefan number, Ste, respectively.

The Biot number, *Bi*, is defined as follows:

$$Bi = \frac{hD}{k} \tag{2}$$

In the literature on food freezing, it is accepted that the characteristic dimension, *D*, is defined to be twice the shortest distance from the thermal center of a food item to its surface. For an infinite slab, *D* is the thickness. For an infinite cylinder or a sphere, *D* is the diameter.

In general, the Plank number, *Pk*, is defined as follows:

$$Pk = \frac{C_l \left(t_i - t_f\right)}{\Delta H} \tag{3}$$

where C_l is the volumetric heat capacity of the unfrozen phase, t_i is the initial temperature of the food and *?H* is the volumetric enthalpy change of the food between t_f and the final food temperature. The Stefan number, *Ste*, is similarly defined as follows:

$$Ste = \frac{C_s \left(t_f - t_m\right)}{\Delta H} \tag{4}$$

where C_s is the volumetric heat capacity of the frozen phase.

In the method of Cleland and Earle (1977, 1979), food freezing times are calculated with a modified version of Plank's equation. Plank's original geometric factors, *P* and *R*, are replaced with the modified values given in Table 1, and the latent heat, L_f, in Plank's equation is replaced with the volumetric enthalpy change of the food, *?H*$_{10}$, between the freezing temperature, t_f, and the final center temperature, assumed to be -10°C. As shown in Table 1, the geometric factors *P* and *R* are functions of the Plank number, *Pk*, and the Stefan number, *Ste*. Both of these parameters should be evaluated using the enthalpy change *?H*$_{10}$. Thus, the modified Plank equation takes the following form:

$$q = \frac{\Delta H_{10}}{t_f - t_m}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right] \tag{5}$$

Precooling, Phase Change and Subcooling Time Calculations

Numerous researchers have taken a different approach to account for the effects of sensible heat removal above and below the initial freezing point. In these methods, the total freezing time, *q*, is the sum of the precooling, phase change and subcooling times:

$$q = q_1 + q_2 + q_3 \tag{6}$$

where q_1, q_2 and q_3 are the precooling, phase change and subcooling times, respectively.

Pham (1984) devised a food freezing time estimation method, similar to Plank's equation, in which sensible heat effects are considered by calculating precooling, phase change and subcooling times separately. In addition, Pham suggested the use of a mean freezing point, which is assumed to be 1.5 K below the initial freezing point of the food, to account for freezing which takes place over a range of temperatures. Pham's freezing time estimation method is stated in terms of the volume and surface area of the food item and is therefore applicable to food items of any shape. This method is given as:

$$q_i = \frac{Q_i}{hA_s \Delta t_{mi}} \left(1 + \frac{Bi_i}{k_i} \right) \quad ; \quad i = 1, 2, 3 \tag{7}$$

where q_1 is the precooling time, q_2 is the phase change time and q_3 is the subcooling time with the remaining variables defined as shown in Table 2.

Heat Transfer Coefficients

In many food processing applications, including cooling and freezing, transient convective heat transfer occurs between a fluid medium and the solid food item (Dincer 1993). Knowledge of the surface heat transfer coefficient is required in order to design equipment in which convection heat transfer is used to process foods and beverages. In addition, the calculation of food freezing times using the prediction methods described above requires the convection heat transfer coefficient.

Newton's law of cooling defines the surface heat transfer coefficient, h, as follows:

$$q = hA(t_s - t_m) \tag{8}$$

- q is the heat transfer rate
- t_s is the surface temperature of the food
- t_m is the surrounding fluid temperature
- A is the surface area of the food through which the heat transfer occurs

A small number of studies have been performed to measure or estimate the surface heat transfer coefficient during cooling, freezing or heating of food items (Alhamdan et al. 1990; Ansari 1987; Chen et al. 1997; Clary et al. 1968; Cleland and Earle 1976; Daudin and Swain 1990; Dincer 1991; Dincer et al. 1992; Dincer 1993, 1994a, 1994b, 1994c; Dincer and Genceli 1994; Dincer 1995a, 1995b, 1995c, 1995d; Dincer and Genceli 1995a, 1995b; Dincer 1996; Dincer and Dost 1996; Dincer 1997; Flores and Mascheroni 1988; Frederick and Comunian 1994; Khairullah and Singh 1991; Kondjoyan and Daudin 1997; Kopelman et al. 1966; Mankad et al. 1997; Smith et al. 1971; Stewart et al. 1990; Vazquez and Calvelo 1980, 1983; Verboven et al. 1997; Zuritz et al. 1990) In addition, a detailed literature survey has been compiled by Arce and Sweat (1980). These studies present surface heat transfer coefficient data and correlations for only a very limited number of food items and process conditions.

Thus, there is clearly a need to expand upon the previous work by developing a comprehensive database of heat transfer coefficients for a wide range of food items and process conditions. Hence, the objective of this study was to determine the surface heat transfer coefficients for a wide variety of foods during cooling and freezing processes.

Review of Existing Techniques to Determine the Surface Heat Transfer Coefficients of Foods

Techniques used to determine heat transfer coefficients generally fall into three categories: steady-state temperature measurement methods, transient temperature measurement methods and surface heat flux measurement methods. Of these three techniques, the most popular methods are the transient temperature measurement techniques.

Transient methods for determining the surface heat transfer coefficient involve the measurement of product temperature with respect to time during cooling or freezing processes. Two cases must be considered when performing transient tests to determine the surface heat transfer coefficient: low Biot number ($Bi \leq 0.1$) and large Biot number ($Bi > 0.1$). The Biot number, *Bi*, defined in Equation (2), is the ratio of external heat transfer resistance to internal heat transfer resistance. A low Biot number indicates that the internal resistance to heat transfer is negligible, and thus, the temperature within the object is uniform at any given instant in time. A large Biot number indicates that the internal resistance to heat transfer is not negligible, and thus, a temperature gradient may exist within the object.

Low Biot Number

Consider a food item with high thermal conductivity (negligible internal resistance to heat transfer) which is subjected to air flow at a constant, colder temperature. Then, during the time interval *dq*,

$$mcdt = h(t - t_m)Adq \tag{9}$$

where *t* is the uniform temperature of the food item, *m* is the mass of the food item and *c* is the specific heat capacity of the food item. By integrating over the time interval, *Dq*, the transient method for determining the heat transfer coefficient may be obtained:

$$h = \frac{mc}{A\Delta q}\ln\left(\frac{t_1 - t_m}{t_2 - t_m}\right) \tag{10}$$

where t_1 and t_2 are the temperatures of the food item at the beginning and end of the time interval, *Dq*, respectively.

Large Biot Number

One method for obtaining the surface heat transfer coefficient of a food product with an internal temperature gradient involves the use of cooling curves. For simple, one-dimensional food geometries such as infinite slabs, infinite circular cylinders or spheres, there exists empirical and analytical solutions to the one-dimensional transient heat equation. The slope of the cooling curve may be used in conjunction with these solutions to obtain the Biot number for the cooling process. The heat transfer coefficient may then be determined from the Biot number.

All cooling processes exhibit similar behavior. After an initial "lag", the temperature at the thermal center of the food item decreases exponentially (Cleland 1990). As shown in Figure 1, a cooling curve depicting this behavior can be obtained by plotting, on semilogarithmic axes, the fractional unaccomplished temperature difference versus time. The fractional unaccomplished temperature difference, Y, is defined as follows:

$$Y = \frac{t_m - t}{t_m - t_i} = \frac{t - t_m}{t_i - t_m} \tag{11}$$

where t_m is the cooling medium temperature, t is the product temperature and t_i is the initial temperature of the product.

This semilogarithmic temperature history curve consists of one initial curvilinear portion, followed by one or more linear portions. Simple empirical formulae, which model this cooling behavior, have been proposed for estimating the cooling time of foods. These models incorporate two factors, f and j, which represent the slope and intercept, respectively, of the temperature history curve.

The j factor is a measure of the "lag" between the onset of cooling and the exponential decrease in the temperature of the food. The f factor represents the time required to obtain a 90% reduction in the non-dimensional temperature difference. Graphically, the f factor corresponds to the time required for the linear portion of the temperature history curve to pass through one log cycle. The f factor is a function of the Biot number while the j factor is a function of the Biot number and the location within the food item.

The general form of the cooling time model is then:

$$Y = \frac{t_m - t}{t_m - t_i} = je^{-2.303q/f} \tag{12}$$

In addition, the slope of the linear portion of the cooling curve, C, can be written in terms of the f factor:

$$C = \frac{2.303}{f} \tag{13}$$

For simple geometrical shapes, such as infinite slabs, infinite circular cylinders and spheres, the simple empirical cooling time model given by Equation (12) can be derived analytically, and thus, analytical expressions can be derived for the f and j factors. To derive these expressions, the following assumptions are made: 1) The thermophysical properties of the food item and the cooling medium are constant, 2) The internal heat generation and moisture loss from the food item are neglected, 3) The food item is homogeneous and isotropic, 4) The initial temperature distribution within the food item is uniform, 5) Heat conduction occurs only in one dimension, and 6) Convective heat transfer occurs between the surface of the food item and the cooling medium. With these assumptions, the solution of the one-dimensional transient heat equation may be written as an infinite series (Carslaw and Jaeger 1980):

$$Y = \sum_{n=1}^{\infty} A_n B_n \tag{14}$$

After the initial "lag" period has passed, the second and higher terms of Equation (14) are assumed to be negligible (Dincer and Dost 1996). Thus, Equation (14) can be simplified as follows:

$$Y = A_1 B_1 \tag{15}$$

Finally, the surface heat transfer coefficient, h, may be obtained from Equations (12) and (15).

Iterative Technique for Determine Heat Transfer Coefficients of Irregularly Shaped Food Items

Existing techniques to determine the heat transfer coefficient are strictly applicable to only regularly shaped food items. Therefore, a unique iterative method was developed to handle irregularly shaped food items. This method utilizes a shape factor called the "equivalent heat transfer dimensionality," developed by Cleland and Earle (1982), to extend the applicability of Dincer's techniques to irregularly shaped food items.

The "equivalent heat transfer dimensionality" compares the total heat transfer to the heat transfer through the shortest dimension. Cleland and Earle (1982) developed an expression, which requires the use of a nomograph, for estimating the equivalent heat transfer dimensionality of irregularly shaped food items as a function of Biot number. Lin et al. (1993, 1996a, 1996b) expanded upon the work of Cleland and Earle (1982) to eliminate the need for a nomograph.

In the method of Lin et al. (1993, 1996a, 1996b), the cooling time of a food is estimated by a first term approximation to the analytical solution for convective cooling of a sphere:

$$q = \frac{3 r c Z^2}{w^2 k E} \ln\left(\frac{j}{Y}\right) \tag{16}$$

where r is the density of the food, E is the equivalent heat transfer dimensionality and w is the first root of the following transcendental function:

$$w \cot w + Bi - 1 = 0 \tag{17}$$

For infinite slabs, Z is equal to the half thickness of the slab. For infinite cylinders and spheres, Z is equal to the radius of the cylinder or sphere.

An iterative algorithm, based upon the slope of the cooling curve and Equations (16) and (17), was developed to calculate the Biot number. The heat transfer coefficient can then be calculated from the definition of the Biot number, Equation (2).

Cooling and Freezing Curves

Members of the food refrigeration industry were contacted to collect cooling and freezing curves and surface heat transfer data for various food items. A typical cooling/freezing curve is shown in Figure 2. These collected cooling and freezing curves were digitized and a database was developed which contains the digitized time-temperature data obtained from these curves. The temperatures were non-dimensionalized according to Equation (11) and the natural logarithm of these non-dimensional temperatures were taken. The slopes of the linear portion(s) of the logarithmic temperature versus time data were determined using the linear least-squares-fit technique. These slopes were then used in conjunction with the techniques described in the previous section to determine the heat transfer coefficients for the food items.

Calculated Heat Transfer Coefficients

To illustrate the data which was obtained from the iterative algorithm, a small sample of these calculated heat transfer coefficients, for packaged burritos, is given in Table 3. This table lists the heat transfer coefficients for the burritos with a description of their packaging, dimensions, and weight, as well as the air temperature and air velocity used to cool or freeze the food items.

Nusselt-Reynolds Correlations

Non-dimensional analyses were performed to obtain simple heat transfer coefficient correlations which can be used to predict the heat transfer coefficients of food items. A linear least-squares-fit was performed on Nusselt Number versus Reynolds Number data to obtain linear a Nusselt-Reynolds correlation. For this correlation, the Nusselt number, *Nu,* is defined as:

$$Nu = \frac{hd}{k_m} \tag{18}$$

where h is the heat transfer coefficient, d is the smallest dimension of the food item and k_m is the thermal conductivity of the cooling medium. The Reynolds number, *Re*, is defined as:

$$Re = \frac{r_m U d}{m_m} \tag{19}$$

where r_m is the density of the cooling medium, U is the free stream velocity of the cooling medium, d is the smallest dimension of the food item and m_m is the dynamic viscosity of the cooling medium.

The resulting Nusselt-Reynolds correlation for packaged burritos is as follows:

$$Nu = 8.434 + 0.000831 Re \quad \text{for } 5000 < Re < 15000 \qquad (20)$$

Figure 3 shows the heat transfer coefficient data and the resulting Nusselt-Reynolds correlation for the packaged burritos.

Conclusions

This paper described the thermodynamics of food freezing and reviewed basic freezing time estimation methods. Members of the food refrigeration industry were contacted to collect cooling and freezing curves and surface heat transfer data.

An iterative algorithm was used to estimate the surface heat transfer coefficients of irregularly shaped food items based upon their cooling and freezing curves. This algorithm utilizes the concept of “equivalent heat transfer dimensionality” to extend to irregularly shaped food items existing techniques for the calculation of the surface heat transfer coefficient, previously applicable to only regularly shaped food items.

Making use of this algorithm, heat transfer coefficients for various food items were calculated from the cooling and freezing curves collected during the industrial survey. A small sample of the calculated heat transfer coefficient data was presented in this paper for packaged burritos. In addition, a Nusselt-Reynolds correlation was developed to summarize the heat transfer coefficient data for packaged burritos.

The algorithm described in this paper was developed and used in a recent ASHRAE research project to generate over 800 heat transfer coefficients which will appear in future additions of the ASHRAE Refrigeration Handbook. These heat transfer coefficients can then be used with the freezing time estimation methods mentioned in this paper and detailed in the ASHRAE Refrigeration Handbook to achieve efficient design of food freezing equipment.

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Table 1. Expressions for P and R from Cleland and Earle (1977, 1979).

Shape	P and R Expressions
Infinite Slab	$P = 0.5072 + 0.2018Pk + Ste\left[0.3224Pk + \frac{0.0105}{Bi} + 0.0681\right]$ $R = 0.1684 + Ste(0.2740Pk - 0.0135)$
Infinite Cylinder	$P = 0.3751 + 0.0999Pk + Ste\left[0.4008Pk + \frac{0.0710}{Bi} - 0.5865\right]$ $R = 0.0133 + Ste(0.0415Pk + 0.3957)$
Sphere	$P = 0.1084 + 0.0924Pk + Ste\left[0.231Pk - \frac{0.3114}{Bi} + 0.6739\right]$ $R = 0.0784 + Ste(0.0386Pk - 0.1694)$

Table 2. Definition of variables for the freezing time estimation method of Pham (1984).

Process	Variables
Precooling	$i = 1$ $k_1 = 6$ $Q_1 = C_l (t_i - t_{fm}) V$ $Bi_1 = (Bi_l + Bi_s)/2$ $\Delta t_{m1} = \frac{(t_i - t_m) - (t_{fm} - t_m)}{\ln\left[\frac{t_i - t_m}{t_{fm} - t_m}\right]}$
Phase Change	$i = 2$ $k_2 = 4$ $Q_2 = L_f V$ $Bi_2 = Bi_s$ $\Delta t_{m2} = t_{fm} - t_m$
Subcooling	$i = 3$ $k_3 = 6$ $Q_3 = C_s (t_{fm} - t_c) V$ $Bi_3 = Bi_s$ $\Delta T_{m3} = \frac{(t_{fm} - t_m) - (t_o - t_m)}{\ln\left[\frac{t_{fm} - t_m}{t_o - t_m}\right]}$

Notes: A_s is the area through which heat is transferred
Bi_l is the Biot number for the unfrozen phase
Bi_s is the Biot number for the frozen phase
Q_1, Q_2 and Q_3 are the heats of precooling, phase change and subcooling, respectively
?t_{m1}, ?t_{m2} and ?t_{m3} are the corresponding log-mean temperature driving forces
t_c is the final thermal center temperature
t_{fm} is the mean freezing point, assumed to be 1.5 K below the initial freezing point
t_o is the mean final temperature
V is the volume of the food item

Table 3. Calculated Heat Transfer Coefficients for Packaged Burritos.

Packaging	Heat Transfer Coefficient, (W m^{-2} K^{-1})	Length (m)	Width (m)	Height (m)	Mass (gm)	Air Temperature (°C)	Air Velocity (m s^{-1})	Air Flow Direction	Product Phase
Mylar wrapper	13.0	0.152	0.064	0.022	142	0.	3.	along width	unfrozen
Plastic wrap	7.03	0.178	0.064	0.025	113	-33.1	3.8	along width	
	11.6	0.191	0.064	0.032	142	-33.1	3.8	along width	unfrozen
	11.6	0.191	0.064	0.032	142	-33.1	3.8	along width	frozen
	11.5	0.254	0.076	0.038	255	-33.1	3.8	along width	unfrozen
	12.7	0.254	0.076	0.038	255	-33.1	3.8	along width	frozen
Unspecified	17.7	0.133	0.054	0.025	144	-30.	3.	along height	unfrozen
	12.7	0.133	0.054	0.025	144	-30.	3.	along height	frozen

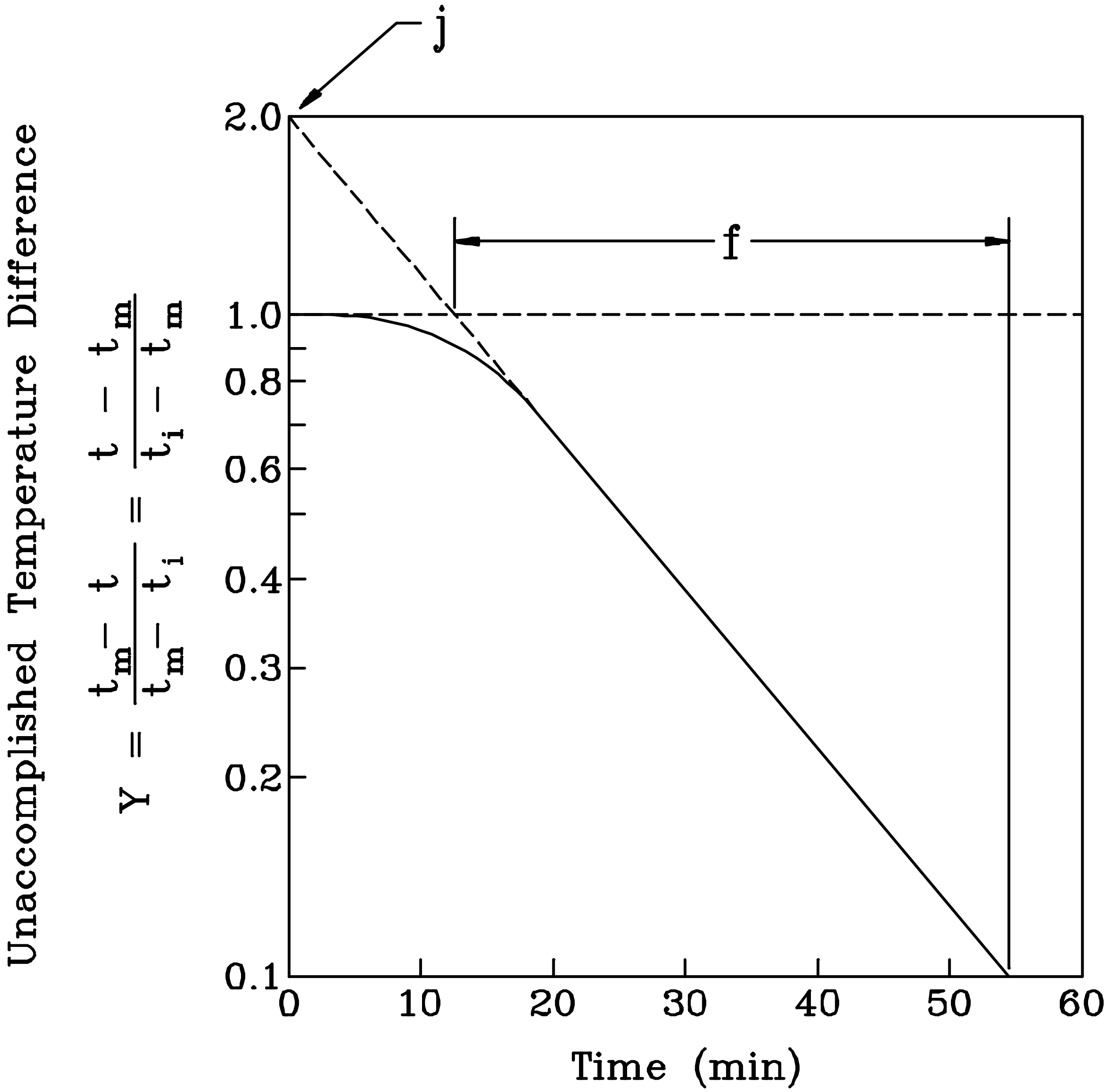

Figure 1. Typical Cooling Curve.

PRODUCT TEST DATA (00-5-01)

GENERIC NAME	BURRITO						
BRAND NAME				PROCESSED BY			
SIZE	L. 6"	W. 2 1/2"		H. 7/8"		UNIT WT.	5 OZ. NET
DENSITY	BULK		lbs/CF	SINGLE LAYER			lbs/SF
TEMP. IN	120 °F.	TEMP. OUT	40 °F.	ENTHALPY BTU/lb.	72		COMPUTED OR TESTED

SAMPLE

PACKAGE DESCRIPTION: (SHAPE/WET/DRY/CONDITION)

BURRITO IN 3 MIL MYLAR WRAPPER.

TRANSFER TEMP.

TEST NO.	1	TEST DATE	2-27-80	TESTED BY	

TEST METHOD AND APPARATUS DATA ON BACK

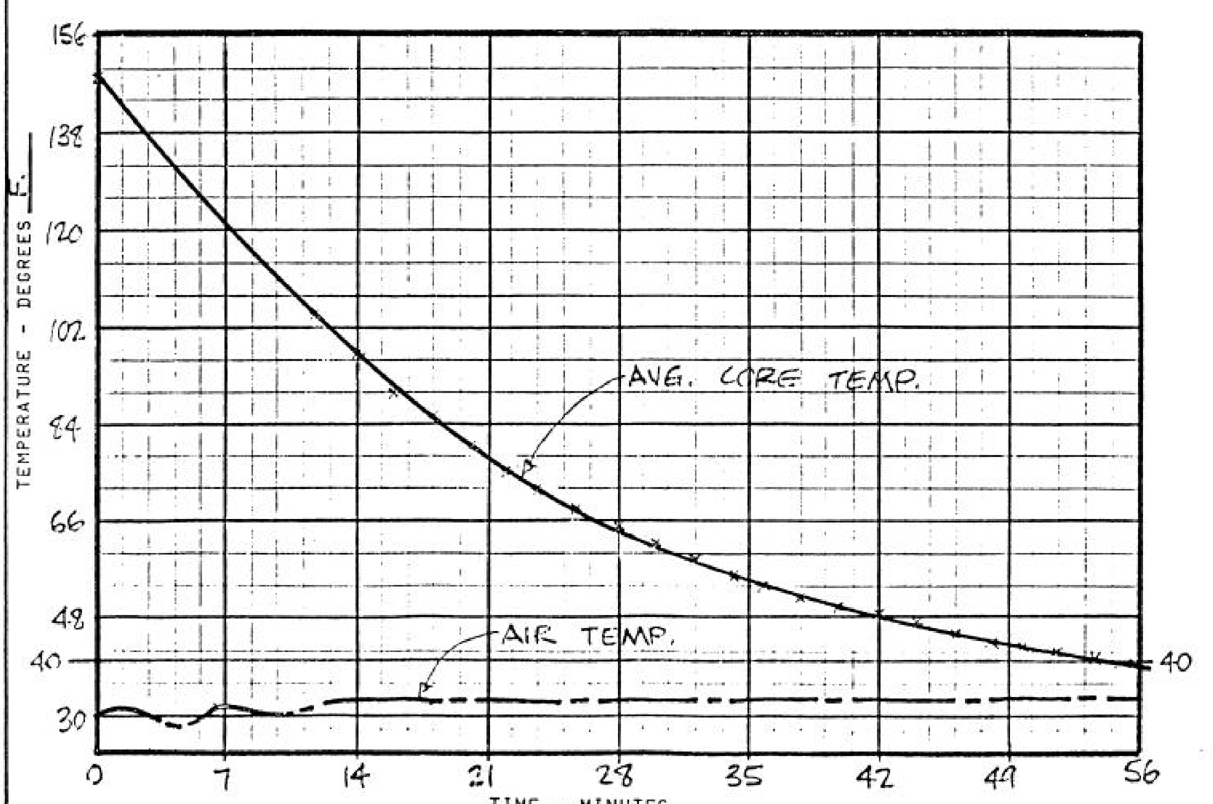

Figure 2. Cooling Curve for Burritos.

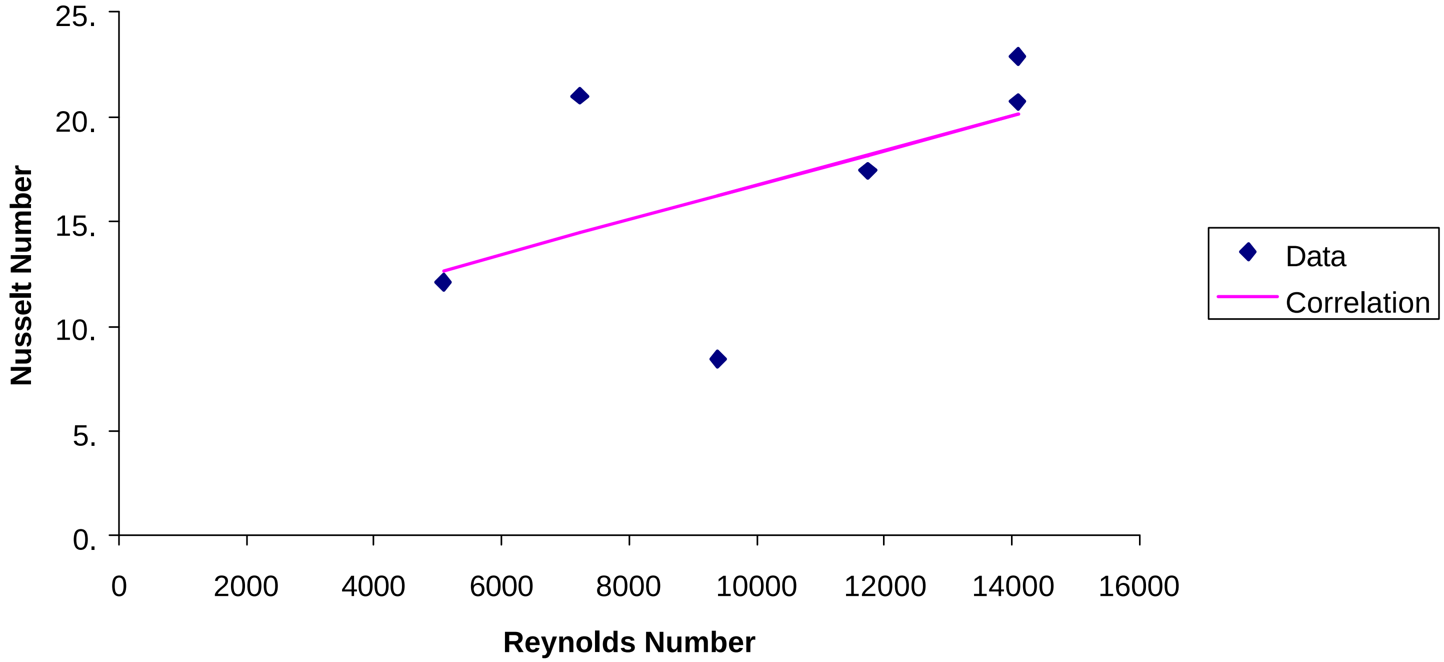

Figure 3. Nusselt-Reynolds Correlation for Burritos.