FREEZING RATE STUDIES IN BLOCKS OF MEAT OF SIMPLE SHAPE

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T.D.C. Cullwick.

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CHAPTER 1

INTRODUCTION

In view of the large quantities of foodstuff now being preserved in the frozen state, it is important to be able to predict the freezing time of a product under specified freezing conditions. An accurate knowledge of the freezing time of a product permits a precise termination to be made to the freezing process and the subsequent improvement possible in plant utilization is significant when large quantities of foodstuff have to be frozen in a given freezing plant. The freezing rate of a foodstuff must be high enough to prevent loss of quality as a result of microbiological and enzymic changes, but a loss of quality may still occur as a result of the nature of ice crystal formation during freezing. Mazur (27) proposed a quantitative relationship between the size and location of the ice crystals and the freezing rate and he considered that high freezing rates gave a high product quality. With these factors in mind the freezing rates obtained during the freezing of a product under different conditions were determined.

The freezing times and freezing rates of a product can be found by experiment. This involves making temperature measurements with suitably located thermocouples, and the product is frozen when a specified centre temperature is reached. To eliminate the necessity for making experimental studies it is desirable to develope a calculation method which will accurately predict the freezing rate and freezing time of a product.

The freezing of a product results in a change of the physical state of the foodstuff which is accompanied by the release of the latent heat of solidification of the large water component of the foodstuff. The latent heat of solidification is released over a temperature range and not at a specific temperature, the freezing point, as in the case of pure water because of the presence of salts in the tissue fluid, which cause a depression of the freezing point of the system. As freezing proceeds water separates out as ice which results in an increase in the concentration of these salts, and this causes a greater depression of the freezing point of that system. This results in the latent heat of solidification being released over a temperature range until finally a temperature is reached when the entire system is frozen. The change of physical state of the system during freezing also results in a change of the thermal property values of the foodstuff. The change in these values is associated with the higher thermal conductivity and lower specific heat of the ice formed during freezing.

The rate of heat transfer which occurs during the freezing of a product is governed by the Fourier heat conduction equation, which is a nonlinear partial differential equation. To determine the freezing rate, solutions of this equation have to be found which satisfy the heat transfer boundary conditions which prevail in the physical system being considered. Neumann (19) obtained an analytical solution for this equation for the case of slab ice formation on the surface of a liquid at its freezing point, with constant free surface temperature which corresponded to an infinite surface heat transfer coefficient. An analytical solution presented presented by Stefan (19) may be considered as a special case of Neumann's general solution. These solutions are of little technical use for the freezing of foodstuffs since generally the product is cooled from both sides and the heat transfer coefficient is far from infinite. Particular solutions are unknown when technically useful heat transfer boundary conditions are imposed. For a normal freezing process the heat transfer boundary conditions must account for the gradual release of the latent heat of solidification at the freezing boundary and for the variation of thermal property values with temperature. Variations in the initial product temperature, the surface heat transfer coefficient, the ambient temperature and the product thickness which occur must also be accounted for by the heat transfer equations.

The difficulties involved in obtaining an exact analytical solution to the freezing problem for technically useful heat transfer boundary conditions, resulted in the development of approximate solutions. These solutions were obtained by making assumptions which simplified the nature of the heat transfer boundary conditions existing in the experimental system. Analytical, graphical and numerical approximate solutions of the freezing problem were obtained when these assumptions were made, the different types of solutions requiring different degrees of assumptions to be made for their development. It was found that the numerical type of solution dealt most adequately with the heat transfer boundary conditions which existed in a normal freezing process. In this type of solution a nonlinear heat transfer equation is replaced by a series of approximately linear equations over restricted temperature ranges and the phase change which occurred in the physical system is taken into account by varying the thermal property values used in the calculations. Calculations in the numerical solutions are repetitive and they would be tedious if they are not made on a digital computer. The availability of a digital computer permitted the use of the numerical solution.

One dimensional freezing of a homogeneous body was studied because of the complexity of the numerical solutions for two and three dimensional freezing. Minced lean beef frozen in a plate freezer, closely approximated this system of a homogeneous product.

The aim of this study was to obtain freezing curves for minced lean beef under a variety of experimental conditions, temperature measurements being made with thermocouples, and to determine the accuracy with which these freezing curves could be estimated by the numerical solutions obtained with a digital computer. From these correlation studies the magnitude of the surface heat transfer coefficient which existed in a plate freezer was determined. Normally routine freezing time determinations are made with Plank's equation (32) which has the practical advantage of simplicity. Assumptions made during its derivation limit the accuracy of these results and thus Plank's equation was modified to give predictions which agreed closely with the experimental freezing times.

C H A P T E R 2

THERMAL PROPERTIES

In this study minced lean beef was frozen because it closely approximated a homogeneous system. To predict the freezing times and freezing rates of this product, it was necessary to know its thermal conductivity and specific heat values over the temperature range studied. The values of these thermal properties vary with meat composition, meat temperature and the orientation of the fibres with respect to the direction of heat flow.

2.1. Composition:

Meat like most foodstuffs contains a large proportion of water and hence the thermal properties of the foodstuff are significantly influenced by those of the water present in the foodstuff. Water has a high latent heat of solidification and a high thermal conductivity in the frozen state and the other components of the meat, e.g. fat, have a constant and low thermal conductivity and no latent heat of solidification in the temperature range being studied. Thus the thermal properties of the meat are fairly close to those of water. If the proportion of these low thermal property value components was increased and the proportion of water decreased as in high fat beef, the thermal property values of the beef would be reduced.

It was thus desirable to determine the composition of the minced lean beef used in these experiments. Moisture determination involved oven drying according to AOAC - 23.003 (a) (3) and fat determination involved an ether extraction according to AOAC - 23.005 (a). The average composition of the minced beef was obtained by determining the fat and moisture levels in ten samples drawn randomly from the product. It was found that the moisture level was 78.6% ± 0.35 S.D., and the fat level was 0.49% ± 0.52 S.D., where S.D. is the standard deviation.

Although the standard deviation of the fat level was high between the samples, the absolute level of fat present was very small in all cases. In a low fat product such as this, the thermal property values depend upon the moisture levels through the samples and it can be seen that these were very uniform. Hence the minced lean beef used in these experiments was considered to be homogeneous.

2.2. Temperature:

The influence of the water component on the thermal properties of foodstuffs was further illustrated by the temperature effect upon these values. The change of state of the physical system which occurs when water is frozen, is accompanied by the release of the latent heat of solidification and a three fold increase in the thermal conductivity of the foodstuff (Fig. 1). The latent heat of solidification is not released at a specific temperature, the freezing point, as in the case of pure water, because of the presence of salts in the tissue fluid which cause a depression of the freezing point of the system. As freezing proceeds water gradually separates out as ice, which results in a gradual increase in the concentration of these salts. This causes an increasing depression of the freezing point of the system until the final freezing point of the system is reached. Hence the latent heat of solidification is released over a temperature range. As water influenced the value of the thermal properties of beef very significantly, the temperature dependent variation of these thermal properties was considered to follow closely the transformation of water to ice (Fig. 1) as determined from data for lean beef presented by Riedel (36).

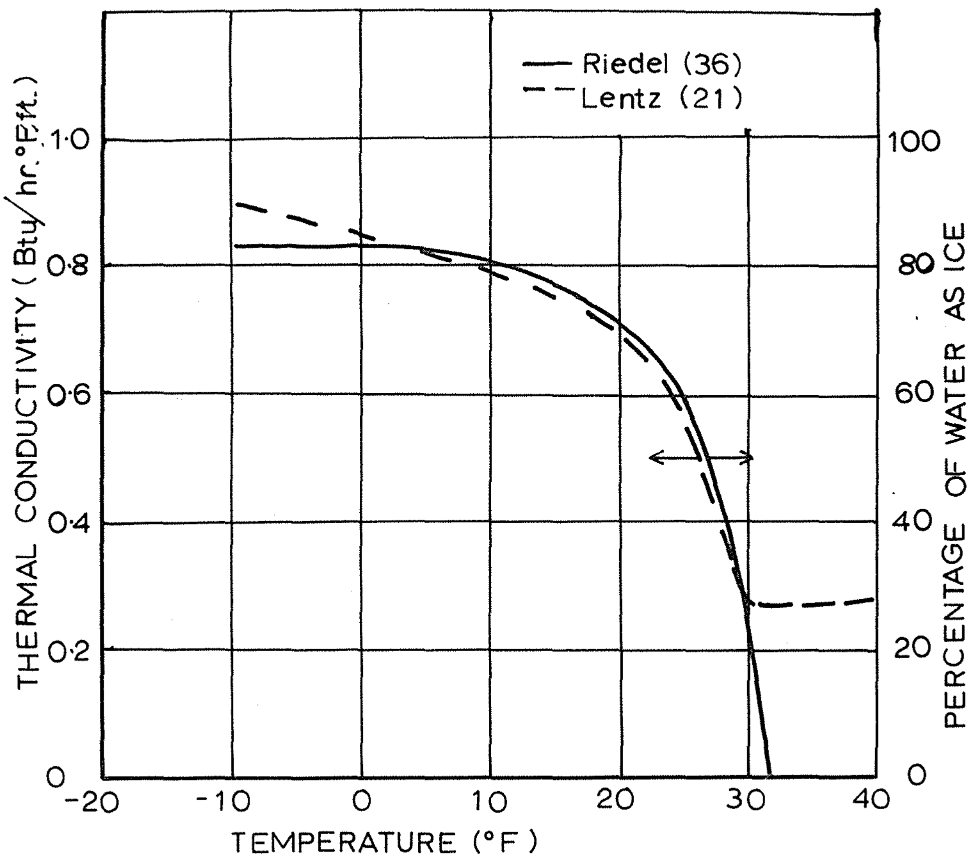


FIG.1 ICE-THERMAL CONDUCTIVITY RELATIONSHIP FOR LEAN BEEF

As the latent heat of solidification is released over a temperature range, it was found more convenient to consider the heat capacity of a foodstuff over a range of temperature in the form of a temperature enthalpy curve. The basis of this temperature enthalpy relationship is that the enthalpy, or heat capacity, at $-40^{\circ}F$ is zero and the enthalpy value increases with temperature to account for the increasing heat capacity of the product and the release of the latent heat of solidification during freezing. A temperature - enthalpy curve for lean beef presented by Riedel (36) is shown in Fig. 2.

2.3. Fibre Orientation:

The thermal conductivity value of meat is significantly affected by the direction of the meat fibres relative to the direction of heat flow. Lentz (21) has shown that the values obtained when heat flow was parallel to the fibres were 10 - 30% higher than those obtained when heat flow was perpendicular to the fibres. As minced beef was used in these experiments, fibre orientation effects were not a problem.

2.4. Thermal Properties of Minced Lean Beef:

Because of the significant effect these factors had upon the thermal property values, it was desirable to determine accurately the value of the thermal properties of the minced lean beef used in these experiments for the temperature range studied.

The thermal conductivity value of the minced lean beef used in these experiments was determined by Benseman (5). In his method a cylinder of product (height of 1 ins., diameter of 1 ins.) was placed between two glass cylinders of similar size. These segments were held firmly together to form a long cylinder which was placed between a hot source and a cold sink and then insulated with a 4 ins. thick layer of polystyrene. The two ends were held at specified

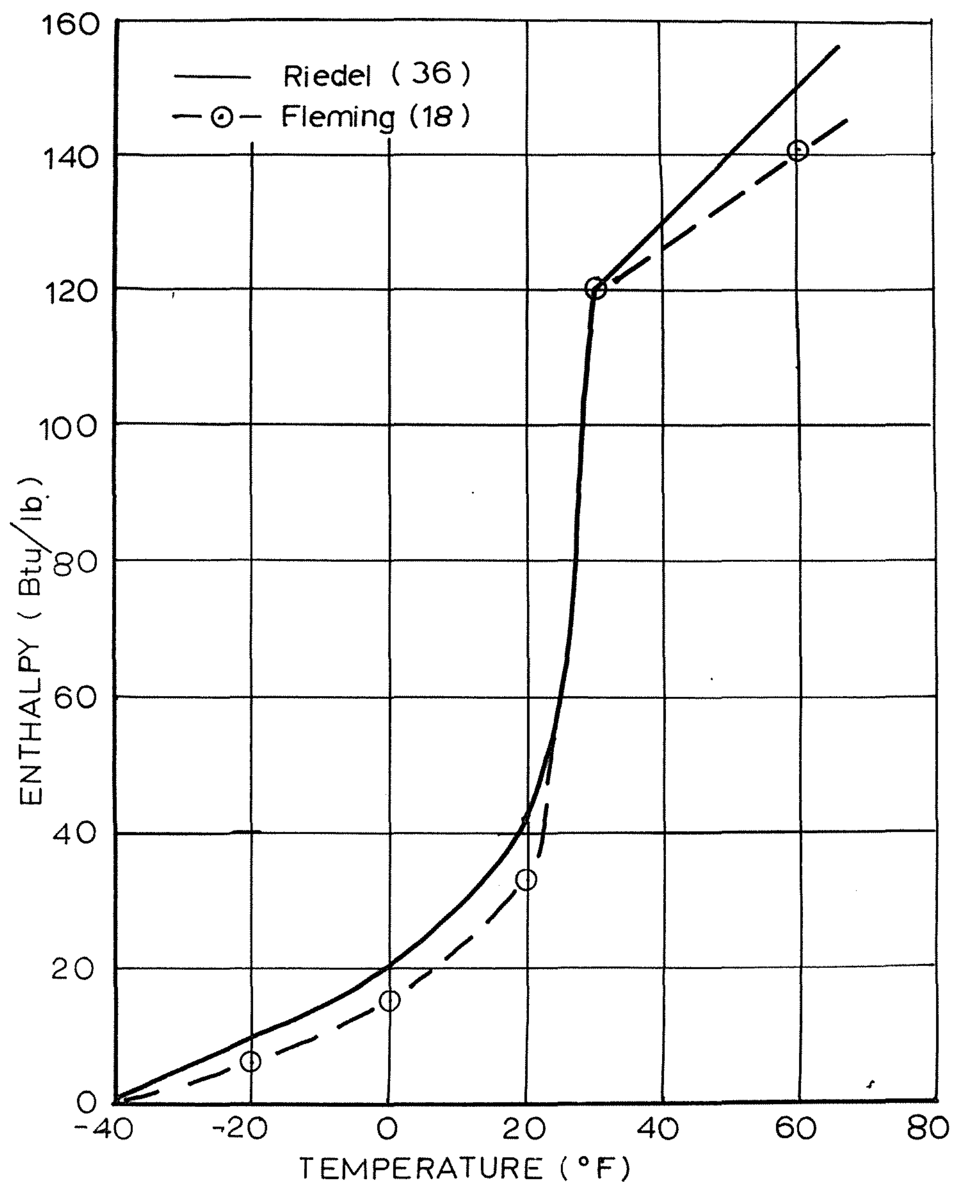


FIG. 2 ENTHALPY OF LEAN BEEF

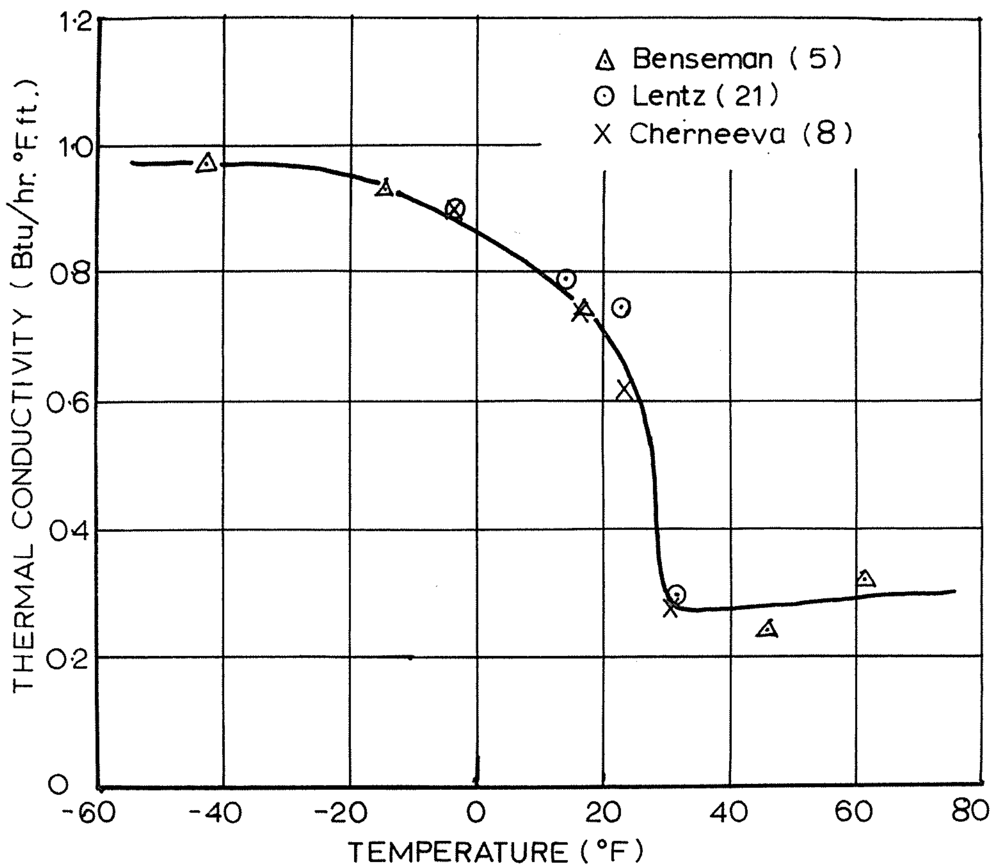


FIG.3 THERMAL CONDUCTIVITY OF LEAN BEEF

temperatures and steady state conditions were established in the system. The temperatures at specific intervals along the two glass cylinders were measured and these in conjunction with a knowledge of the glass thermal conductivity permitted the heat flow in the cylinder to be established. This heat flow value was corrected for the known heat leakage which occurred in the experimental system and the minced beef thermal conductivity was then determined. The experimental values are shown in Fig. 3 with the documented values of Cherneeva (8) and Lentz (21) for lean beef. All the values agree closely and the curve represents the values used in the numerical solution calculations.

A temperature - enthalpy curve of the minced lean beef used in these experiments was determined by Fleming (18) by the use of an adiabatic calorimeter in which measured quantities of heat are added to the sample and the consequent rises in temperature measured. The minced lean beef used in the experiment work was placed in the calorimeter and its temperature enthalpy characteristics determined over the whole range of interest. The experimental values are shown in Fig. 2 with the documented values of Riedel (36) for lean beef. The values of Riedel and Fleming agree closely except in the regions of very high and low temperature. In these studies the temperature - enthalpy curve of Riedel was used and the specific heat value was equal to the slope of the curve at the temperature being considered.

For calculation purposes, the temperature range was divided into intervals over which the thermal conductivity and specific heat values were considered constant. The size of the intervals was dependent upon the rapidity of the change in the thermal property values with temperature. Table I shows the thermal conductivity and specific heat values used in the calculations, and they are considered constant over the temperature ranges shown.

TABLE I Thermal Properties of Minced Lean Beef

Temperature	-40	-30	-20	-10	0	10	20	21	22	23	24	25
Specific Heat	.50	.50	.50	.50	.90	1.30	1.80	2.00	2.30	2.50	3.10	
Thermal Conductivity	.96	.96	.93	.89	.83	.77	.71	.69	.67	.65	.62	

Temperature	25	26	27	28	29	30	35	40	50	60	79
Specific Heat	3.30	4.60	6.80	27.00	23.00	1.00	1.00	1.00	1.00	1.00	
Thermal Conductivity	.58	.53	.46	.36	.32	.27	.27	.28	.29	.30	

Units Thermal Conductivity (Btu/hr ^{o}F ft)

Temperature (^{o}F)

Specific Heat (Btu/lb ^{o}F)

CHAPTER 3

APPROXIMATE SOLUTIONS

Solutions of the Fourier heat conduction equation had to be found which satisfied the heat transfer boundary conditions which prevail in the physical system being considered. For a normal freezing process the heat transfer boundary conditions must account for the gradual release of the latent heat of solidification and for the existence of different thermal properties in the unfrozen and frozen layers. Variations in the initial product temperature, the surface heat transfer coefficient, the ambient temperature and the product thickness which occur must also be accounted for by the heat transfer equations. Exact analytical solutions of the freezing problem which satisfy these boundary conditions have not been found. The analytical solution developed by Neumann (19) was for slab ice formation on the surface of a liquid, the free surface temperature of which was constant corresponding to an infinite heat transfer coefficient. This solution is of little technical use since generally the product is cooled from both sides and the heat transfer coefficient is far from infinite. The difficulties involved in obtaining a technically useful analytical solution led to the development of approximate solutions of the freezing problem.

Most foodstuffs contain 65 to 90% water and the interrelationships of this water to other constituents complicate the relationship between the heat capacity of the foodstuff and its temperature, over the freezing range. This relationship is presented in the form of a temperature enthalpy curve, Fig. 2. It is evident that the latent heat of solidification forms a very large proportion of the total change in heat content, or enthalpy change, between the initial and final product temperature and because of this it is possible to make simple approximations to the heat transfer calculations. In these approximations the following assumptions are made:-

: that the product is initially uniformily at its freezing point and unfrozen.

: that the latent heat of solidification is released at a fixed temperature, the freezing point.

: that the thermal properties of the unfrozen and frozen states are constant.

: that the freezing boundary proceeds so slowly that steady state conditions exist in the frozen state.

3.1. Analytical Solutions:

Equations for calculating the freezing time of a product based upon these assumptions were first presented by Plank (32) for the symmetrical freezing of a slab, a cylinder, and a sphere and were later extended (33) to include the freezing of a rectangular parallelepiped (brick shape). London and Seban (23) gave an approximate solution to the freezing problem of the slab, cylinder and sphere in which the specific heats of the two phases were neglected. Nagaoka (30) studied the freezing of fish in air blast freezers and modified Plank's equation to account for the elliptical cross-section of fish and for an initial product temperature above the freezing point. Levy (22) modified Plank's equation to account for the shape of different fish and discussed the effect of air speed, when fish were frozen in an air blast freezer. Eddie and Pearson (16) discussed these last two papers comprehensively and introduced a more generalised shape factor to Plank's equation. Rutov (38) modified Plank's equation to allow for an initial product temperature above the freezing point and a final temperature below the freezing point. Tanaka (39) developed a modified form of Plank's equation to predict the freezing time of whalemeat in a plate freezer. Watzinger (40) studied the freezing of fish fillets in a plate freezer and modified Plank's equation to account for an initial fish temperature above the freezing point and a final temperature below the freezing point.

3.2. Graphical Solutions:

Ede (17) presented a graphical solution to the freezing problem, the method utilising a variant of the Schmidt graphical method and incorporating a step proceedure to determine the exact location of the freezing boundary. This solution does not consider the heat capacity of the frozen layer which was considered in the graphical solution presented by Longwell (24).

3.3. Numerical Solutions:

Numerical solutions are based upon the use of finite difference approximations to the heat conduction equation and have successfully been used by Albasiny (1) for calculating the freezing times of fish slabs, and Earle (15) utilised the method of Dusinberre (12) for calculating the freezing time of minced beef in simple shapes.

This type of solution deals adequately with the heat transfer boundary conditions which exist in a normal freezing process. The variations in the thermal property values which occur with the change of phase in the physical system are accounted for by varying the thermal property values used in the calculations, and the experimental values of the process parameters are inserted directly into the calculations. Further, with this type of solution it is possible to obtain the temperature profile existing across the product at any time.

CHAPTER 4

A NUMERICAL PREDICTION OF THE FREEZING CURVE

4.1. Introduction:

In this study the freezing curve of a product was predicted by using a numerical solution of the freezing problem. Numerical solutions are available for the one-, two- and three-dimensional freezing of a homogeneous product but the solutions for two- and three-dimensional freezing are very complex. Hence the one-dimensional freezing of a homogeneous product was studied for which the following heat conduction equation in Cartesian coordinates is appropriate

$$\rho c \left(\frac{\partial T}{\partial t} \right) = \frac{\partial}{\partial x} k \left(\frac{\partial T}{\partial x} \right) \qquad (4.1)$$

and it is considered that the specific heat, c, and the thermal conductivity, k, are temperature dependent. The heat transfer boundary conditions for one-dimensional heat transfer which occurs during the plate freezing of a slab of side, 2a, and with centre x = a are:-

(i) Initial condition, T constant when t = 0,

$$0 \leq x \leq 2a \qquad (4.2)$$

(ii) Surface condition, $h(T_0 - T_1) = k \left(\frac{\partial T}{\partial x} \right)$ (4.3)

at $x = 0 \quad t > 0$

and $h(T_{2a} - T_1) = -k \left(\frac{\partial T}{\partial x} \right)$ (4.4)

at $x = 2a \quad t > 0$

and for symmetry about the centre where x = a.

$$T_n = T_{a + n} \qquad (4.5)$$

To solve these equations, the temperature range was divided into intervals over which it could be considered that the specific heat and the thermal conductivity values were constant (Table I). The size of the intervals depended upon the rate of change of the thermal property values with temperature.

For calculation purposes, the equations (4.1), (4.3), (4.4), were replaced by finite difference approximations and solved subject to the conditions outlined by equations (4.2) and (4.3). Effectively this proceedure replaces a non-linear partial differential equation by a series of approximately linear equations over restricted temperature ranges and the phase change which occurs in the physical system accounted for by the temperature dependent thermal property values. This is the basis of the numerical solution of the freezing problem.

4.2. Finite Difference Heat Transfer Equations:

The calculations in which these finite difference approximations were used follows the method outlined in Dusinberre (12). In this method, the general equation used for determining the temperature at a point, n, after a time interval, Δt, is

$$T_{n,t+\Delta t} = \frac{T_{n-1,\,t} + (M-2)T_{n,t} + T_{n+1,\,t}}{M} \qquad (4.6)$$

where $T_{n,t+\Delta t}$ is the temperature at a point, n, after a time interval, Δt, when $T_{n,t}$ is the temperature there after a time, t.

and $$M = \frac{\rho c (\Delta x)^2}{k \Delta t}$$

where ρ - product density (lbs/ft^3)

c - specific heat of product (Btu/lb)

k - thermal conductivity of product (Btu/hr ^oF ft)

Δx - distance between successive points across the product (ft)

Δt - time interval between calculations (hrs)

The thermal property values are those appropriate to the temperature $T_{n, t}$.

For calculation purposes the product being frozen was divided into a number of segments of width, Δx, with $T_{n-1, t}$, $T_{n, t}$, $T_{n+1, t}$ representing the temperature at successive points across this matrix at a time, t. The number of divisions across the matrix was n and hence the width of product, to the product centre was $n\Delta x$.

By examination of equation (4.6) it is evident that $T_{n, t+\Delta t}$ depends upon the temperature of the adjacent points, and if M is greater than two, also upon the original temperature of the point being considered. The larger, the value of M, the greater the influence the original temperature at n, $T_{n, t}$ has upon the new temperature, $T_{n, t+\Delta t}$ and the larger the number of calculations required to obtain a given temperature change. If M is equal to two, then the new temperature is the mean of the temperature of the adjacent points and this is the basis of the Schmidt (26) graphical method of analysis of a cooling system, a variant of which was used by Ede (17) in his graphical analysis of freezing problems. The value of M selected thus has to be a compromise between calculation accuracy, requiring a large M value, and brevity of calculation time, requiring a small value of M.

4.3. Selection of Parameter Values:

In view of the importance of the ultimate M value used, it is of interest to determine which parameter could be adjusted to obtain a given value M. Now M is defined according to

$$M = \frac{\rho c}{k} \frac{(\Delta x)^2}{\Delta t}$$

Of the parameters determining the value of M, the density, ρ, was assumed to be constant, and the thermal conductivity, k, and specific heat, c, were fixed by the temperature at the point at the beginning of the time interval being studied. The distance between successive calculation points, Δx, was a calculation time - calculation accuracy compromise; the smaller the spacing, the more accurate the time-temperature profile obtained. It was found that the profiles obtained during the cooling of a 4 ins. thick slab, initial temperature 60°F, ambient temperature -40°F thermal conductivity 0.78 Btu/hr °F ft, specific heat 0.5 Btu/lb °F, S.H.T.C. of 99 Btu/hr °F ft^2 agreed quite closely when grid spacings of 0.5 ins. and 1.0 ins. were used, as shown in Table II. For the calculations a grid spacing of 0.5 ins. was selected for 3, 4 and 5 ins. thick slabs and 0.25 ins. for a 2 ins. thick slab.

The selection of a grid spacing size left the time between successive calculations, Δt, as the only parameter effecting the value of M. In these calculations a value of M was selected, leaving Δt as the variable. The M value selected was a compromise between calculation accuracy and calculation time. The effect of the value of M selected was studied for the cooling of a 4 ins. thick slab, initial temperature 60°F, ambient temperature -40°F, grid spacing 0.5 ins, thermal conductivity 0.78 Btu/hr °F ft, specific heat 0.5 Btu/lb °F, S.H.T.C. of 99 Btu/hr °F ft^2 as shown in Table III. As a result of this an M value of 4.0 was selected for the calculations in this study.

Table II. Effect of Grid Spacing Size on Numerical Solution.

Time (hrs)	Centre Temperature (°F)	
	Grid Spacing (Δx)	
	0.5 ins	1.0 ins
0.11	57.16	56.21
0.25	39.03	39.79
0.50	9.68	11.47
0.69	- 5.28	- 3.61
1.00	- 20.88	- 19.38
1.14	- 25.15	- 24.05
1.35	- 30.01	- 29.15
1.50	- 32.47	- 31.75

Having selected these parameters, Δt was the unknown parameter and varied as the calculations proceeded since

$$\Delta t = \frac{\rho c}{k} \frac{(\Delta x^2)}{M}$$

For computation purposes, a constant time increment was required. This was obtained by selecting a time value smaller than the smallest Δt obtained during the calculations, and interpolating the temperature obtained for a given value of Δt, to that temperature which corresponded to the constant time increment. This technique is outlined below.

$$T_{n,\ t\ +\ D.D.T.} = \frac{D.D.T.}{\Delta t} (T_{n,\ t\ +\Delta t} - T_{n,\ t}) + T_{n,\ t} \qquad (4.7)$$

where

$T_{n,\ t\ +\Delta t}$ — temperature at point n, after a time increment Δt (^{o}F).

$T_{n,\ t\ +\ D.D.T.}$ — temperature at point n, after a time increment D.D.T. (^{o}F).

D.D.T. — constant time increment. (hrs).

Table III Effect of M Value on Numerical Solution

Time (hrs)	Centre Temperature (^{o}F) Modulus Value (M)			
	2	4	6	8
0.29	38.75	34.81	33.97	34.85
0.50	12.46	10.58	9.98	9.68
0.87	- 13.89	- 14.83	- 15.13	- 15.28
1.00	- 19.57	- 20.31	- 20.54	- 20.66
1.50	- 32.05	- 32.23	- 32.43	- 32.47
2.00	- 36.90	- 37.01	- 37.05	- 37.07
2.50	- 38.79	- 38.83	- 38.85	- 38.86

4.4. Finite Difference Equations for Surface Calculations:

To initiate the calculations made in obtaining a time-temperature profile, it was necessary to have an equation for calculating the surface conditions. The accuracy of the time-temperature profile obtained by a numerical solution depends significantly upon the accuracy with which the surface calculations are made. In an effort to obtain accurate surface calculations, one equation was used for the initial surface calculation and one for the subsequent surface calculations.

(i) Initial Surface Calculation:

This equation is recommended by Mickley, Sherwood and Reid (28).

$$T_{n-1,t+\Delta t} = \frac{1}{2}\left[T_{n-1,\,t} + \frac{NT_a + NT_{n,\,t}}{N+1}\right] \qquad (4.8)$$

where $N = \dfrac{h\,\Delta x}{k}$

h - surface heat transfer coefficient (Btu/hr °F ft^2)

This coefficient also includes any packaging resistance to heat transfer present in the system and

$$\frac{1}{h} = \frac{1}{h_s} + \frac{\Delta x}{k}$$

where h_s - surface film heat transfer coefficient (Btu/hr °F ft^2)

$\sum \dfrac{\Delta x}{k}$ - packaging film resistance (Btu/hr °F ft^2)

T_a - ambient temperature (°F)

(ii) Subsequent Surface Calculations:

The equation for this calculation is given by Dusinberre (12)

$$T_{n-1,\,t+\Delta t} = \frac{NT_{a,\,t+\Delta t} + 1/M\,(T_{n-1,\,t} + [M-2]T_{n,\,t} + T_{n+1,\,t})}{N+1} \qquad (4.9)$$

In the derivation of equation (9) it is assumed that the temperature gradient at the surface is equal to the slope of the chord of the surface.

4.5. Calculation Procedure:

Calculation procedure involved an initial surface calculation, followed by calculations at each selected point across the product for a time period t. After the product centre had been reached, a repeat set of calculations was made for the time period $t + \Delta t$, the temperature so obtained being used to calculate the temperatures after a time $t + 2\Delta t$. For each calculation, the thermal properties appropriate to the temperature of the point at the beginning of the time element being considered, were selected. In this cyclic way the time-temperature profile existing in the product could be obtained.

The determination of a time-temperature profile by this calculation method is a repetitive procedure and the calculations were made quickly on a digital computer. A Fortran - 2 programme was developed in which were incorporated the finite difference equations appropriate to one dimensional freezing of a homogeneous product. The programme was developed in such a manner that,

(i) the calculation procedure could be carried out either for a product of uniform or non uniform initial temperature.

(ii) the relevant thermal properties could be introduced into the system in a suitable form so that the values appropriate to the temperature being considered were selected.

(iii) the relevant values of the process parameters could be introduced.

(iv) a constant time increment for print out was available.

(v) the distance temperature profile was printed out at selected time and centre temperature intervals.

(vi) the calculations could be terminated when the desired final centre temperature had been reached.

The block diagram for this programme is shown in Fig. 4 and the Fortran - 2 programme used for these calculations in the IBM 1620 computer is shown in Fig. 5 and follows the general method used by Earle (15).

The numerical solution results obtained for the freezing of a 2 ins thick slab, initial temperature 62^{o}F, ambient temperature -40^{o}F and S.H.T.C. of 99 Btu/hr ^{o}F ft^{2} are shown in Fig. 6.

The initial table of values represents the thermal property values used in the calculations which are presented in a form similar to that of Table I. The number zero, indicates that one-dimensional freezing of the slab is being considered and the list of numbers across the page represents the following:-

5 - width factor which equals (n + 1) where n was the number of divisions required.

4.0 - value of modulus, M selected.

-40 - plate temperature (^{o}F).

62 - initial product temperature (^{o}F).

0.005 - constant time increment (hrs).

0.25 - grid spacing width (ins).

67 - product density (lbs/ft^{3}).

99 - surface heat transfer coefficient (Btu/hr ^{o}F ft^{2}).

0.25 - time increment between temperature profile printouts (hrs).

FIG. 4. BLOCK DIAGRAM OF PROGRAMME FOR NUMERICAL SOLUTION

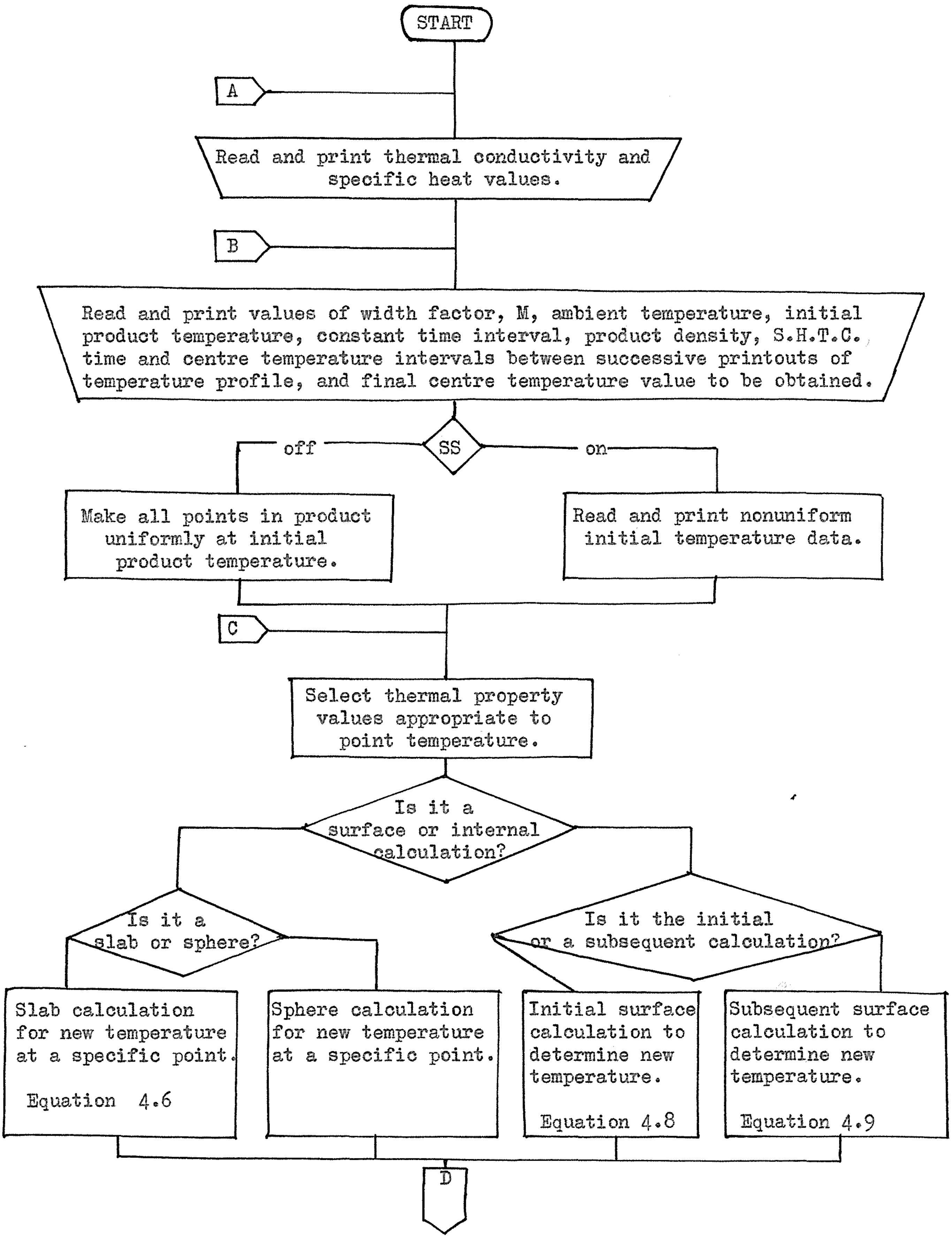


FIG.4. (Continued)

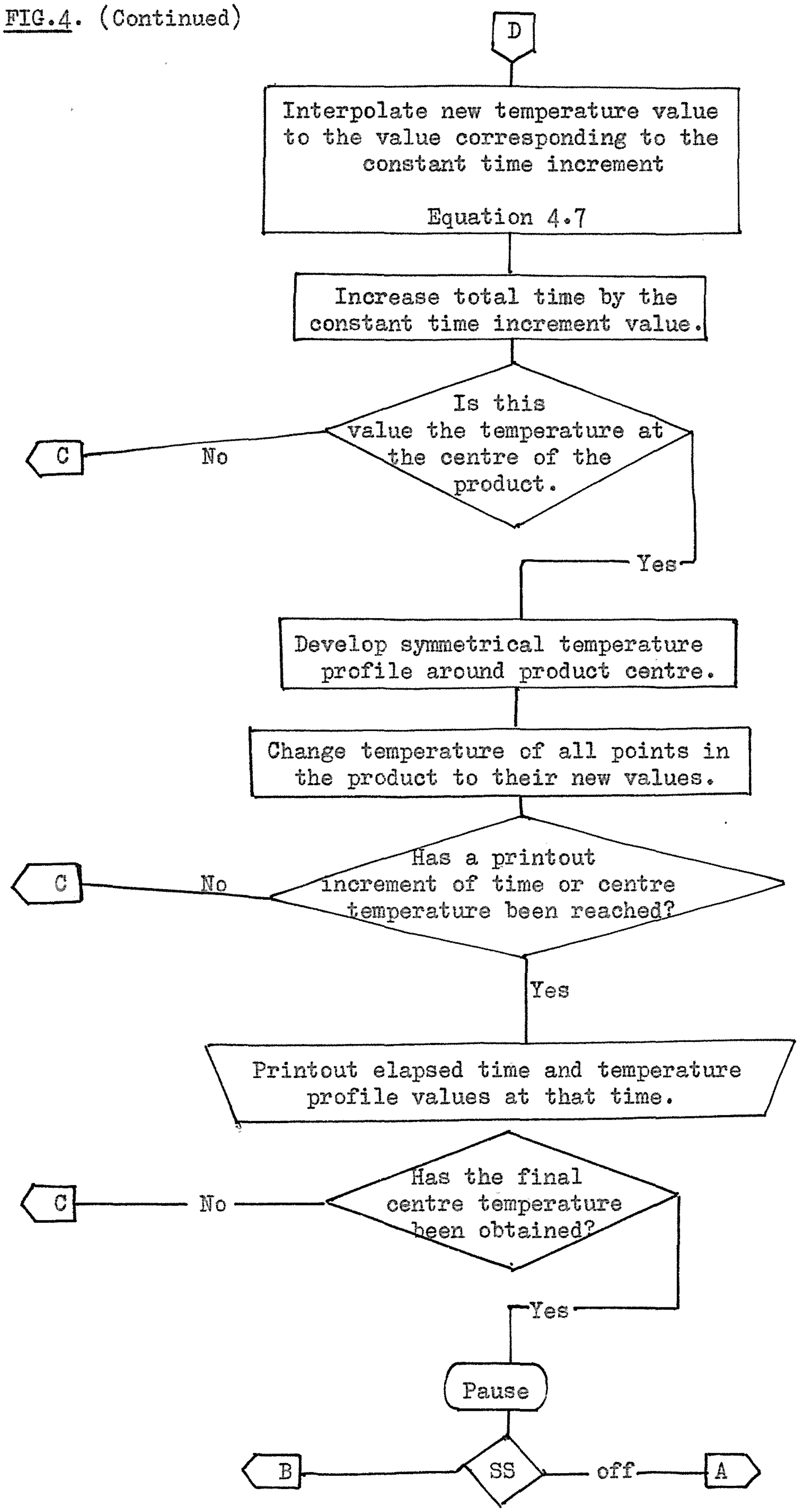


FIG. 5. FORTRAN - 2 PROGRAMME FOR NUMERICAL SOLUTION OF FREEZING PROBLEM

```
      DIMENSION T(50),TI(50),CON(20),SPEC(20)
 57   READ 200,IQ
200   FORMAT(I2)
      DO 102 I = 1,50
      T(I) = 0.
102   TI(I) = 0.
      DO 100 I = 1,20,5
      READ 1,CON(I),CON(I+1),CON(I+2),CON(I+3),CON(I+4)
100   PRINT1,CON(I),CON(I+1),CON(I+2),CON(I+3),CON(I+4)
      DO 101 I = 1,20,5
      READ 1, SPEC(I),SPEC(I+1),SPEC(I+2),SPEC(I+3),SPEC(I+4)
101   PRINT 1, SPEC(I),SPEC(I+1),SPEC(I+2),SPEC(I+3),SPEC(I+4)
 26   READ 2,N,EM,TS,B,DDT,DZ,DEN,H,TMN,TNP,TTP
      PRINT 300,IQ
300   FORMAT(I2)
      PRINT 2,N,EM,TS,B,DDT,DZ,DEN,H,TMN,TNP,TTP
      IX = 0
      NX = N+1
      IF(SENSE SWITCH 2)66,5
 66   DO 103 I = 1,NX,5
      READ 1,T(I),T(I+1),T(I+2),T(I+3),T(I+4)
103   PRINT1,T(I),T(I+1),T(I+2),T(I+3),T(I+4)
      GO TO 67
  5   DO 9 I = 1,NX
  9   T(I) = B
 67   BZ = DZ*DZ*DEN/EM/144.
      BM = EM-2.
      T1M = O.
      TNP = B-5.
      TMM = TMN
 21   DO10I = 1,N
      TY = T(I)
      L = TY/10.+4.
      IF (L)69,70,69
 70   L = L+1
      GO TO 3
 69   IF(L-6)3,4,8
  8   IF(L-7)4,6,7
  7   L = L-2
      GO TO 3
  4   L = TY-11.
      GO TO 3
  6   L = TY/5.+13.
  3   BNT = H*DZ/CON(L)/12.
      BT = BNT*TS
      BY = BM*TY
      IF(I-1)201,201,12
201   IF(IX)203,204,203
```

FIG. 5. (Continued)

```
204   IX = 1
      TX = .5*(T(1) + (BNT*TS + T(2))/(BNT + 1.))
      GO TO 10
203   TQ = (T(1) + (EM - 2.)*T(2) + T(3))/EM
      TX = (BNT*TS + TQ/(BNT + 1.)
      GO TO 10
 12   TX = 0.
      IF(IQ)30,14,30
 30   IF(I-N)13,31,13
 31   TX = (6.*T(I+1) + (EM-6.)*TY/EM
      GO TO 10
 13   R = N-I
      TX = (T(I-1)-T(I+1))/EM/R
 14   TX = TX + (T(I+1) + T(I-1) + BY)/EM
 10   TI(I) = DDT/BZ*(TX-TY)*CON(L)/SPEC(L) + TY
      TIM = TIM + DDT
 39   DO 16 I = 1,N
      IF(I-N)16,17,16
 17   T(I+1) = TI(I-1)
 16   T(I) = TI(I)
      M = 3
      IF(TIM-TMM)32,33,33
 33   TMM = TMM + TMN
      M = 2
 32   IF(T(N)-TNP)18,18,19
 18   TNP = TNP-5.
      M = 2
 19   IF(T(N)-TTP)23,23,22
 22   IF(M-2)24,20,24
 24   IF(SENSE SWITCH 1)20,21
 23   M = 1
 20   TYPE1,TIM
 25   DO 51 I = 1, N,5
 51   TYPE1,TI(I),TI(I+1),TI(I+2),TI(I+3),TI(I+4)
 40   IF(M-2)56,21,21
 56   PAUSE
      IF (SENSE SWITCH 3) 26,57
  1   FORMAT(5F8.2)
  2   FORMAT(I2,10F7.3)
      END
```

FIG. 6. NUMERICAL SOLUTION FOR THE FREEZING OF A 2 INS THICK SLAB

.96	.93	.89	.83	.77
.28	.29	.30	.71	.69
.67	.65	.62	.58	.53
.46	.36	.32	.27	.27
.50	.50	.50	.90	1.30
1.00	1.00	1.00	1.80	2.00
2.30	2.50	3.10	3.30	4.60
6.80	27.00	23.00	1.00	1.00

0

5 4.000-40.000 62.000 .005 .250 67.000 99.000 .250 5.000-10.000

.18	-21.16	26.84	43.80	53.74	56.89
.25	-24.35	10.91	37.31	49.14	52.64
.26	-24.79	9.19	35.96	48.32	51.93
.32	-26.76	1.82	29.40	42.41	46.83
.39	-26.97	1.04	28.88	38.11	41.68
.47	-27.11	.58	28.10	34.39	36.86
.50	-27.18	.40	27.46	33.53	35.76
.59	-29.27	-6.21	15.12	29.60	31.80
.75	-30.77	-10.95	8.79	28.31	29.84
1.00	-32.55	-16.56	-.90	14.30	28.14
1.03	-32.71	-17.06	-1.60	13.49	26.98
1.06	-32.87	-17.57	-2.61	11.62	21.54
1.08	-33.04	-18.09	-3.69	9.50	15.92
1.10	-33.34	-19.03	-5.75	5.52	10.99
1.12	-33.67	-20.07	-7.61	2.71	6.77
1.14	-34.28	-22.02	-11.28	-3.31	.77
1.16	-34.77	-23.55	-13.86	-7.07	-4.59
1.17	-35.27	-25.13	-16.61	-10.85	-8.82
1.18	-35.44	-25.66	-17.49	-12.04	-10.06

5.0 - centre temperature increment between temperature profile printouts (^{o}F).

-10.0 - final value of centre temperature required (^{o}F).

The temperature profile presentation is as follows:-

Time (hrs)	·18				
Temperature (^{o}F)	-21.16	26.84	43.80	53.74	56.89
	1	2	3	4	5

1. Surface temperature.
2. Temperature 0.25 ins. below surface.
3. " 0.50 " " "
4. " 0.75 " " "
5. Centre temperature, 1.00 ins. below the surface.

4.6. Validity of Numerical Solution:

Having established a suitable computer programme it was necessary to check the validity of the solution against an analytical solution. This was necessary because the numerical solution was only an approximate solution to the freezing problem. It was desirable to check the solution for a freezing problem but as no suitable analytical solutions were available the validity check was made for the cooling of a slab with finite surface heat transfer coefficient, for which an analytical solution is available in the literature, Dalgleish (10).

In this solution the centre temperature of the slab was calculated by using the following equation:-

$$\theta_c = \sum_{n=1}^{\infty} \frac{2N}{(N^2 + N + V_n^2) \cos V_n} \exp(-V_n^2 T)$$

where θ_c - centre temperature of slab (^oF).

V_n - n^{th} root of the transcendental equation $V \tan V = N$.

$N = \frac{ha}{k}$ $\quad 0 \leq N \leq \infty$

h - surface heat transfer coefficient (Btu/hr ^oF ft^2).

a - product thickness $= 2a$ (ft).

k - thermal conductivity of slab (Btu/hr ^oF ft).

$\tau = \frac{kt}{c\, a^2}$ $\quad 0 \leq \tau \leq \infty$

t - elapsed time (hrs).

ρ - product density (lbs/ft^3).

c - specific heat (Btu/lb ^oF).

The roots of the transcendental equation $V \tan V = N$ were obtained from Carslaw and Jaeger (7) and it was found that only the first root of the equation was significant in the solution except when the value of t was less than 0.4 hrs.

The cooling curves were obtained for the cooling of a 3 ins thick slab, initial temperature 60^oF, ambient temperature -40^oF surface heat transfer coefficient of 99 Btu/hr ^oF ft^2, thermal conductivity of 0.78 Btu/hr ^oF ft, specific heat of 0.5 Btu/lb ^oF. The values obtained by calculation from the analytical and numerical solution are shown in Table IV.

A significant deviation was found to exist in the initial stages of cooling, but after that the temperatures obtained from the two solutions correlated closely. It was considered that despite the initial deviation which existed between the two solutions, the numerical solution gave an accurate prediction of the time-temperature profile which would exist in a product.

Table IV. Validity of Numerical Solution

Time (hrs)	Centre Temperature (^{o}F)	
	Analytical	Numerical
0.2	24.50	26.61
0.4	- 5.70	- 5.25
0.6	-21.75	-21.91
0.8	-30.19	-30.58
1.0	-34.81	-35.10
1.2	-37.19	-37.45

4.7. Conclusions:

A numerical solution of the freezing problem was used to predict the freezing curves obtained during the one-dimensional freezing of a homogeneous product. It was found that after careful selection of the parameter values in the modulus M, the numerical solution closely approximated the analytical solution for the cooling of a slab with constant thermal properties. From this it was assumed that the numerical solution also gave a valid solution of the freezing problem. It was thus concluded that the numerical solution of the freezing problem deals adequately with the heat transfer boundary conditions which exist under normal freezing conditions.

CHAPTER 5

EXPERIMENTAL DETERMINATION OF FREEZING CURVE

In this study the accuracy with which the freezing curve of a product could be predicted by a numerical solution of the freezing problem was determined by comparing the numerical solution and experimental freezing curves obtained under the same freezing conditions. The numerical solution was for the one-dimensional freezing of a homogeneous product, conditions which were closely approximated experimentally by freezing minced lean beef in a plate freezer.

Accurate determination of the experimental freezing curves necessitated precise low temperature measurement with thermocouples, the establishment of a one-dimensional freezing system and the availability of a homogeneous product. It was shown in Section 2.1 that the minced lean beef used in these experiments closely approximated a homogeneous product.

5.1. Temperature Measurement with Thermocouples:

Temperature measurements were made by using 24 gauge copper-constantan thermocouple wires in conjunction with a 12 point Brown potentiometric recorder. This recorder had an automatic temperature compensating cold junction. The recording system was set against an ice junction and the temperatures recorded were $\pm$ 0.5^{o}F. For precise temperature measurement it was necessary to minimise any errors resulting from heat transmission along the thermocouple leads, and inaccuracies in the thermocouple location.

(i) Heat Transmission along the Leads:

The temperatures recorded were considered to be those of the product at the site of the thermocouple location. This assumption was not valid if heat was transferred along the thermocouple leads; either to or away from the measuring junction, a possibility which may occur in a copper-constantan thermocouple. This was because of the high thermal conductivity of the copper wire in the thermocouple. The quantity of heat flowing along the leads is proportional to the thermal conductivity, the cross-sectional area, and the temperature gradient along the wire.

Errors in temperature measurement caused by such heat transfer were minimised by:-

(i) Decreasing the cross-sectional area of the wire which involves using a higher gauge wire. The higher the gauge, the thinner the wire and this caused difficulties in its practical use.

(ii) Decreasing the temperature gradient along the leads. This was done by introducing the thermocouple leads to the measuring junction through an isothermal zone.

In these experiments, 24 gauge thermocouple wire was used, and the existence of heat transmission along the leads was checked by measuring the temperature of the point immediately adjacent to the 24 gauge thermocouple wire with 36 gauge and 18 gauge thermocouple wire. It was considered that if heat transmission along the leads was significant, then the temperatures recorded by the thermocouples made of different gauge wire would be different. The centre temperatures of a 4 ins. thick slab of minced meat measured with the different gauge thermocouple wires are shown in Fig. 7. and it can be seen

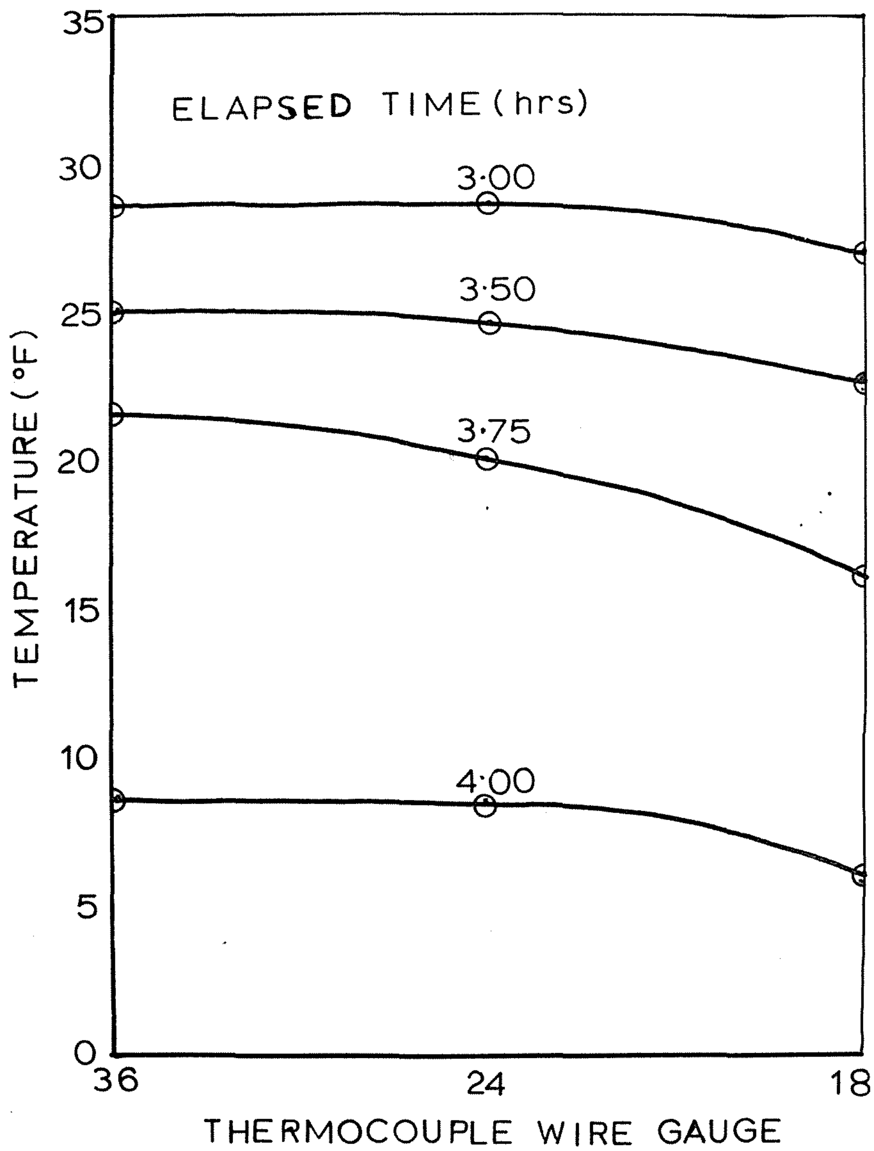


FIG. 7 Effect of Thermocouple Wire Gauge on Temperature of Measuring Junction at Slab Centre During Freezing

that the temperatures measured with 36 gauge and 24 gauge wire were generally the same, but different from those measured with 18 gauge wire. Hence in this experimental system, the temperatures measured using thermocouples made of 24 gauge wire were not subject to significant error because of heat transmission along the leads.

(ii) Location of Thermocouples:

For the measured temperatures to be of value, it was necessary to know the exact location in the experimental system at which they were obtained. The experimental system consisted of a wooden mould made of $\frac{3}{4}$ ins. wood, which was filled with minced lean beef and it was desired to measure the temperatures at different points in this system.

The two wires of the thermocouple pair were introduced into the meat from opposite ends of the mould (Fig. 8) and by keeping the wires taut after the junction had been made between them, it was possible to accurately locate the vertical plane in which the thermocouple junction was located. Accurate location of the thermocouple junction in a specific horizontal plane was critical because the one-dimensional freezing of a product was being studied, and it was obtained by the following technique.

The minced lean beef was placed in a rigid wooden mould (Fig. 8) of selected height before being frozen. Guide rods were passed across this mould at different selected heights and the thermocouple junction was placed on top of the appropriate guide rod. The guide rods were rigid, being $\frac{1}{8}$ ins. bronze welding rods, and when these were passed through close tolerance holes of $\frac{3}{4}$ ins. depth on each side of the rigid mould, the horizontal plane was precisely located. The minced lean beef was packed around the thermocouples until the

FIG. 8 Thermocouple Entry into Experimental Mould.

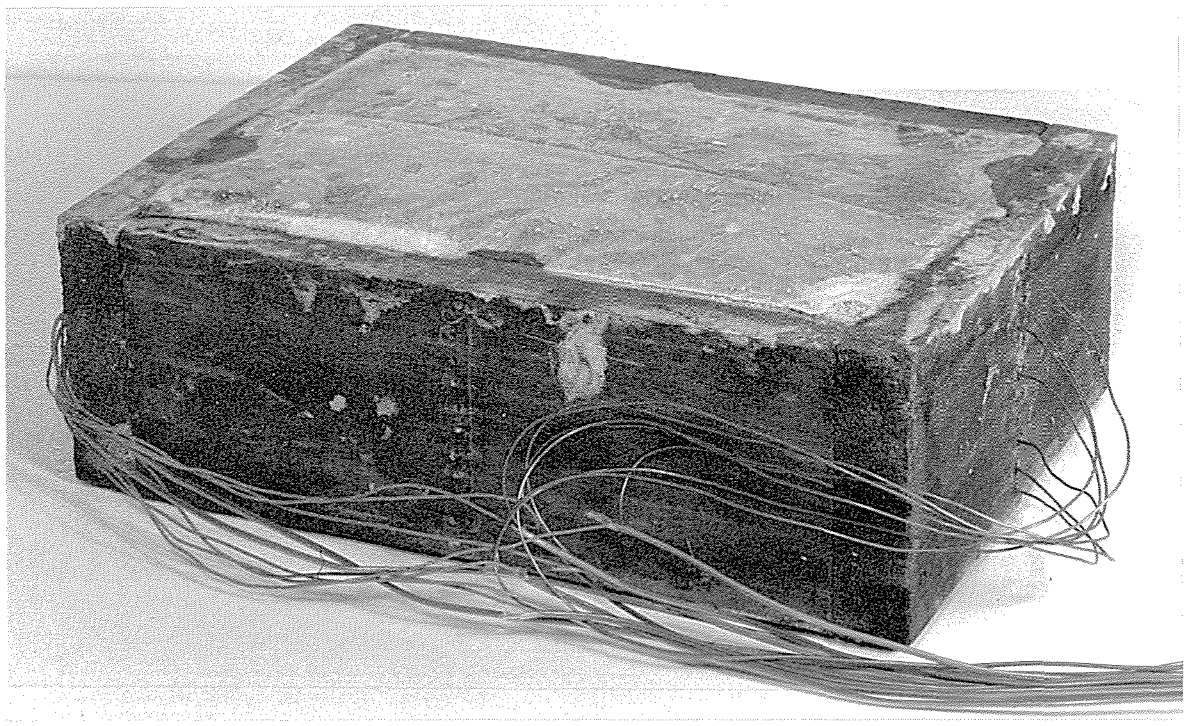
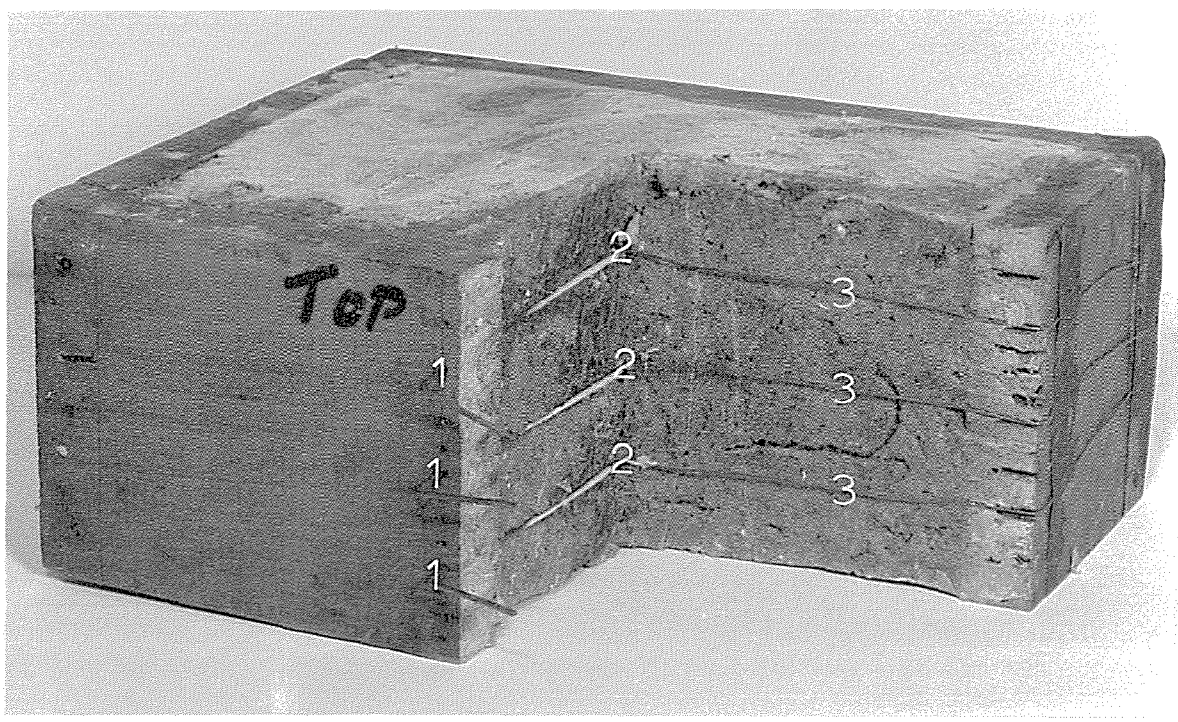


FIG. 9 Thermocouple Location Technique.



1. Guide rods.

2. Thermocouple junctions.

3. Isothermal entry of thermocouple leads.

mould was full, when the guide rods were carefully removed. It was thus possible to accurately locate the thermocouple junctions at specified positions in the mould.

A cutaway section of a mould with the guide rods still in position, is shown in Fig. 9. The thermocouple junctions are located directly on top of the guide rods. It can also be seen that the thermocouple leads enter the product on the same plane as their junction, giving an isothermal entry of the lead which minimises any heat transmission along the lead.

The accuracy of this location technique was checked by cutting the mould in half after the product had been frozen and determining the exact location of the thermocouples. As a result of such checks, it was considered that this technique gave an accurate means of locating the thermocouples in the product.

5.2. Establishment of a One-Dimensional Freezing System:

The freezing of a large slab of product in a plate freezer represented a one-dimensional freezing system. In these experiments small slabs were used to minimise the amount of a product used, but with small slabs heat loss from the sides of the slab may become significant. In the slabs used in these experiments heat transfer from the sides of the slabs did occur, but the freezing curve of the slab was unaffected because a one-dimensional system was still maintained in the central region of the slab, where temperature measurements were made. The use of a wooden mould helped to minimise this loss of heat from the slab sides.

If one-dimensional freezing was established in the slab then the temperatures at any point in a given horizontal plane would be the same at any given time. The temperatures measured at different points in the horizontal plane at

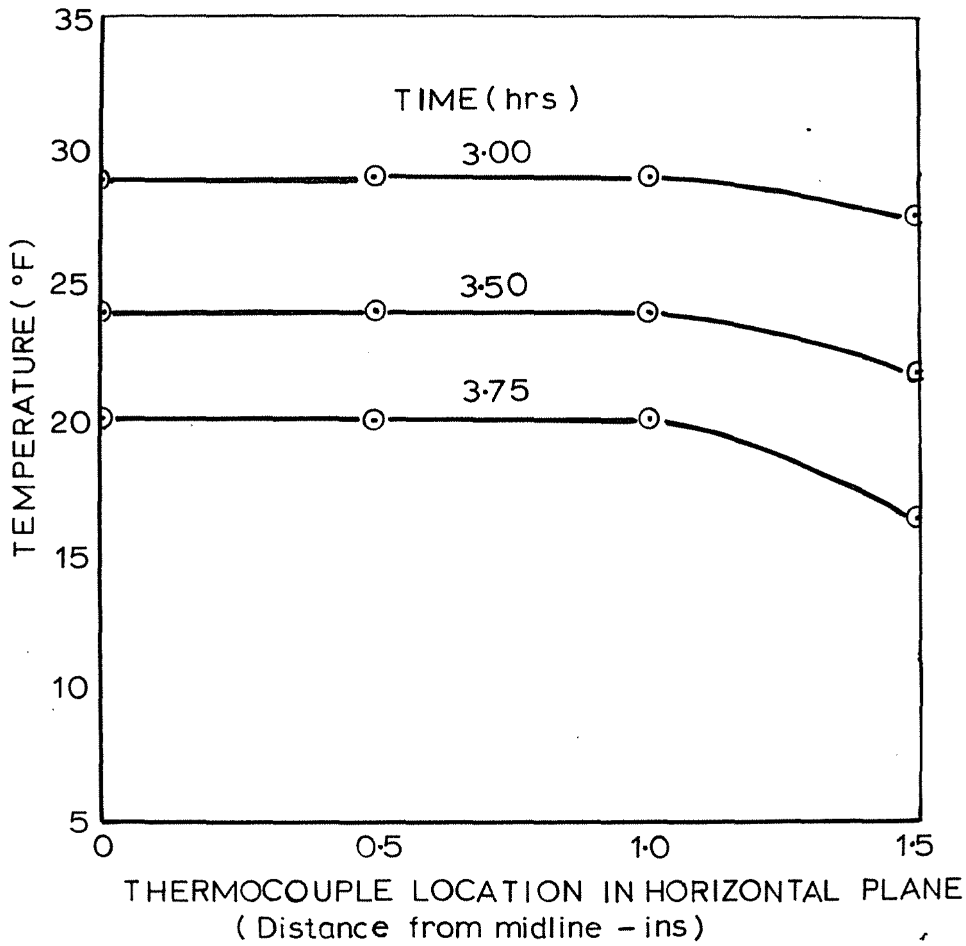


FIG.10 Establishment of One-Dimensional Freezing

the centre of a slab of width 6 ins., length 8 ins. and thickness 4 ins. are shown in Fig. 10. Whilst the temperature of the outer region is lower than the centre, indicating some surface cooling, the central points are at the same temperature, indicating one-dimensional freezing in this region.

Similar checks made upon the slabs of 5 ins., 3 ins. and 2 ins. thickness showed that one-dimensional freezing occurred in these slabs.

5.3. Establishment of Controlled Experimental Conditions:

To be of value for the comparisons with numerical solution freezing curves, the experimental freezing curves had to be obtained under a variety of controlled experimental conditions. The parameters to be controlled were the plate temperature, the initial product temperature and the product thickness.

(i) Plate Temperature:

The temperature of the plates was determined by the refrigerant passing through them, the refrigerant flow being determined by the operation cycles of the compressor. Accurate plate temperature control thus required a system in which the operation cycles of the compressor were controlled by the deviations of the plate temperature from some set point. As the plate temperature was the sensory element of the control, it required accurate measurement and this was done using a copper-constantan thermocouple soldered to the bottom plate. This temperature measurement activated a Honeywell on/off controller to control the operation of the compressor. Use of this type of system resulted in plate temperature control of $\pm$ 2^{o}F. Ostensibly the top plate should have been at the same temperature and within the same limits as the bottom plate, because they were operating off a common refrigerant feed line. However, it was found that because of the basic design of the freezing plates the top plate responded more quickly to the operation cycles of the compressor and this resulted in a plate temperature 2°F below the bottom plate temperatures and control limits of ± 3°F. The layout of the control system used in the experiments is shown in Fig. 11.

(ii) Initial Product Temperature:

At the start of each experimental run it was desired to have the product mass uniformily at some selected temperature. This was achieved by placing the minced lean beef in a cool room of the appropriate temperature until such time that the product was uniformly at the required temperature. The uniformity of product temperature was checked by measuring the temperature at different points in the product mass and determining their uniformity.

(iii) Product Thickness:

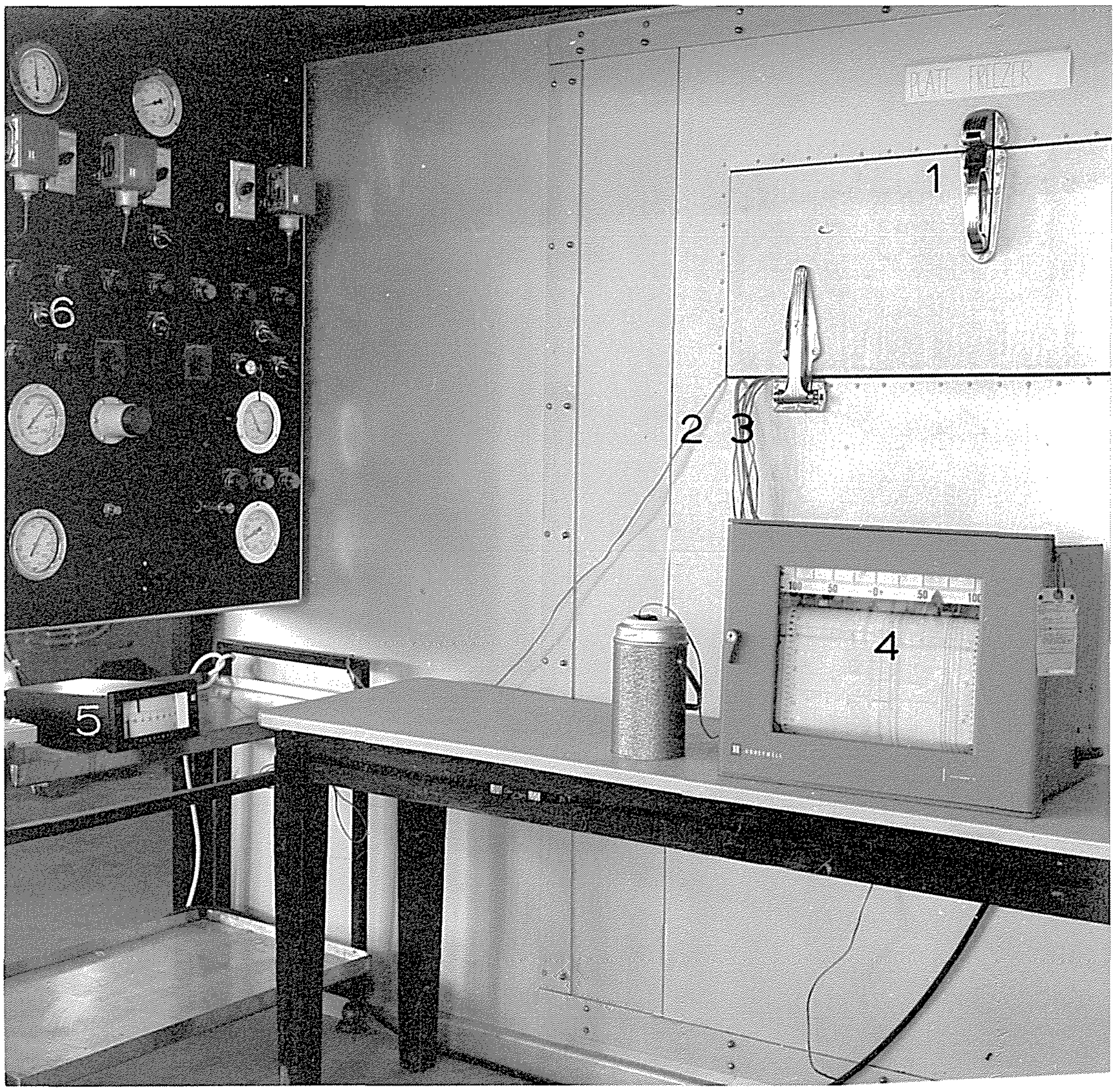
The moulds in which the minced beef was placed were made to specific heights and by filling them exactly to the top with minced beef, the slab thickness was controlled. As freezing proceeded, the product thickness was found to increase a small amount due to the volume changes occuring in the product as a result of the freezing. No account was made in the numerical solution for this volume change.

5.4. Experimental Procedure:

For a given experiment, the plate temperature, the product thickness and the initial product temperature were fixed and these conditions were obtained by the procedures outlined.

The minced lean beef at the required temperature was packed into the appropriate wooden mould and the thermocouples were located in the required positions in the minced beef. The mould was filled and then was ready to be

FIG. 11 Layout of Experimental Equipment.



1. Plate freezer.

2. Thermocouple activating Honeywell controller.

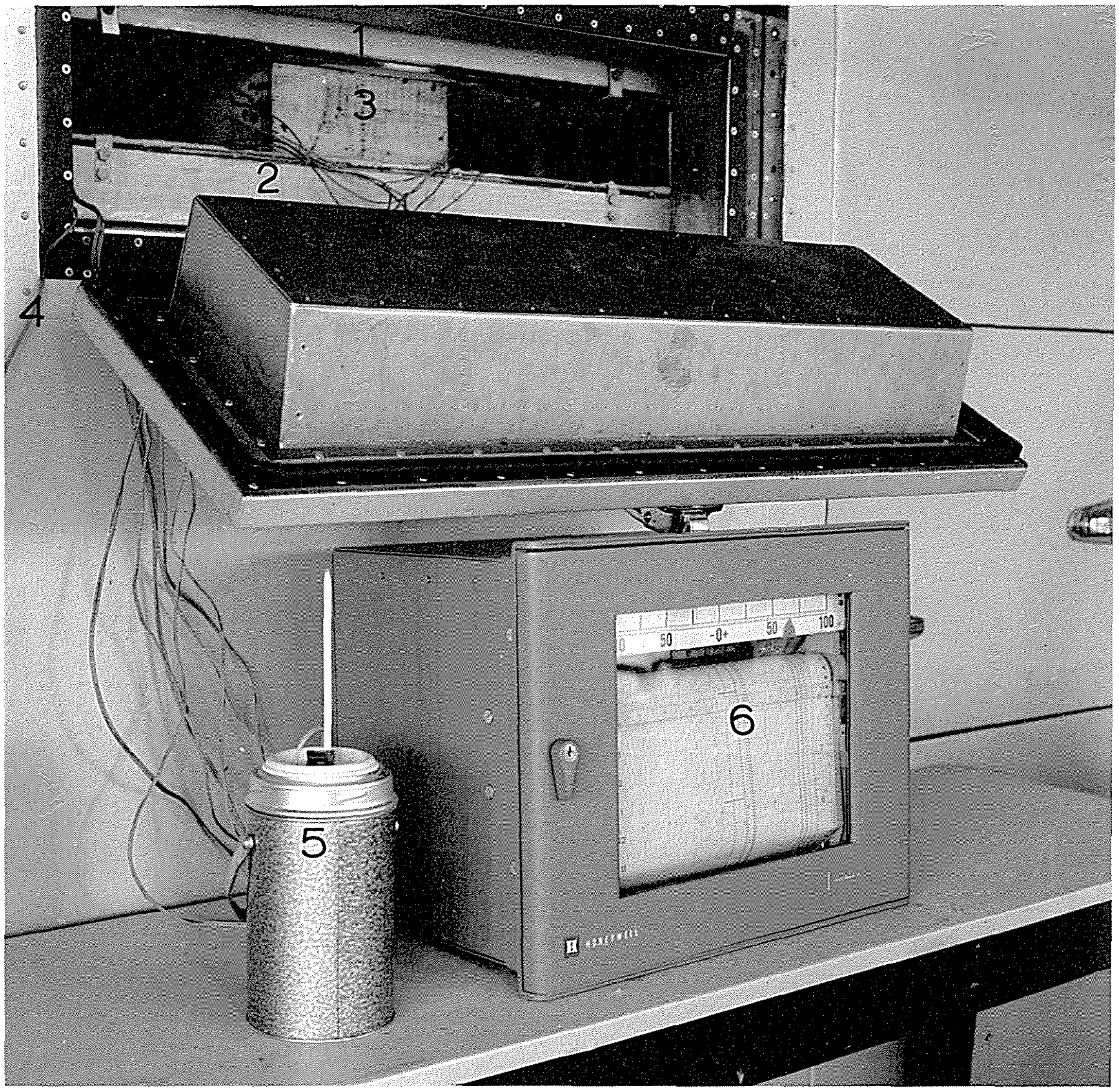
3. Thermocouples from meat mould.

4. Temperature recorder.

5. Honeywell controller.

6. Control switchboard for plate freezer.

FIG. 12 Location of Mould in Plate Freezer.



1. Top plate of plate freezer.

2. Bottom plate of plate freezer.

3. Experimental mould.

4. Thermocouple activating Honeywell controller.

5. Ice junction.

6. Temperature recorder.

frozen. Initially the temperatures at the different points were recorded to check the uniformity of product temperature. When this had been established, the mould was slid off a stainless steel plate onto its position on the freezing plate, by now at its required temperature. The top plate was then brought into firm contact with the top of the mould. To maintain standard surface conditions on the plates, they were wiped free of any snow prior to placing the mould into position as shown in Fig. 12. The minced beef was then cooled and gradually frozen, the temperature at different points being recorded by the Brown recorder. The product was considered to be frozen when the temperature of the thermodynamic centre reached -10°F. During the freezing of the product, the two plate temperatures were also recorded.

A variety of experimental conditions were considered and they included:-

(i) Product thickness (ins.) 2, 3, 4, 5.

(ii) Plate temperature ($^{\circ}$F.) -23, -31, -40.

(iii) Initial product temperature in the range of 40°F., 50°F., 60°F.

Freezing curves were obtained for the various combinations of these parameters.

5.5. Conclusion:

An experimental system was developed in which the one-dimensional freezing of a homogeneous product occurred. This involved freezing suitably sized slabs of well mixed minced lean beef in a plate freezer. By suitable temperature measurements, the freezing curve of the product for a given set of experimental freezing conditions was obtained.

CHAPTER 6

DETERMINATION OF THE SURFACE HEAT TRANSFER COEFFICIENT

The surface heat transfer coefficient (S.H.T.C.) is a measure of the total resistance to heat transfer between the minced beef surface and the refrigerated plate surface. It includes any resistance to heat transfer offered by packaging material present in the contact surface. The S.H.T.C. was determined by the following methods.

6.1. Freezing Curve Correlation:

Experimental freezing curves were obtained when slabs of minced lean beef were placed in direct contact with the refrigerated plates of a plate freezer. The freezing conditions of a given experiment specified the values of the process parameters, the thermal property values of the minced lean beef had been determined and hence it was possible to obtain the appropriate numerical solution freezing curve if a suitable S.H.T.C. was selected. A trial and error selection of the S.H.T.C. value was made until a value was obtained which gave a close correlation between the numerical solution and experimental curves. It was assumed that this value was the S.H.T.C. value which existed in the experimental system. Correlations of this type were made for a range of experimentally determined freezing curves and it was found that an S.H.T.C. value of 99 Btu/hr ^{o}F ft^2 gave a close correlation for the 4 and 5 ins. thick slabs of minced lean beef. The numerical solution and experimental freezing curves for these correlations are shown in Fig. 13 and Fig. 14 respectively. It must be noted that the nature of the computer programme prevented the selection of a S.H.T.C. value higher than 99. Further the selection of a S.H.T.C.

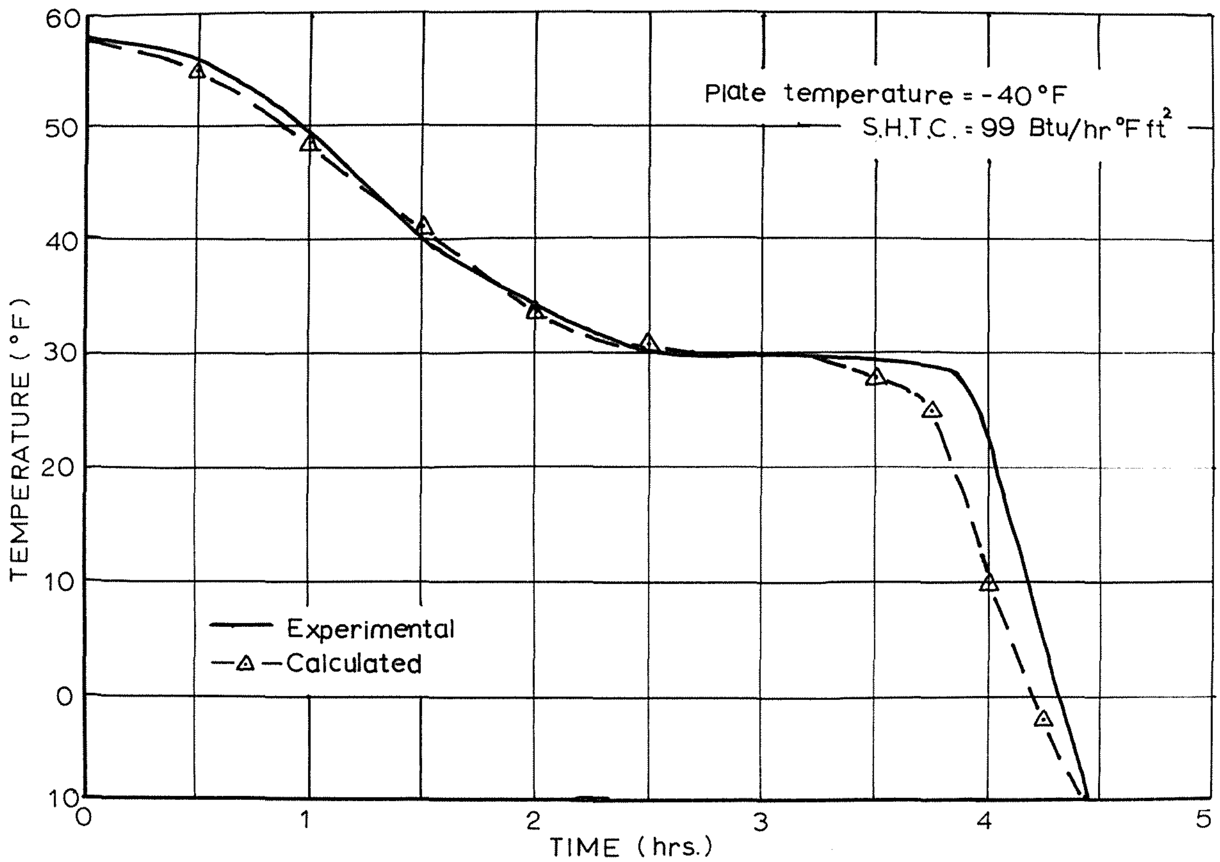


FIG.13 FREEZING CURVE for 4ins thick slab

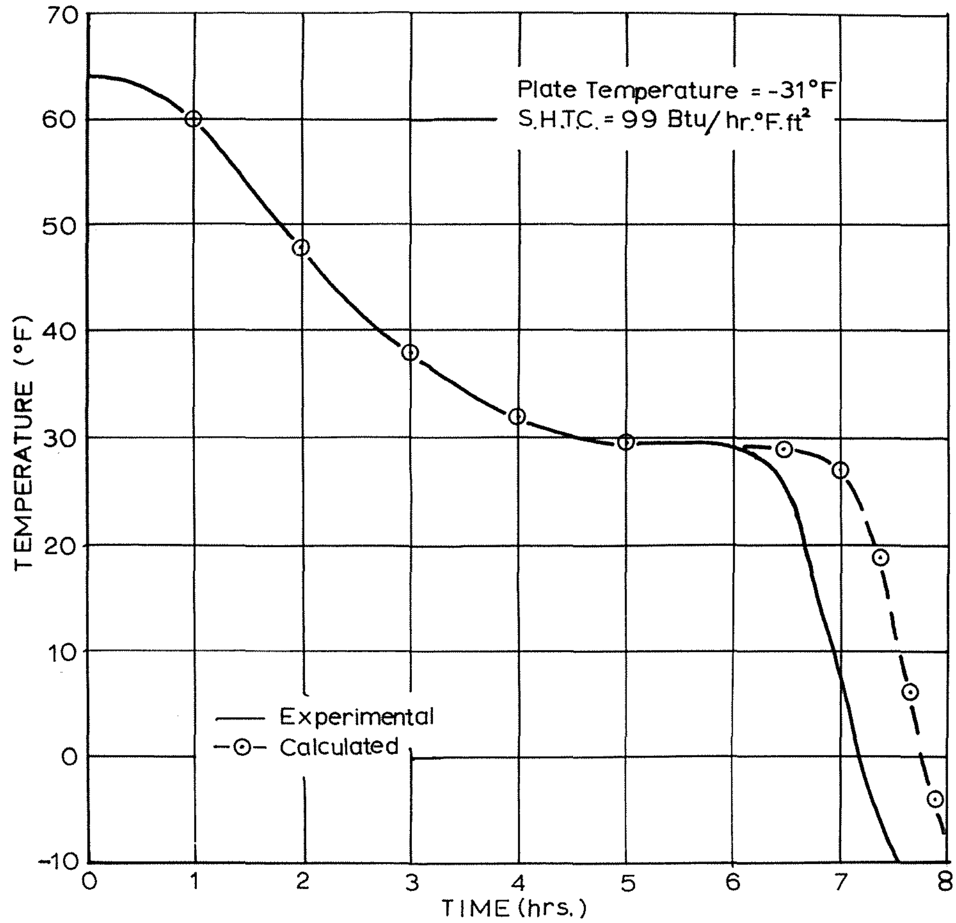


FIG.14 FREEZING CURVE for 5 ins thick slab

value by this technique did not give a precise S.H.T.C. value but rather a value of the correct order of magnitude. The computed S.H.T.C. value of 99 was thus in accordance with the value of 100 proposed by Rutov (38) for a direct contact system, and Watzinger (40) for a slab covered with a layer of cellophane. To obtain a similarily close correlation between the numerical solution and experimental freezing curves for 2 ins. and 3 ins. thick slabs it was necessary to select a value of 23 and 35 Btu/hr $^{o}F\ ft^{2}$ and this indicated that a lower S.H.T.C. existed in the experimental system when thin slabs of minced beef were frozen. This variation in S.H.T.C. value with slab thickness was surprising because in these experiments all the slabs had been frozen under the same surface conditions. It was thus necessary to make a closer examination of the nature of the contact surface established between the beef surface and the refrigerated plate surface.

6.2. Contact Surface:

When the refrigerated plates were brought into contact with the beef slab surfaces a contact surface was established, the nature of which determined the level of the S.H.T.C. of the system. A solid contact surface was established when direct contact was made between the refrigerated plate and the beef slab over the entire contact surface. This type of contact surface offered a low resistance to heat transfer and thus had a high S.H.T.C. It was also possible to establish a contact surface in which there were regions of direct contact and regions of small air pockets. The presence of such air pockets significantly reduces the S.H.T.C. value of the contact surface, relative to a solid contact surface because the air pockets represent regions in which a stationary phase of a low thermal conductivity medium exists. The S.H.T.C. of the contact surface established in the experimental system may be determined from the following equation.

$$\frac{1}{h_c} = \frac{A_1}{h_s} + \frac{A_2}{h_a}$$

where h_c - S.H.T.C. of experimental contact surface (Btu/hr ^oF ft^2)

h_s - S.H.T.C. of solid contact surface (Btu/hr ^oF ft^2)

h_a - heat transfer coefficient of air pockets (Btu/hr ^oF ft^2)

A_1 - proportion of solid contact surface area in the total contact area.

A_2 - proportion of air pocket contact area in the total contact area.

The S.H.T.C. of the solid contact surface was assumed to be 100 Btu/hr ^oF ft^2 and the heat transfer coefficient of the air pockets, 1/16 ins. in depth, thermal conductivity 0.014 Btu/hr ^oF ft (Earle 14) was 2.7 Btu/hr ^oF ft^2. From these heat transfer coefficient values it was possible to determine the S.H.T.C. values which would be obtained in typical experimental contact surfaces.

Example 1

A contact surface in which 90% of contact area was solid contact and 10% of contact area was air pockets. Hence

$$\frac{1}{h_c} = \frac{0.90}{100} + \frac{0.10}{2.7}$$

$$= 0.046$$

$$h_c = 21.7$$

Example 2

A contact surface in which 95% of contact area was solid contact and 5%

of contact area was air pockets. Hence

$$\frac{1}{h_c} = \frac{0.95}{100} + \frac{0.05}{2.7}$$

$$= 0.028$$

$$= 35.6$$

From these examples it was evident that a contact surface which contains small regions of air pockets could have a much lower S.H.T.C. than a solid contact surface. The significance of the change in S.H.T.C. caused by the presence of air pockets in the contact surface depends upon the magnitude of the S.H.T.C. of the solid contact surface. In these experiments the solid contact surface appeared to have a high S.H.T.C. (100 Btu/hr ^{o}F ft^{2}) and hence the presence of even small regions of air pockets would significantly reduce the S.H.T.C. of the contact surfaces.

Standard surface conditions were maintained between experiments by wiping the refrigerated plates free of snow and smoothing the slab surface. However, there was a variation of S.H.T.C. value with product thickness in the experiments and this was assumed to indicate that despite these precautions there was a variation in the amount of air pockets present in the contact surface. Because the S.H.T.C. values established during the freezing of a 2 ins. and 5 ins. thick slab were 23 Btu/hr ^{o}F ft^{2} and 99 Btu/hr ^{o}F ft^{2} respectively, it was assumed that air pockets were more prevalent in the contact surface developed during the freezing of thin slabs. This was possibly caused by the existence of a higher contact pressure between the slab surface and the refrigerated plate surface when thick slabs were frozen. If this was so then any air pockets in the contact surface would be shallower than when a low contact pressure existed and this would cause a higher S.H.T.C. value to be established in the experimental system. As yet, positive confirmation of this theory has not been established, but the nature of the freezing system could cause a variation in the contact pressure. The refrigerated plates were brought into firm contact with the top of the slab but the expansion of the minced lean beef during freezing (approximately 10% in these experiments) caused an increase in the slab thickness. This increase in slab thickness would directly cause an increase in the contact pressure between the slab surface and the refrigerated plates because the refrigerated plates were held firmly in their original positions. As the absolute increase in thickness was largest for thick slabs, the probable increase in contact pressure would be greater with thick slabs. This theory would plausibly account for the experimental variations of S.H.T.C. with slab thickness but it has not been experimentally substantiated.

6.3. Packaging Material Studies:

The nature of the contact surface and its S.H.T.C. value were modified by introducing packaging materials of different thermal resitances into the contact surface. A variety of modifications was possible because of the range of thermal resistances of commercial packaging materials. The heat conductance of different packaging materials are shown in Table V. Other published values, Dunker and Hankins (11) and Bratzler and Tucker (6) were in terms of a percentage increase in freezing times as a result of using certain packaging materials around a product frozen in an air blast freezer.

In these experiments the nature of the contact surface was modified in an effort to minimise the apparent presence of air pockets in the contact surface. The beef slab surface was wetted; smoothed and carefully covered

Table V. Heat Conductance of Packaging Materials

Packaging Material	Heat Conductance $\frac{Btu}{hr\ ^oF\ ft^2}$
(i) MacFarlane (25)	
Solid Fiberboard 080	5.40
Corrugated Cardboard 313C	1.98
Corrugated Cardboard 616B	2.68
(ii) Watzinger (40)	
Waxed Paper in Outer Cardboard Box	10.3
Waxed Paper Cardboard Box	15.4
Waxed Paper	33.9
Alfol Wrapping	53.6
Cellophane	100.0
(iii) Rutov (38)	
No wrapping	100.0
Parchment	55.4
Parrafined Semiparchment	33.2
Parrafined Cardboard	25.8
Tin Sheets	24.4
Cardboard & Semiparchment	20.4

with a layer of 0.0025 ins. thick polyethylene, thermal conductivity of 0.19 Btu/hr °F ft (Perry 31), has a heat conductance of 916 Btu/hr °F ft^2. This heat conductance value indicated a very small resistance to heat transfer and was neglected for calculation purposes. Hence experimental results obtained when the product surface was covered with 0.0025 ins. thick polyethylene were the same as a no-packaging contact system. From correlations made between the numerical solution and experimental freezing curves for a 2 ins. slab covered with a layer of 0.0025 ins. polyethylene it was found that an S.H.T.C. of 40 Btu/hr °F ft^2 existed in the system. Although not as high as the S.H.T.C. value of 99 Btu/hr °F ft^2 obtained during the initial correlation studies for a 4 ins. and 5 ins. thick slab, it was much higher than the S.H.T.C. value of 23 Btu/hr °F ft^2 found in the same studies. This technique thus presumably reduced the amount of air pockets present in the contact surface.

In other experiments the contact surface was modified by inserting a layer of solid fiberboard 080 on the top of the polyethylene layer. This packaging material had a heat conductance of 5.4 Btu/hr °F ft^2 (MacFarlane 25) which constituted a high resistance to heat transfer. It was a much lower value than the S.H.T.C. of a solid contact system or the heat conductance of the apparent air pockets and hence the overall S.H.T.C. of the experimental system was very low. This also meant that any presumed air pockets in the contact surface had a small effect upon the overall S.H.T.C. Correlations were made between the numerical solution and experimental freezing curves obtained during the freezing of slabs whose surfaces were covered with a layer of 0.0025 ins. thick polyethylene and a layer of solid fiberboard 080. It was found that an S.H.T.C. of 8 Btu/hr °F ft^2 gave a good correlation for a 4 ins. thick slab, Fig. 15; for a 3 ins. thick slab and for a 2 ins. thick slab, Fig. 16. The establishment of a constant S.H.T.C. value with different slab thicknesses indicated that the high thermal resistance of the packaging material had masked

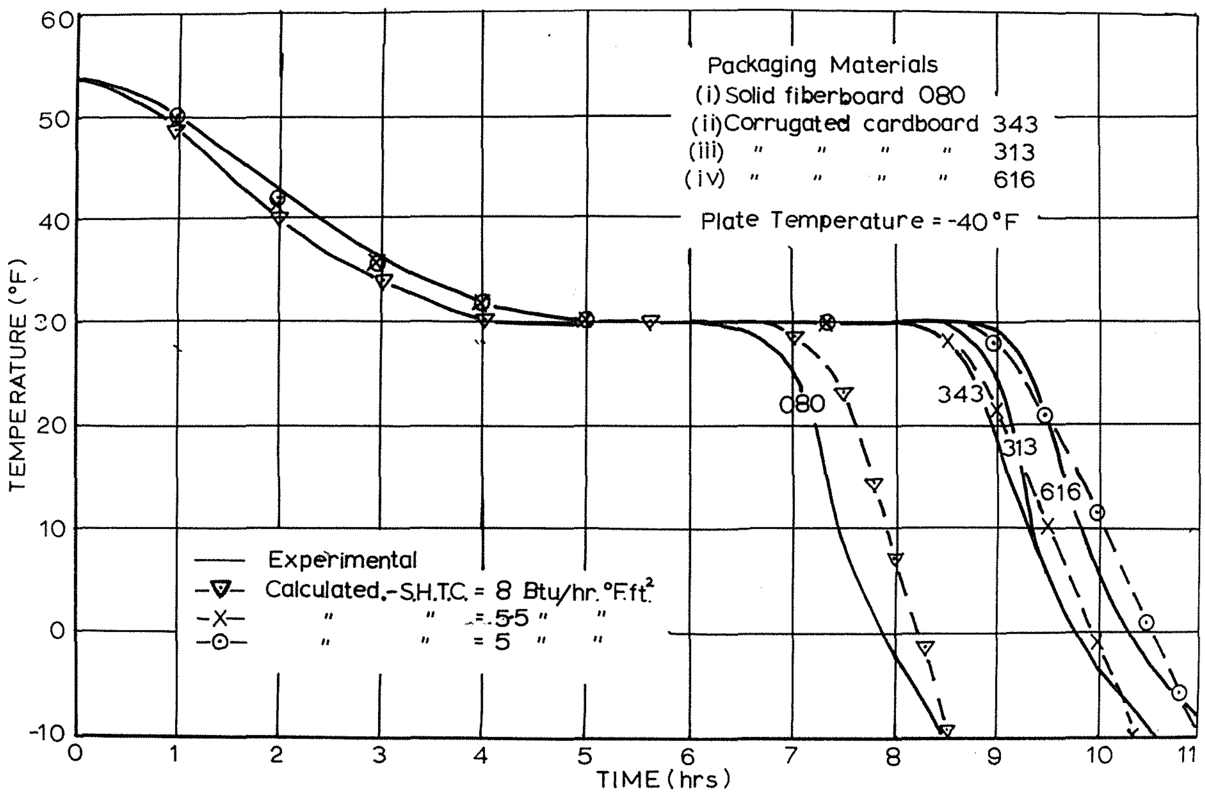


FIG.15 FREEZING CURVES for 4 ins thick slab covered with different packaging materials

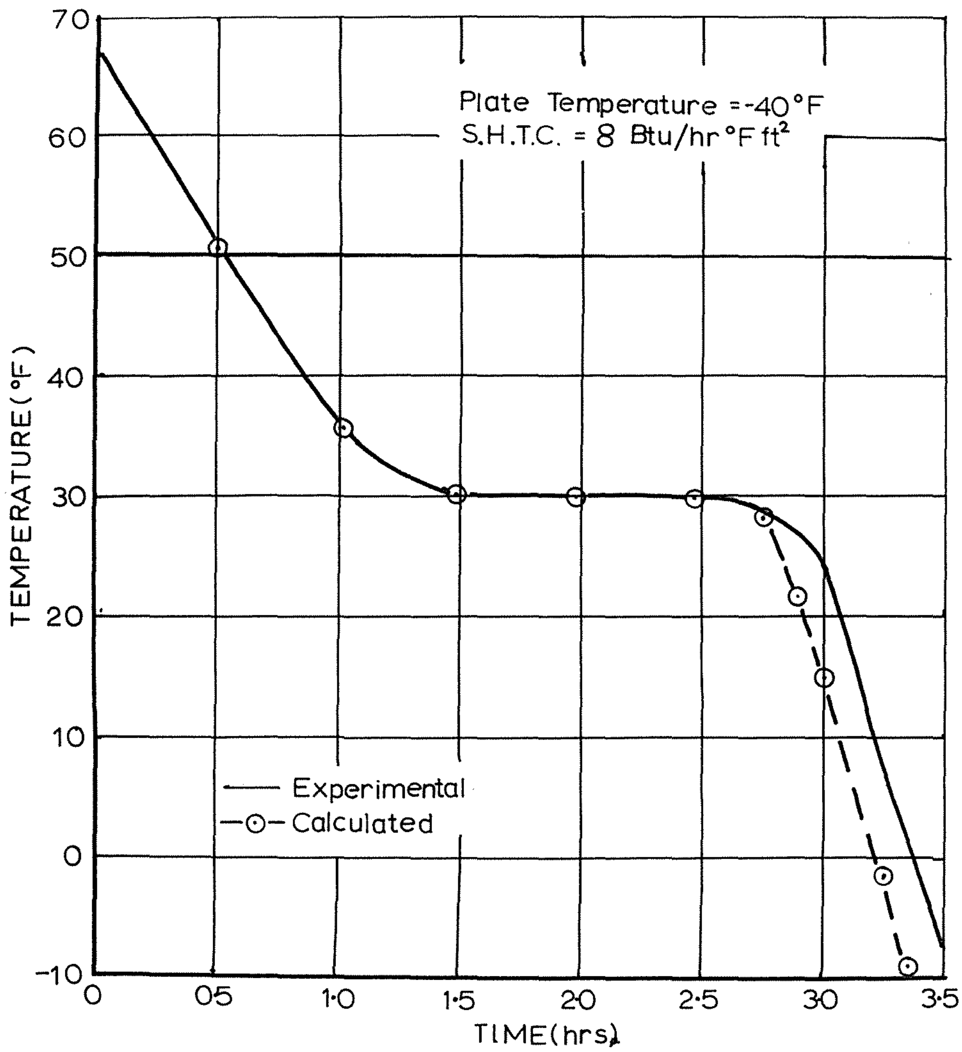


FIG. 16 FREEZING CURVE for 2 ins. thick slab covered with solid fiberboard 080

the effects on the S.H.T.C. of any presumed air pockets still present in the contact surface.

The apparent existence of air pockets in the contact surface of the system was thus a significant problem. A closer examination of the nature of the contact surface, its S.H.T.C., the effect of air pockets in the contact surface upon its S.H.T.C. would be necessary to a full understanding of the system.

When packaging materials were present in the contact surface, the S.H.T.C. value obtained by correlation studies between the numerical solution and experimental freezing curves was an overall term defined by the following equation.

$$\frac{1}{h} = \frac{1}{h_c} + \frac{1}{h_p}$$

h - surface heat transfer coefficient of experimental system Btu/hr ^{o}F ft^2.

h_c - surface heat transfer coefficient of contact surface containing no packaging material Btu/hr ^{o}F ft^2.

h_p - heat transfer coefficient of packaging material Btu/hr ^{o}F ft^2.

Hence it is possible to determine h_c, if the S.H.T.C. of the experimental system and the heat conductance of the packaging material is known. Freezing curves were obtained for slabs of minced lean beef whose surfaces were covered with a layer of 0.0025 ins. polyethylene and a layer of packaging material of known heat conductance. The S.H.T.C. value was obtained from correlation studies and the h_c value was determined. However, because the documented heat conductances of the packaging material (MacFarlane 25) were lower than the S.H.T.C. values obtained by correlation studies it was impossible to determine a precise value of h_c. From these results it was inferred that h_c was very high, and hence that h_c value of 99 Btu/hr ^oF ft^2, as found in the earlier studies, would be reasonable.

Thus with h_c assumed to be 99 Btu/hr ^oF ft^2 and the S.H.T.C. value of the experimental system known, it was possible to estimate the heat conductance of the packaging material used in the experiments and compare the values obtained with any documented values. The results obtained are shown in Table VI. The heat conductance values of the packaging materials obtained from these studies were higher than those presented by MacFarlane (25) and this could have been caused by the packaging materials becoming slightly crushed in the plate freezer. The heat conductance for an undocumented material, corrugated cardboard 343 was obtained and was the same as the heat conductance of corrugated cardboard 313.

Table VI Heat Conductance of Experimental Packaging Materials

PACKAGING MATERIAL		h	$\frac{1}{h}$	h_c	$\frac{1}{h_c}$	$\frac{1}{h_p}$	h_p	h_p*
Solid Fiberboard	080	8	.125	99	.01	.115	8.7	5.4
Corrugated Cardboard	313	5.5	.18	99	.01	.170	5.8	2.0
Corrugated Cardboard	616	5.0	.20	99	.01	.190	5.3	2.7
Corrugated Cardboard	343	5.5	.18	99	.01	.170	5.8	-

* Values of MacFarlane (25)

6.4. Temperature Profiles:

To predict the freezing curve of a product using a numerical solution approximation of the freezing problem, it was necessary to know the S.H.T.C. value which existed in the experimental system. So far it has been assumed that the S.H.T.C. value which gave a close correlation between the numerical solution and experimental freezing curves was the S.H.T.C. value existing in the experimental system. It was desirable, however, to determine the S.H.T.C. in the experimental system by a method which was independent of the correlation studies. This desire led to the examination of the heat flows occurring near the product surface. A knowledge of these, in conjunction with several temperature measurements, permitted the experimental S.H.T.C. to be calculated. It was assumed that no heat leakages occurred away from the contact surface and thus that the heat flux out of a small surface element of product was equal to the corresponding heat flux into the refrigerated plate:

The heat flux into the refrigerated plate may be determined by the following equation:-

$$q = h\,A\,(T_1 - T_2)$$

where
- h - surface heat transfer coefficient (Btu/hr ^oF ft^2)
- A - heat transfer area (ft^2)
- T_1 - plate temperature (^oF)
- T_2 - surface temperature of product (^oF)

It was possible to measure the two temperatures and if the heat flow per unit area into the plates was determined, it was possible to calculate the S.H.T.C. value existing in the experimental system.

The heat flow out of the surface element was equal to the sum of the heat flow into the element and the change of heat content of this element during a time interval $\Delta\theta$. The heat flow out of the element may be determined by

(i) Direct Measurement:

Attempts were made to measure the heat flow in the product at a distance Δx below the product surface by using a J.L.C. Hatfield Heat Flow Meter Disc (low temperature type). These discs were composed of a Telluruim element with copper surfaces and heat flow measurements depended upon the measurement of the voltage output of the element, a function of the temperature differential across the element. This voltage output (μv) in conjunction with a calibration factor (μv)/(Btu/hr ft^2) gave the heat flow in the product at that point. The heat flow values obtained with these discs were very low relative to the values obtained from the temperature profile curves and it was decided that a parasitic emf may have been introduced from the meat salts which were in direct contact with the discs. Accurate heat flow measurement by an element of this type would be useful in heat flow studies but no detailed heat flow investigation was made with these heat flow discs.

(ii) Heat Flow Equations:

A study of the temperature of the product surface, at a distance, Δx, below the surface, and of the rate of temperature change at that point led to a determination of the heat flow per unit leaving the surface element by using the following equation.

$$q/_A = \frac{k(T_2 - T_3)}{\Delta x} + \frac{\Delta x \rho c(T_3' - T_3)}{\Delta \theta}$$

where q/A – heat flow per unit area leaving the surface element (Btu/hr ft^2)

k – thermal conductivity (Btu/hr ^oF ft)

T_2 – surface temperature of product (^oF)

T_3 – product temperature at a distance Δx below the product surface (^oF)

T_3' – product temperature at a distance Δx below the product surface at a time interval $\Delta\theta$ (hrs) after the measurement of T_3 (^oF)

Δx – thickness of surface element (ft)

ρ – density of product (lbs/ft^3)

c – specific heat (Btu/lb ^oF)

Now the heat flow per unit area leaving the surface element, equals the heat flow per unit area entering the refrigerated plate surface. By equating these heat flows it was possible to determine the S.H.T.C. of the experimental system by using the following equation:-

$$h = \frac{\dfrac{k(T_2 - T_3)}{\Delta x} + \dfrac{\Delta x \rho c(T_3' - T_3)}{\Delta \theta}}{(T_1 - T_2)}$$

The values of the variables in this equation were obtained from the temperature profiles obtained whilst the product was being frozen under specific experimental conditions. The temperature profile of a 5 ins. thick slab, in direct contact with the refrigerated plates at -31^oF is shown in Fig. 17 and the values obtained after a time of 3 hours gave a S.H.T.C. value of 85 Btu/hr ^oF ft^2 which confirmed the value of 99 Btu/hr ^oF ft^2 obtained in the earlier correlation studies (Fig. 14).

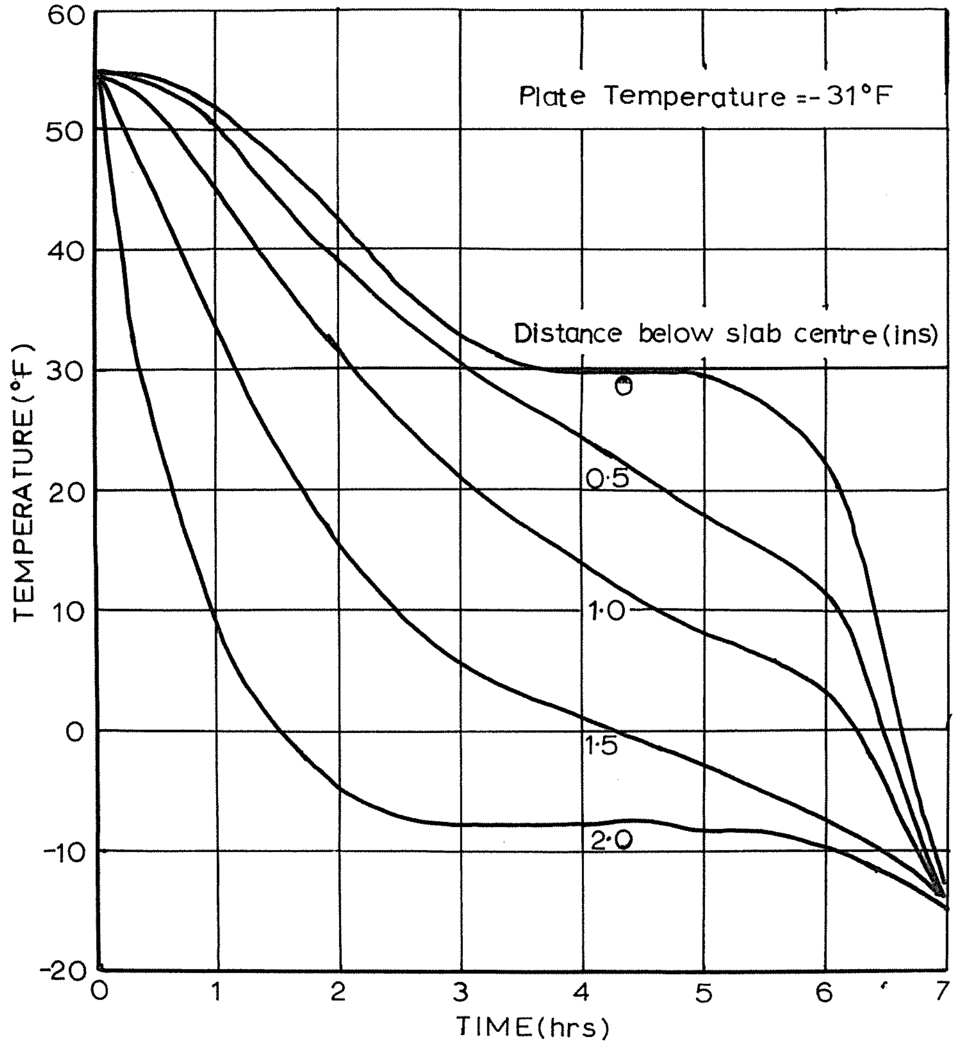


FIG. 17 TIME-TEMPERATURE PROFILES for 5ins. thick slab - experimental -

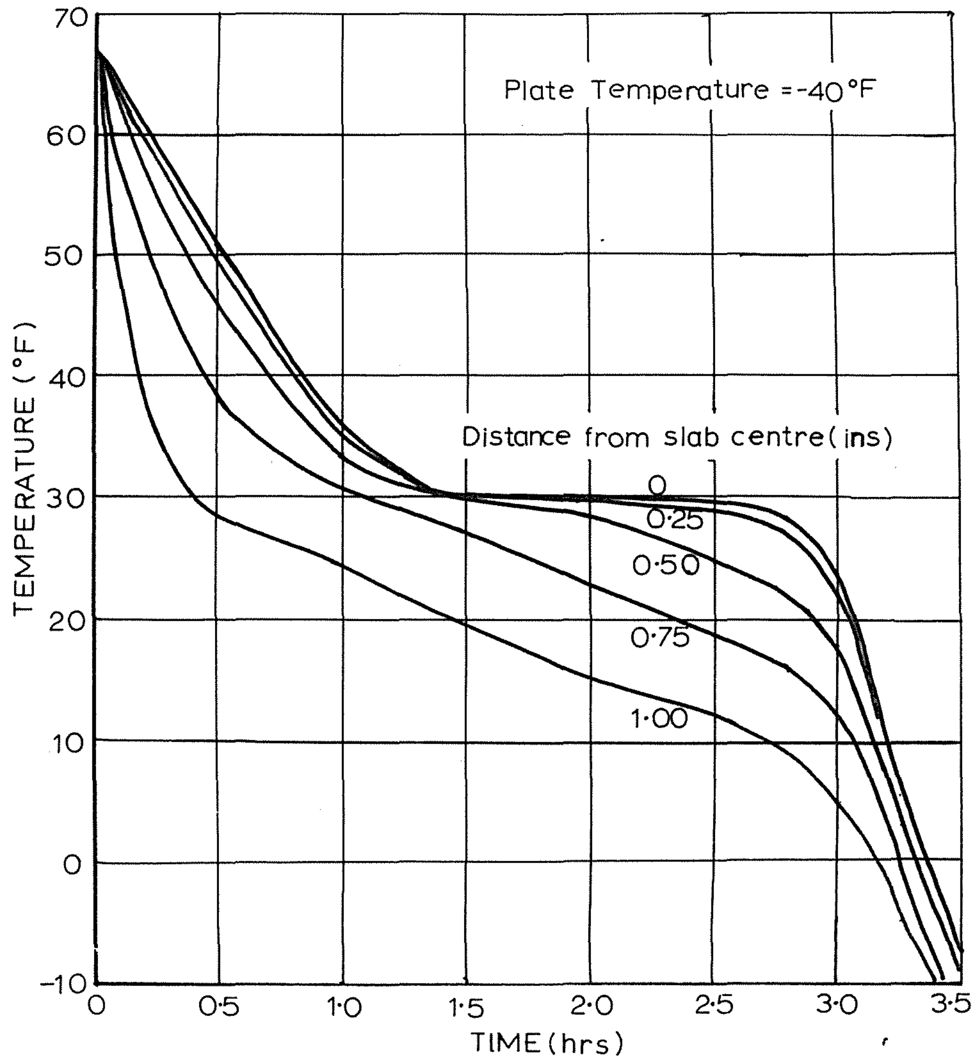


FIG. 18 TIME-TEMPERATURE PROFILES for 2 ins thick slab covered with solid fiberboard 080 - experimental -

The temperature profile for a 2 ins. slab, its surfaces covered with a layer of 0.0025 ins. polyethylene and solid fiberboard 080, plate temperature $-40^{o}F$ is shown in Fig. 18 and the values obtained after $3\frac{1}{2}$ hours gave a S.H.T.C. value of 6.0 Btu/hr ^{o}F ft^2 compared with a value of 8.0 Btu/hr ^{o}F ft^2 obtained in the correlation studies (Fig. 16).

6.5. Conclusions:

The surface heat transfer coefficient (S.H.T.C.) was determined by correlation between the numerical solution and the experimental freezing curves and the magnitude of these values was confirmed by studying the heat flux around the slab surface which was obtained from the appropriate time-temperature profiles. From these studies it appeared that a S.H.T.C. of approximately 100 Btu/hr ^{o}F ft^2 existed in the experimental system when solid contact was made between the surface of the refrigerated plates and the surfaces of the beef slab. It has also been shown that the S.H.T.C. value of a given experimental system depended very significantly upon the nature of the contact surface established.

CHAPTER 7

EVALUATION OF FREEZING RESULTS

7.1. Numerical Solution:

The aim of this study was to determine the accuracy with which the freezing curve of a product could be predicted by a numerical solution of the freezing problem. The one-dimensional freezing of a homogeneous product was considered, a system which was closely approximated by the plate freezing of slabs of minced lean beef. The accuracy of this freezing curve prediction method was determined by comparing the numerical solution and experimental freezing curves obtained under the same freezing conditions. From these freezing curves it was possible to obtain the freezing time of a product for specified freezing conditions.

7.1.1. Accuracy of Freezing Curve Determination:

The numerical solution and experimental freezing curves obtained for a variety of freezing conditions are shown.

(i) Fig. 13 shows the freezing curve obtained during the freezing of a 4 ins. thick slab of minced lean beef, of initial temperature 58^{o}F, plate temperature -40^{o}F and the slab surfaces were in direct contact with the refrigerated plates. A S.H.T.C. value of 99 Btu/hr ^{o}F ft^{2} was used in the numerical solution.

(ii) Fig. 14 shows the freezing curve obtained during the freezing of a 5 ins. thick slab of minced lean beef, of initial temperature -64^{o}F, plate temperature -31^{o}F and the slab surfaces were in direct contact with the refrigerated plates.

A S.H.T.C. value of 99 Btu/hr ^{o}F ft^{2} was used in the numerical solution.

(iii) Fig. 15 shows the freezing curves obtained during the freezing of a 4 ins. thick slab of minced lean beef of initial temperature 54^{o}F, plate temperature -40^{o}F and the slab surfaces were covered with a layer of 0.0025 ins. polethylene and a layer of selected packaging material before being placed in contact with the refrigerated plates. S.H.T.C. values of 8, 5, and 5.5 Btu/hr ^{o}F ft^{2} were used in the numerical solution and gave close correlations when solid fiberboard 080, corrugated cardboard 616 and corrugated cardboards 313 and 343 were used respectively.

(iv) Fig. 16 shows the freezing curve obtained during the freezing of a 2 ins. thick slab of minced lean beef of initial temperature 67^{o}F, plate temperature -42^{o}F and the slab surfaces were covered with a layer of 0.0025 ins. polethylene and solid fiberboard 080 before being brought into contact with the refrigerated plates. A S.H.T.C. value of 8 Btu/hr ^{o}F ft^{2} was used in the numerical solution.

(v) Fig. 19 shows the freezing curve obtained during the freezing of a 3 ins. thick slab of minced lean beef of initial temperature 55^{o}F, plate temperature -40^{o}F and the slab surfaces were in direct contact with the refrigerated plates. S.H.T.C. values of 35 and 99 Btu/hr ^{o}F ft^{2} were used in the numerical solution.

(vi) Fig. 20 shows the freezing curve obtained during the freezing of a 2 ins. thick slab of minced lean beef of initial temperature 62^{o}F, plate temperature -40^{o}F and the slab surfaces were in direct contact with the refrigerated plates. S.H.T.C. values of 23 and 99 Btu/hr ^{o}F ft^{2} were used in the numerical solution.

(vii) Fig. 21 shows the freezing curve obtained during the freezing of a 4 ins. thick slab of minced lean beef, of varying initial temperature, plate temperature

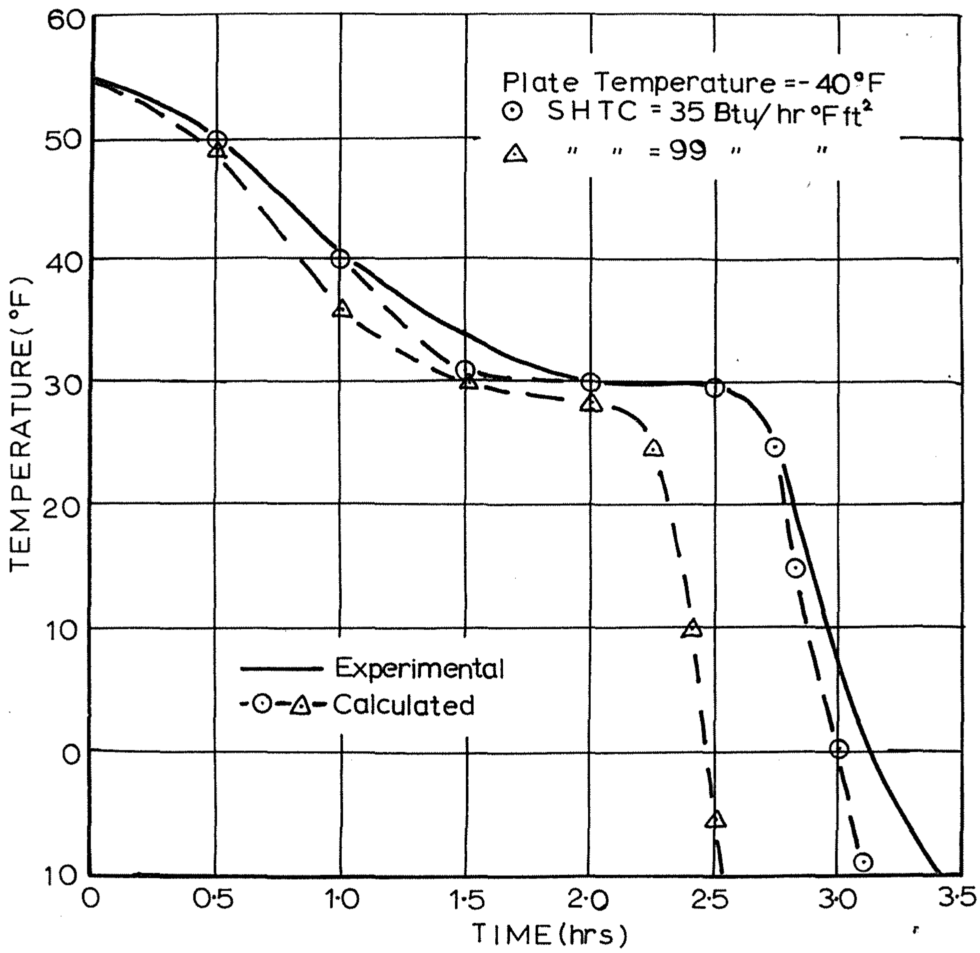


FIG. 19 FREEZING CURVE for 3ins thick slab

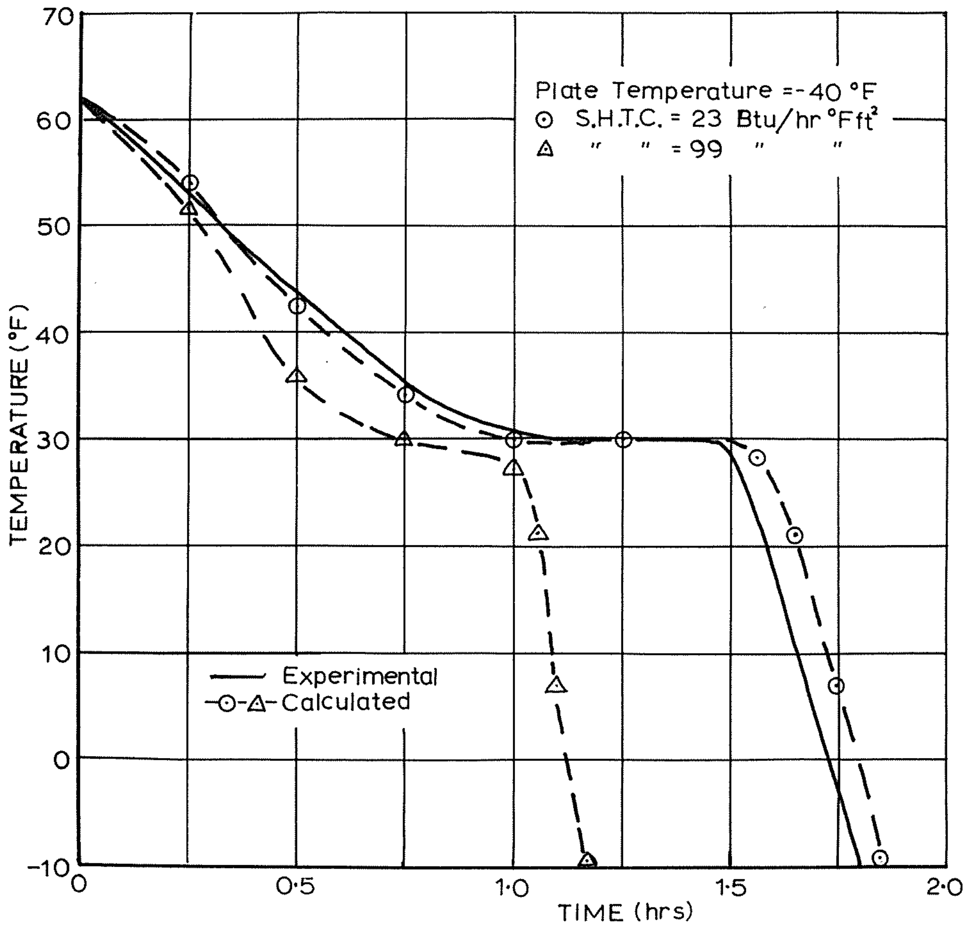


FIG.20 FREEZING CURVE for 2ins thick slab

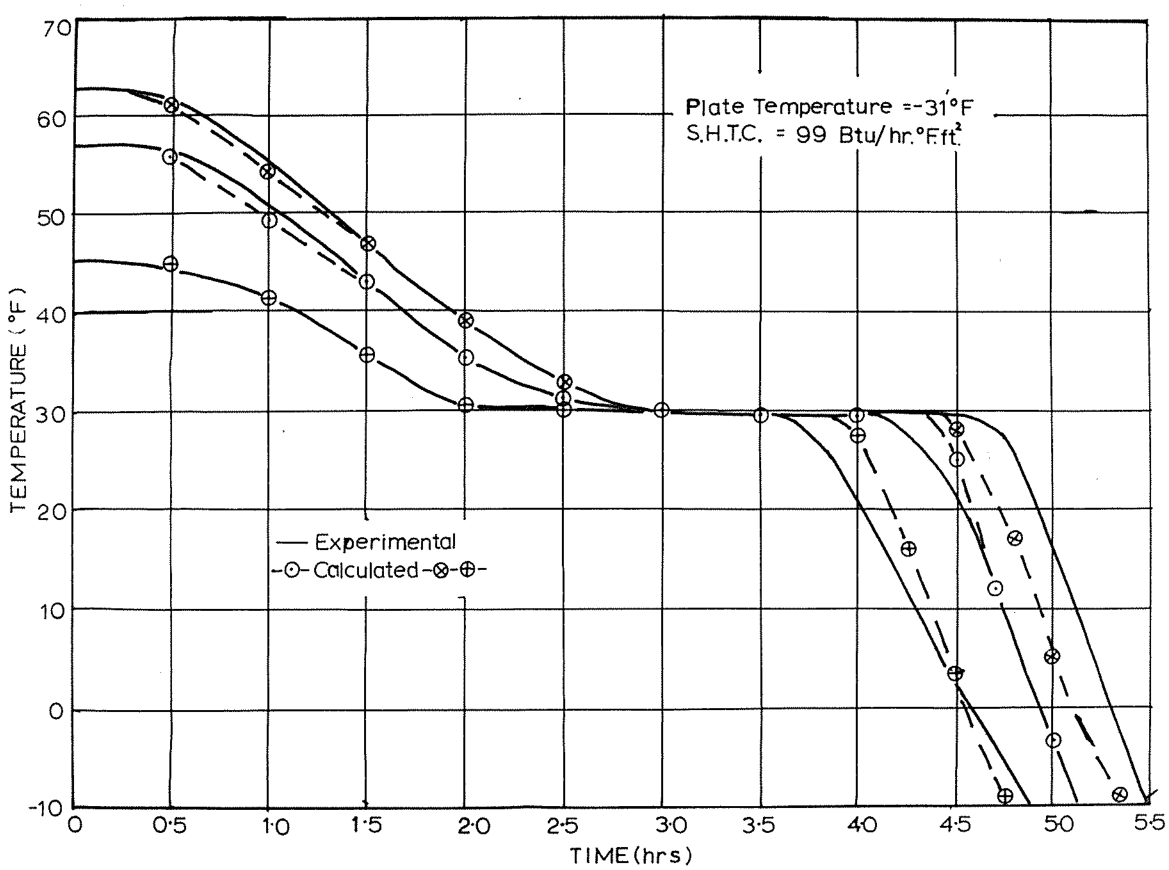


FIG. 21 FREEZING CURVES for 4 ins thick slab

$-31^{\circ}F$ and the slab surfaces were in direct contact with the refrigerated plates. A S.H.T.C. value of 99 Btu/hr $^{\circ}F$ ft^2 was used in the numerical solution.

From these comparisons it was evident that the numerical solution freezing curves closely approximated the experimental freezing curves when accurate values of the parameters were used in the calculations. This was particularly true of the S.H.T.C. and the minced lean beef thermal property values.

7.1.2. Accuracy of Freezing Time Determination:

In these studies the freezing time of the product was considered to be the time for the thermodynamic centre of the product to pass from some initial temperature to $-10^{\circ}F$. The final temperature level of $-10^{\circ}F$ was chosen because cold stores often operate at this temperature and the product enters the cold store at the storage temperature.

The freezing times obtained from the freezing curves for a variety of freezing conditions are shown in Table VII. The accuracy of the freezing time prediction could be improved by selecting a S.H.T.C. value for the numerical solution which gave a close correlation between the location of the knee of the two freezing curves. In these studies the S.H.T.C. value selected was that which gave the closest correlation between the two curves over the entire freezing curve as discussed in Section 7.1.1.

7.1.3. Practical Application:

Having established that the numerical solution of the freezing problems gave an accurate prediction of the product freezing curve and freezing time for specific freezing conditions, it is possible to rapidly predict the product

Table VII Numerical Solution Determination of Freezing Time:

Surface Conditions	Product Thickness (ins)	Plate Temperature ($^{\circ}$F)	Initial Product Temperature ($^{\circ}$F)	Freezing Time (hrs) Experimental	Freezing Time (hrs) Numerical	% Deviation
	5	-40	64	6.75	8.10	+6.6
	5	-31	64	7.55	7.15	+4.4
Direct Contact	4	-40	58	4.45	4.45	0.0
S.H.T.C. = 99	4	-31	64	5.50	5.27	-4.2
	4	-31	57	5.17	5.15	-0.4
	4	-31	46	4.85	4.75	-2.1
S.H.T.C. = 35	3	-40	55	3.40	3.10	-8.7
S.H.T.C. = 23	2	-40	62	1.80	1.85	+2.8
0.0025 ins polyethylene	2	-40	67	3.55	3.35	-6.0
plus						
(i) solid fiberboard 080	3	-40	60	5.90	5.76	-2.4
S.H.T.C. = 8	4	-40	54	8.50	8.55	-0.6
(ii) corrugated board 313						
S.H.T.C. = 5.5	4	-40	54	10.5	10.32	-1.7
(iii) corrugated board 343						
S.H.T.C. = 5.5	4	-40	54	10.5	10.32	-1.7
(iv) corrugated board 616						
S.H.T.C. = 5.0	4	-40	54	11.3	10.90	-3.5

S.H.T.C. units - Btu/hr $^{\circ}$F ft^2

freezing curve and freezing time for any new freezing conditions, and further to study the effect of variations in plate temperature, slab thickness and initial product temperature upon the product freezing curve and freezing time.

(i) Slab thickness:

Fig. 22 shows the freezing curves obtained by numerical calculations for the freezing of slab of minced lean beef of varying thickness, initial product temperature 60°F, plate temperature -40°F and a S.H.T.C. value of 99 Btu/hr °F ft^2. The freezing times for these conditions are shown in Table VIII.

Table VIII Effect of Slab Thickness on Freezing Time

Thickness (ins)	Freezing Time (hrs)
5	6.93
4	4.54
3	2.61
2	1.87

(ii) Plate Temperature:

Fig. 23 shows the freezing curves obtained by numerical calculations for the freezing of a 4 ins. thick slab of minced lean beef of initial temperature 60°F, varying plate temperature and a S.H.T.C. of 99 Btu/hr °F ft^2. The freezing times for these conditions are shown in Table IX.

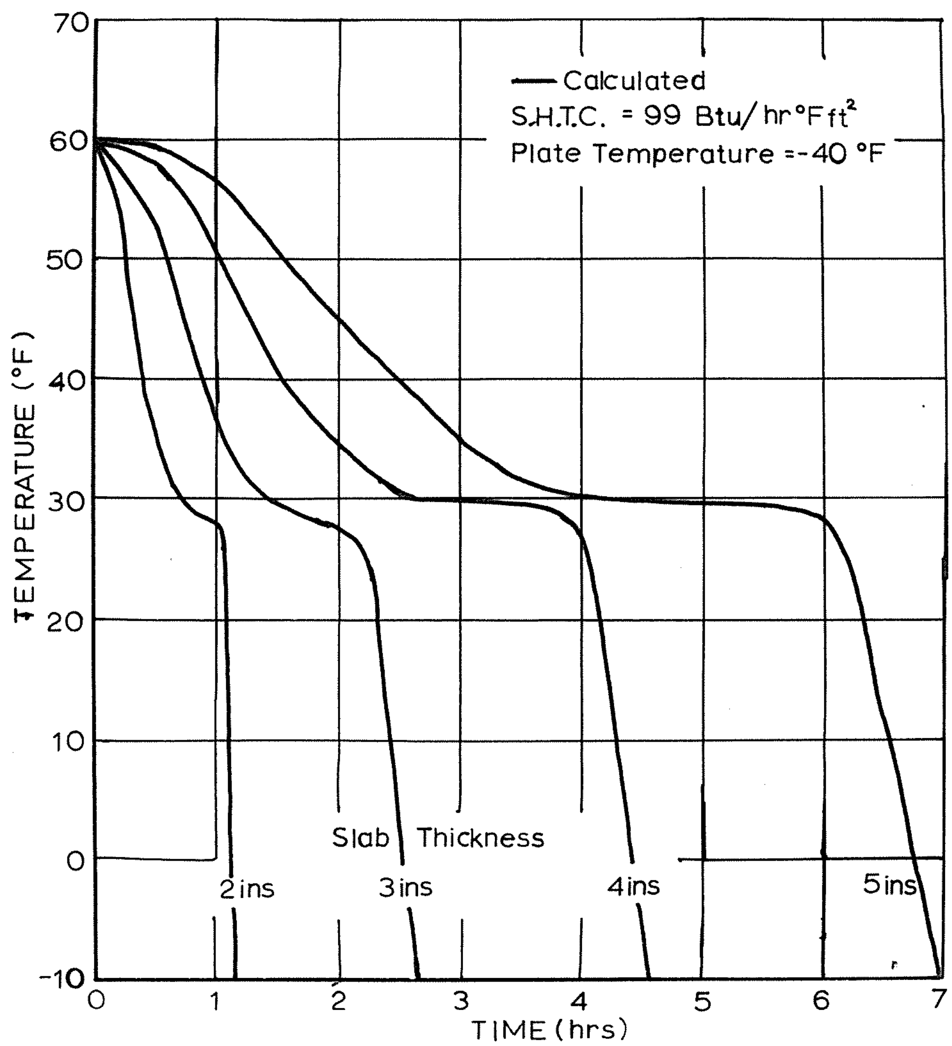


FIG. 22 Effect of Slab Thickness upon Freezing Curve

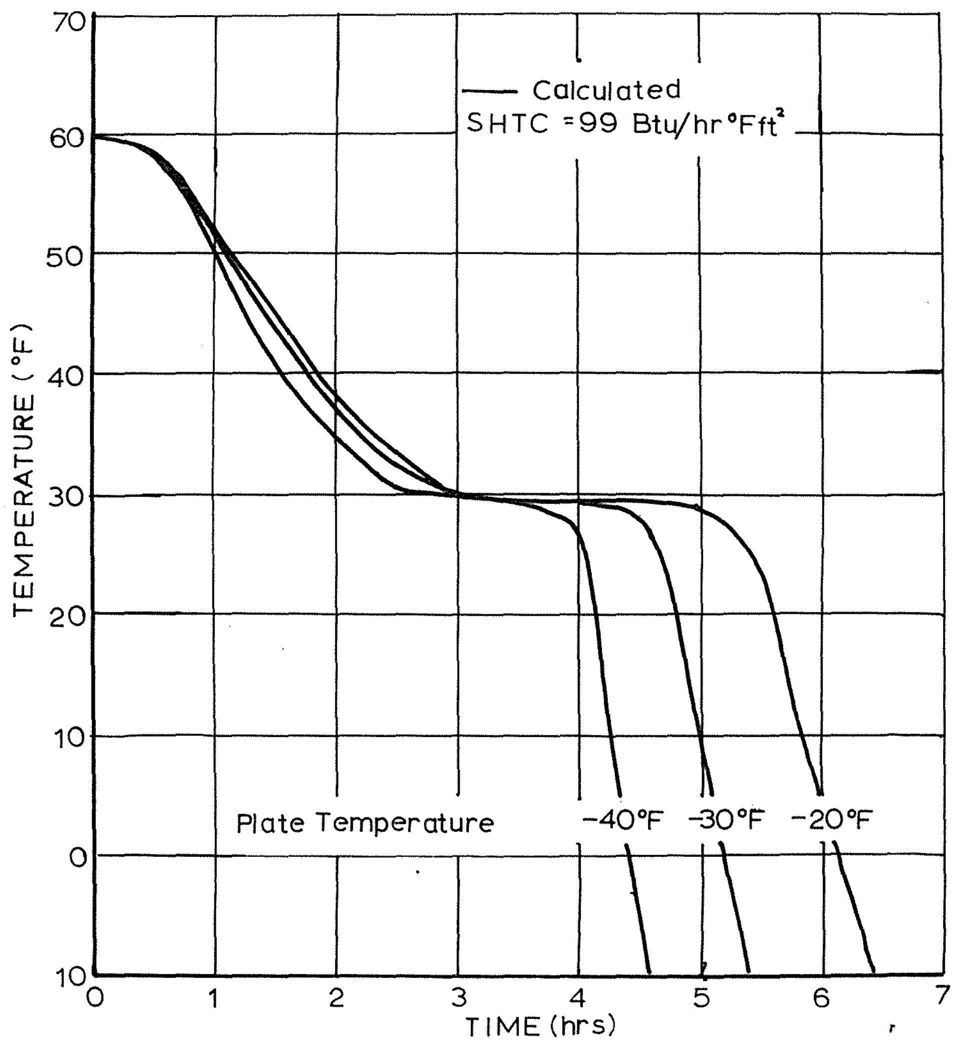


FIG. 23 Effect of Plate Temperature upon Freezing Curve of a 4ins thick slab

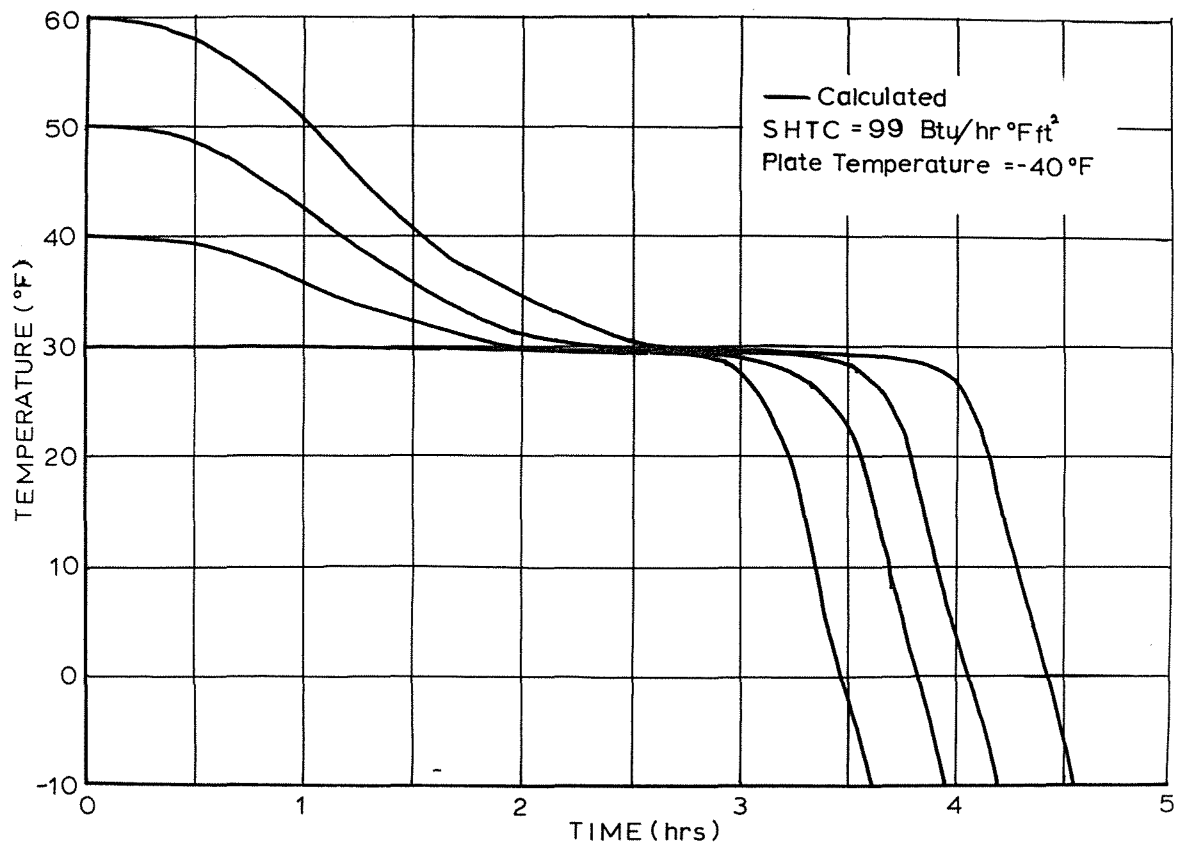


FIG. 24 Effect of Initial Temperature upon Freezing Curve of a 4 ins thick slab

Table IX Effect of Plate Temperature on Freezing Time

Plate Temperature (°F)	Freezing Time (hrs)
-40	4.54
-30	5.36
-20	6.46

(iii) Initial Product Temperature:

Fig. 24 shows the freezing curves obtained by numerical calculations for the freezing of a 4 ins. thick slab of minced lean beef of varying initial temperature, plate temperature -40^{0}F and an S.H.T.C. value of 99 Btu/hr ^{o}F ft^2. The freezing times for these conditions are shown in Table X.

Table X Effect of Initial Product Temperature on Freezing Time

Initial Product Temperature (°F)	Freezing Time (hrs)
60	4.54
50	4.18
40	3.94
30	3.61

7.2. Modified Plank's Equation:

It has been shown that a numerical solution of the freezing problem predicted accurately the freezing time of a product for a variety of freezing conditions. However for routine freezing time determinations a simpler calculation sequence is required. Plank (32) developed an equation for determining the freezing time of a slab shaped product which is simple and has been used widely for routine calculations. The results so obtained were of limited value because of the nature of the assumptions made during the derivation of this equation. These assumptions are

: that the product is initially uniformly at its freezing point and unfrozen.

: that the latent heat of solidification is released at a fixed temperature, the freezing point.

: that the thermal properties of the unfrozen and frozen states are constant.

: that the freezing boundary proceeds so slowly that steady state conditions exist in the frozen state.

The basic equation developed by Plank (32) when these assumptions were made is

$$\theta = \frac{L\rho}{T}\left[\frac{P\,a}{h} + \frac{R\,a^2}{k}\right] \qquad (7.1)$$

where θ - the time to freeze a product initially uniformly at its freezing point and unfrozen (hrs).

L - latent heat of solidification (Btu/lb).

ρ - density of frozen product (lbs/ft^3).

T - the temperature differential between the ambient temperature and the freezing point of the product (^oF).

a - product thickness (ft).

h - surface heat transfer coefficient which includes packaging resistance to heat transfer (Btu/hr ^oF ft^2).

k - thermal conductivity of frozen product (Btu/hr ^oF ft).

P,R, - shape factors and P = 1/2, R = 1/8 for one dimensional freezing.

It was necessary to examine these assumptions and to determine which of them were valid under normal freezing conditions. The basic equation was then modified to overcome the limitation of the assumptions which were not valid.

7.2.1. Validity of Plank's Assumptions:

The assumption of steady state conditions in the frozen layer of the product has been shown to be valid by Cochran (9). He postulated that steady state conditions existed when the ratio of the latent heat of solidification to the total sensible heat change was greater than or equal to 3.0. In foodstuffs the latent heat of solidification of the large water content forms a very large proportion of the total enthalphy change which occurs during freezing and thus the ratio value was greater than 3.0. In the distance - temperature profiles obtained by experiment (Fig. 25) and by numerical calculation (Fig. 26,27); there exists a linear temperature gradient through much of the frozen layer of foodstuff. This was assumed to indicate the existence of steady state conditions in this layer.

During the freezing of foodstuffs the latent heat of solidification is released over a range of temperature and not at a specific temperature. This is caused by the presence of salts in the tissue fluid which result in a depression of the freezing point of the system. Further as freezing proceeds water separates out as ice which causes a continued increase in the salt concentration and an associated depression of the freezing point. The latent heat of solidification is thus released over a temperature range but the modifications required in the equation to overcome this assumption are complex. Hence this assumption was retained. The error arising from assuming a constant freezing point was relatively small because the total temperature differential between the freezing point and the plate temperature was between 50 and 70^{o}F and a change of 2 to 3^{o}F in the freezing point represented a small error in the temperature differential value used.

The change of state of the foodstuff during freezing causes substantial changes in the thermal property values of the foodstuff. The change in the values closely follows the transformation of water to ice (Fig. 1) which has a higher thermal conductivity and lower specific heat than water. The thermal property values are thus very temperature dependent and it was untrue to assume that they are constant in the unfrozen and frozen layers of the product. For

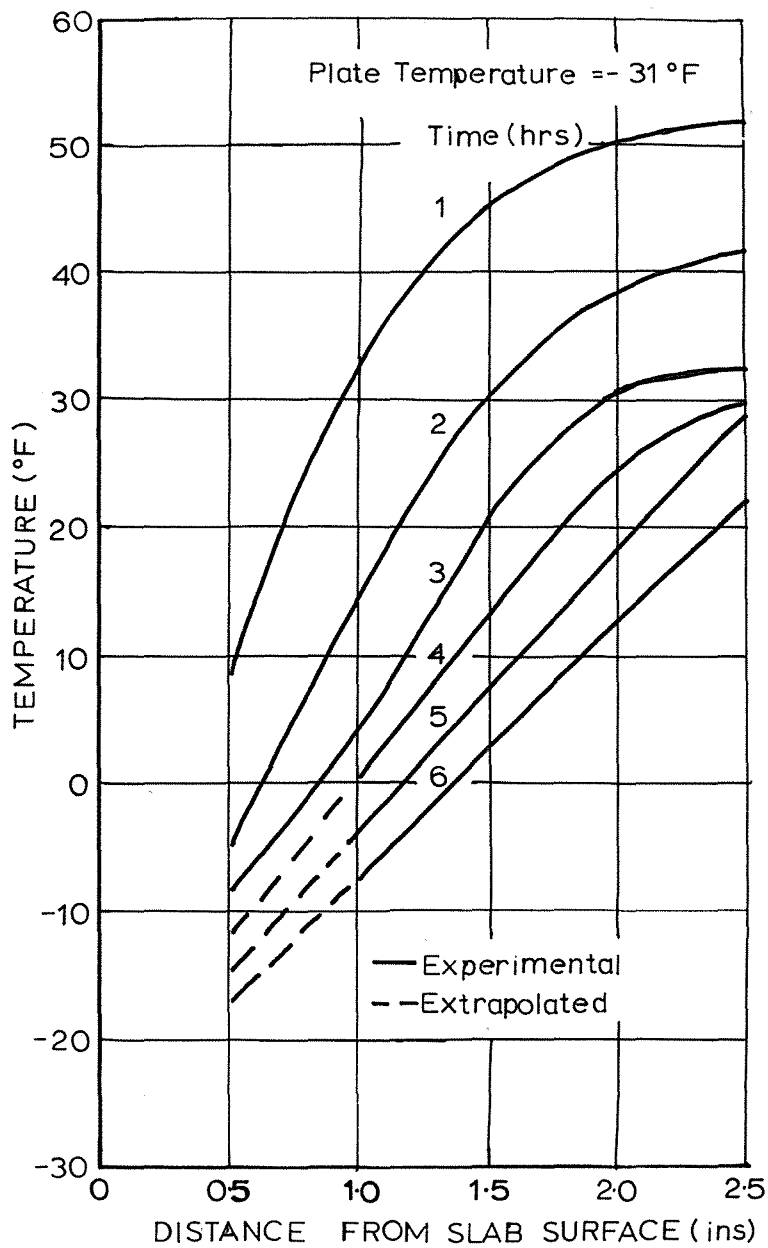


FIG. 25 DISTANCE-TEMPERATURE PROFILES for 5 ins thick slab

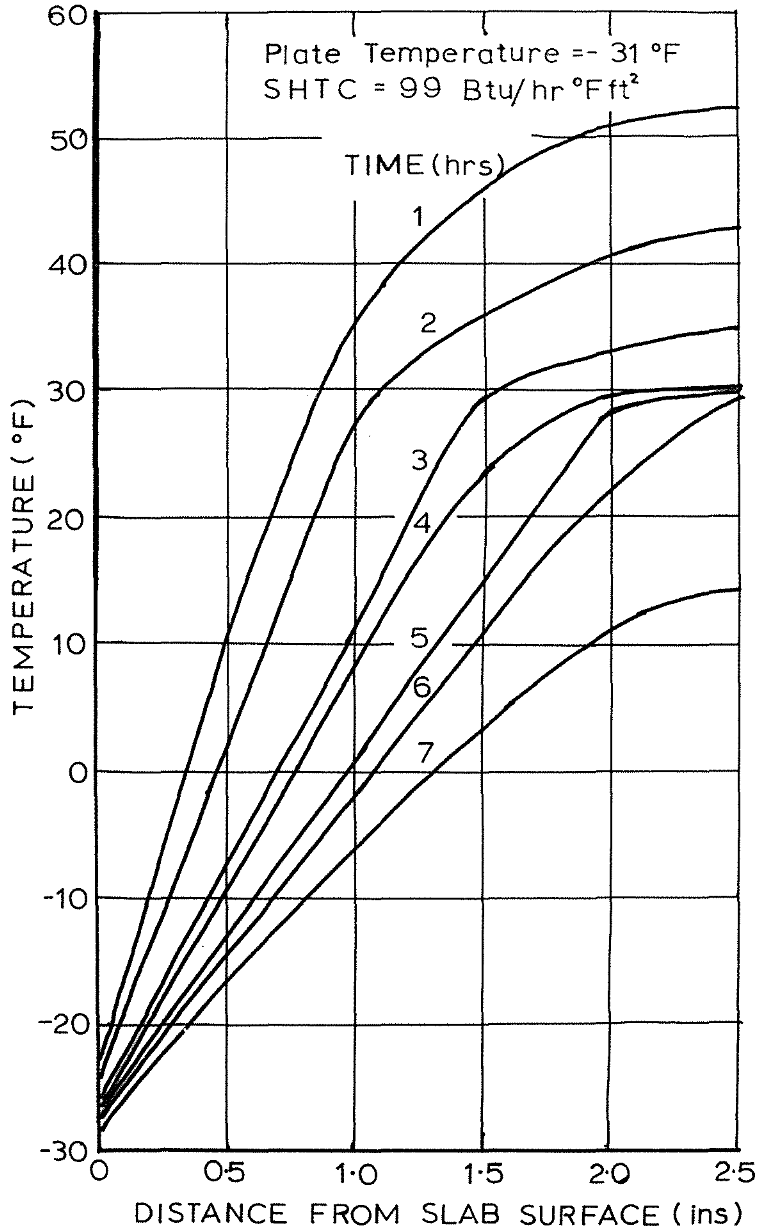


FIG. 26 DISTANCE-TEMPERATURE PROFILES for 5 ins thick slab —calculated—

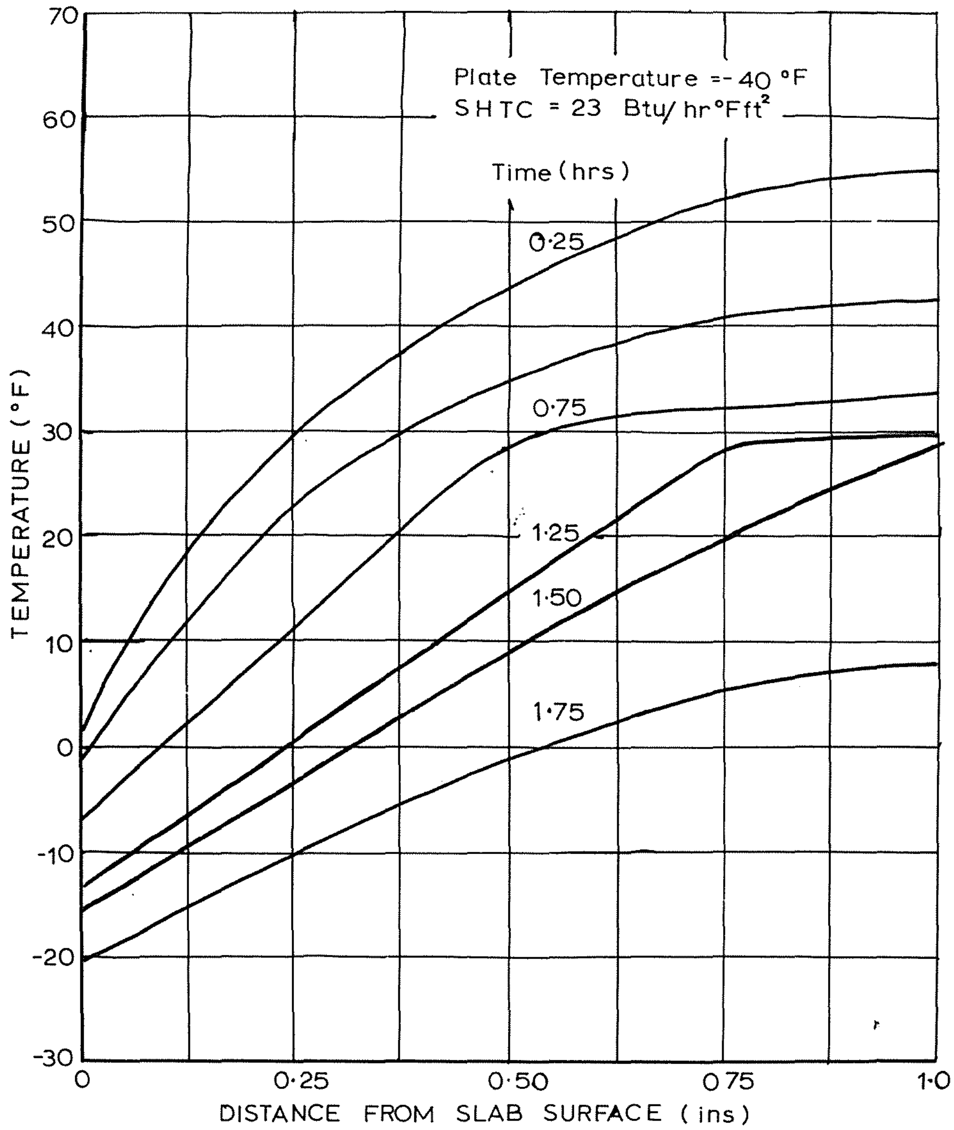


FIG. 27 DISTANCE-TEMPERATURE PROFILES for 2ins thick slab
— calculated —

calculation purposes the mean value for the temperature range $-40^{\circ}F$ to $30^{\circ}F$ was used. The frozen product value was selected because of the existence of steady state conditions in the frozen layer from which it was assumed that the frozen product thermal property values are the limiting thermal property values with respect to the heat transfer which occurs during freezing.

Under normal freezing conditions the foodstuff was at temperature above the freezing point and was frozen to a temperature below the freezing point. It was desirable to modify Plank's equation to allow for these factors.

7.2.2. Freezing Time Determination by a Modified Plank's Equation:

A number of modified forms of Plank's equation have been presented in the literature to overcome the limitations imposed by Plank's assumptions. These include equations presented by Levy (22), Khatchaturov (20), Nagaoka (30) and Watzinger (40) which were of the following basic type:-

$$\theta = \left[1 + A(T_1 - T_f)\right] \frac{Z\rho}{\Delta T} \left(P\frac{a}{h} + \frac{Ra^2}{k} \right) \qquad (7.2)$$

where θ - freezing time of a product initially at T_1 and frozen to T_2(hrs).

A - constant in the initial temperature correlation factor. Published values were in the range 0.003 to 0.0045.

T_f - freezing point of product ($^{\circ}F$).

Z - total enthalpy change where occurred over the temperature range T_1 to T_2 (Btu/lb).

and Z $-$ $C_1 (T_1 - T_f) + L + C_2 (T_f - T_2)$.

C_1, C_2 $-$ specific heat values of unfrozen and frozen products respectively. (Btu/lb ^oF).

P, R are shape factors

P	=	1/2	R	=	1/8	for slabs
P	=	1/4	R	=	1/16	for cylinder
P	=	1/8	R	=	1/24	for spheres

Equations of this type retain the basic simplicity of Plank's equation and provide a more reliable estimate of the freezing time of the foodstuff. However to use this equation it was necessary to calculate the enthalpy change which occurred because temperature - enthalpy curves were only available for a few foodstuffs (Riedel 34, 35, 36, 37). The initial product temperature above the freezing point was accounted for in the enthalpy term and in the $\left[1 + A (T_1 - T_f)\right]$ factor, and the final product temperature below the freezing point was accounted for in the enthalpy term.

In these studies an equation was developed in which the case of an initial temperature above the freezing point and a final temperature below the freezing point was accounted for by a term $\left[1 + A (T_1 - T_2)\right]$, where A was a constant whose value depended upon the final product temperature chosen. The latent heat of solidification was used instead of the enthalpy change because the latent heat of solidification values for foodstuffs were readily available in the literature Andersen (2) A.S.R.E. (4) .

When a final product temperature of -10^oF was used, the following equation was found to give reliable estimation of the freezing time of slabs of minced lean beef frozen under a variety of freezing conditions, see Table XI.

$$\theta = \left[1 + 0.019\,(T_1 + 10)\right] \frac{L\rho}{\Delta T} \left(\frac{1}{2}\frac{a}{h} + \frac{1}{8}\frac{a^2}{k} \right) \qquad (7.3)$$

L – latent heat of solidification (Btu/lb).

In these calculations, a latent heat of solidification value of 105 Btu/lb, a thermal conductivity value of 0.8 Btu/hr ^{0}F ft^2 were used. All S.H.T.C. values were in Btu/hr ^{0}F ft^2.

For a final product temperature of +10^{0}F, the following equation is proposed and for the freezing time estimates see Table XII.

$$\theta = \left[1 + 0.022\,(T_1 - 10)\right] \frac{L\rho}{\Delta T} \left(\frac{1}{2}\frac{a}{h} + \frac{1}{8}\frac{a^2}{k} \right) \qquad (7.4)$$

By the use of the appropriate equation it is possible to obtain a reasonable estimate of the freezing time of a slab frozen under given freezing conditions. In these calculations, the S.H.T.C. values used were those obtained from the correlation studies between the numerical solution and experimental freezing curves appropriate to the freezing conditions being studied, and they varied with thickness of the slab. For calculation purposes it is desirable to have a mean S.H.T.C. value which would give a reasonable estimate of the freezing times over the range of slab thickness. A S.H.T.C. value of 50 Btu/hr ^{0}F ft^2 was used in the freezing time determination made with Equation (7.3) and shown in Table XIII. From these results it was evident that whilst some of the freezing time predictions were quite accurate, in general a substantial error existed. Hence it was desirable to use S.H.T.C. values in the calculations

Table XI Freezing Time Determinations with a Modified Plank's Equation ($T_2 = -10^{o}F$)

Surface Conditions	Product Thickness (ins)	Plate Temperature (^{o}F)	Initial Product Temperature (^{o}F)	Freezing Time (hrs) Experimental	Freezing Time (hrs) Modified Plank	% Deviation
Direct Contact S.H.T.C. = 99	5	-40	64	6.75	7.06	+4.6
	5	-31	64	7.55	8.16	+8.1
	4	-40	58	4.45	4.40	-1.1
	4	-31	63	4.50	5.25	-4.6
	4	-31	57	5.17	5.00	-2.0
	4	-31	46	4.85	4.56	-5.0
S.H.T.C. = 35	3	-40	60	3.65	3.38	-7.4
	3	-40	55	3.40	3.25	-4.4
	3	-40	42	3.15	2.76	-11
	3	-31	62	3.60	3.92	+8.9
	3	-31	58	3.50	3.79	+8.3
	3	-31	49	3.30	3.50	+6.1
	3	-23	60	4.56	4.46	-3.5
S.H.T.C. = 23	2	-40	62	1.80	1.87	+3.9
	2	-31	60	1.75	1.94	+10.9
	2	-23	59	2.15	2.43	+13.0
0.0025 ins polyethylene	2	-40	67	3.55	3.70	+4.2
plus (i) solid fiberboard 080 S.H.T.C. = 8	3	-40	66	5.90	5.95	+0.9
	4	-40	54	8.50	8.50	+0.0
(ii) corrugated cardboard 313 S.H.T.C. = 5.5	4	-40	54	10.50	10.50	0.0
(iii) corrugated cardboard 343 S.H.T.C. = 5.5	4	-40	54	10.50	10.50	0.0
(iv) corrugated cardboard 616 S.H.T.C. = 5.0	4	-40	54	11.30	11.30	0.0

Table XII Freezing Time Determination with a Modified Plank's Equation ($T_2 = +10^{\circ}F$)

Surface Conditions	Product Thickness (ins)	Plate Temperature (°F)	Initial Product Temperature (°F)	Freezing Time (hrs)		% Deviation
				Experimental	Modified Plank	
	5	-40	64	5.90	6.45	+9.3
Direct Contact	5	-31	64	6.95	7.45	+7.2
	4	-40	58	4.17	3.94	-5.5
S.H.T.C. = 99	4	-31	63	5.11	4.76	-6.8
	4	-31	57	4.75	4.50	-5.3
	4	-31	46	4.27	3.94	-7.2
	3	-40	60	3.20	3.05	-4.7
	3	-40	55	2.95	2.88	-2.4
S.H.T.C. = 35	3	-40	42	2.90	2.46	-15.0
	3	-31	62	3.35	4.02	+23.0
	3	-31	58	3.17	3.40	+ 7.2
	3	-31	49	2.90	3.08	+6.2
	3	-23	60	4.02	4.02	0.0
	2	-40	62	1.60	1.70	+6.4
S.H.T.C. = 23	2	-31	60	1.52	1.91	+25.4
	2	-23	59	1.92	2.16	+7.3
0.0025 ins polyethylene	2	-40	67	3.20	3.65	+13.6
plus						
(i) solid fiberboard 080	3	-40	66	5.20	5.75	+11.9
S.H.T.C. = 8	4	-40	54	7.45	7.55	+1.3
(ii) corrugated cardboard 313						
S.H.T.C. = 5.5	4	-40	54	9.35	9.45	+1.1
(iii) corrugated cardboard 343						
S.H.T.C. = 5.5	4	-40	54	9.35	9.45	+1.1
(iv) corrugated cardboard 616						
S.H.T.C. = 5.0	4	-40	54	9.8	10.05	+2.0

Table: XIII Freezing Time Determination with a Modified Plank's Equation ($T_2 = -10^oF$, Constant S.H.T.C.)

Surface Conditions	Product Thickness (ins)	Plate Temperature (^oF)	Initial Product Temperature (^oF)	Freezing Time (hrs)		% Deviation
				Experimental	Modified Plank	
	5	-40	64	6.75	7.57	+12.0
Direct Contact	5	-31	64	7.55	8.66	+14.6
	4	-40	58	4.45	4.80	+7.3
S.H.T.C. = $50 \frac{Btu}{hr\ ^oF\ ft^2}$	4	-31	63	5.50	5.73	+4.2
	4	-31	57	5.10	5.45	+6.9
	4	-31	46	4.80	4.98	+3.7
	3	-40	60	3.65	2.88	-21.0
	3	-40	55	3.40	2.76	-18.8
	3	-40	42	3.15	2.45	-22.2
	3	-31	62	3.60	3.38	-6.1
	3	-31	58	3.50	3.25	-7.1
	3	-23	60	4.56	3.82	-16.2
	2	-40	62	1.80	1.42	-21.0
	2	-31	60	1.75	1.62	-7.4
	2	-23	59	2.15	1.86	-11.1
	2	-23	49	1.95	1.70	-12.7

which were closer to that existing in the experimental system than a value of 50 Btu/hr ^{o}F ft^2.

7.3. Freezing Rates Established During Freezing:

It is necessary to freeze the foodstuff fast enough to minimise enzymic and microbiological activity and the associated loss of product quality. Even when this requirement is met it is still possible for a loss of product quality to occur as a result of the nature of the ice crystals formed during freezing. Mazur (27) developed a quantitative relationship between the freezing rate and the size and location of the ice crystals formed. If a quantitative relationship was established between the level of product quality and the nature of the ice crystals formed then it would be possible to specify the product quality in terms of a freezing rate.

It is thus desirable to determine the rates of temperature change which occurred in a product whilst it was being frozen. The time-temperature profiles which exist in the product as it is frozen, were obtained by measuring the temperatures at different points in the product and from these profiles it was possible to determine the rates of temperature change which occurred. Fig. 17 shows the time-temperature profiles obtained during the freezing of a 5 ins. thick slab of initial temperature 55^{o}F, plate temperature -31^{o}F and the slab surfaces were in direct contact with the refrigerated plates. The temperatures were measured at 0.5 ins. intervals from the slab surface to the slab centre. It was also possible to obtain time-temperature profiles by numerical calculations. Fig. 28 shows such a profile obtained under the same freezing conditions as Fig. 17 and a S.H.T.C. of 99 Btu/hr ^{o}F ft^2 was used in the calculations. Fig. 29 shows the time-temperature profiles obtained by numerical solution calculation for the freezing of a 2 ins. thick slab of minced lean beef, plate temperature

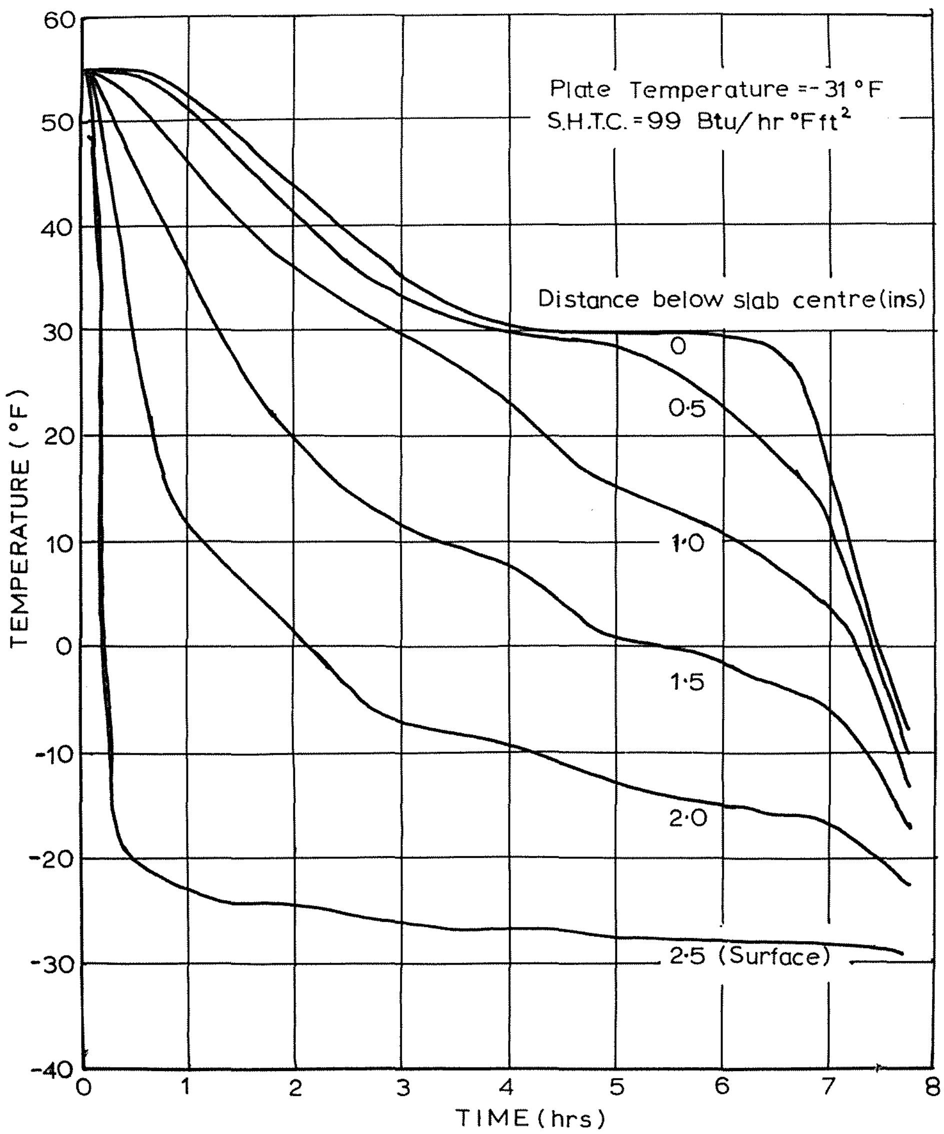


FIG. 28 TIME - TEMPERATURE PROFILES for 5 ins thick slab
— calculated —

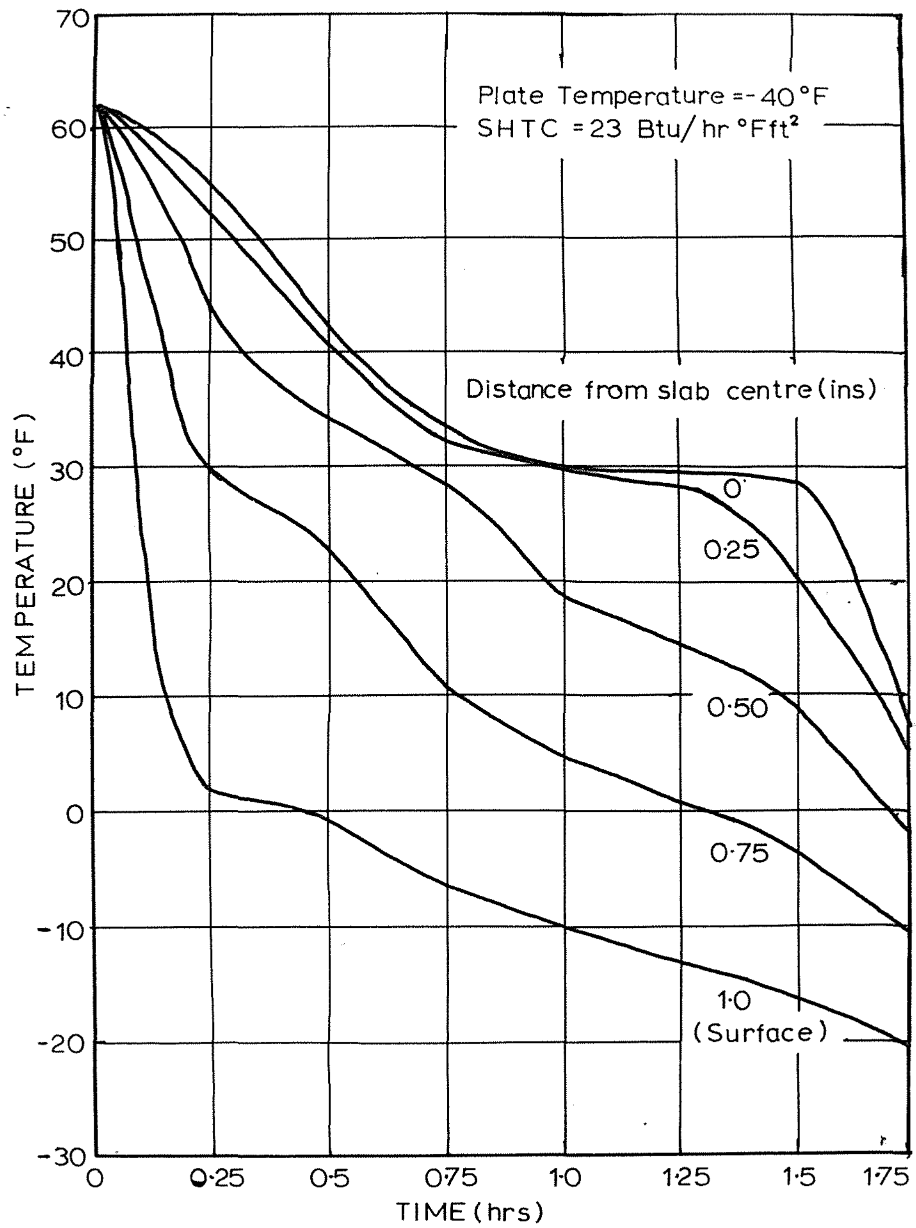


FIG. 29 TIME-TEMPERATURE PROFILES for 2ins thick slab
— calculated —

-40°F, initial temperature 62°F, S.H.T.C. 23 Btu/hr $^{\circ}$F ft^{2}.

From the appropriate time-temperature profile the rates of temperature change in the experimental freezing of a 5 ins. thick slab of minced lean beef under the conditions outlined above were obtained and are shown in Fig. 30. It was readily evident that the rates were high in the surface layers of the slab in the initial stages of freezing, and then a low rate period existed in the entire slab. This was followed by a final stage in which higher rates existed, the highest being in the centre region of the slab. In Fig. 31 the rates of temperature change obtained from the numerical solution profiles shown in Fig. 28 and Fig. 29 are presented. From these results it is evident that the same pattern of rates existed in both slabs as was shown in Fig. 30 and also that the rates obtained in a 2 ins. thick slab were approximately twice those obtained in the 5 ins. thick slabs for the freezing conditions outlined.

The maximum rate of temperature change which existed at the surface of a 2 ins. thick slab was about 100 $^{\circ}$F/hr and about 50 $^{\circ}$F/hr for the slab centre. Mazur (27) postulated that the ice crystals would be formed outside the cells when the rate of temperature change was less than 120°F/hr and hence this would occur under these freezing conditions. It is generally believed that the ice crystals formed outside the cells (extracellular ice crystal formation) are larger than the intracellular crystals and cause more damage to the tissue and associated loss of product quality. Hence it would appear desirable to obtain rates of temperature change which would cause intracellular ice crystal formation, but they are very much higher than those obtained during the freezing of a 2 ins. thick slab of minced lean beef in a plate freezer under the conditions already specified.

It was evident that the rate of temperature occurring in the system

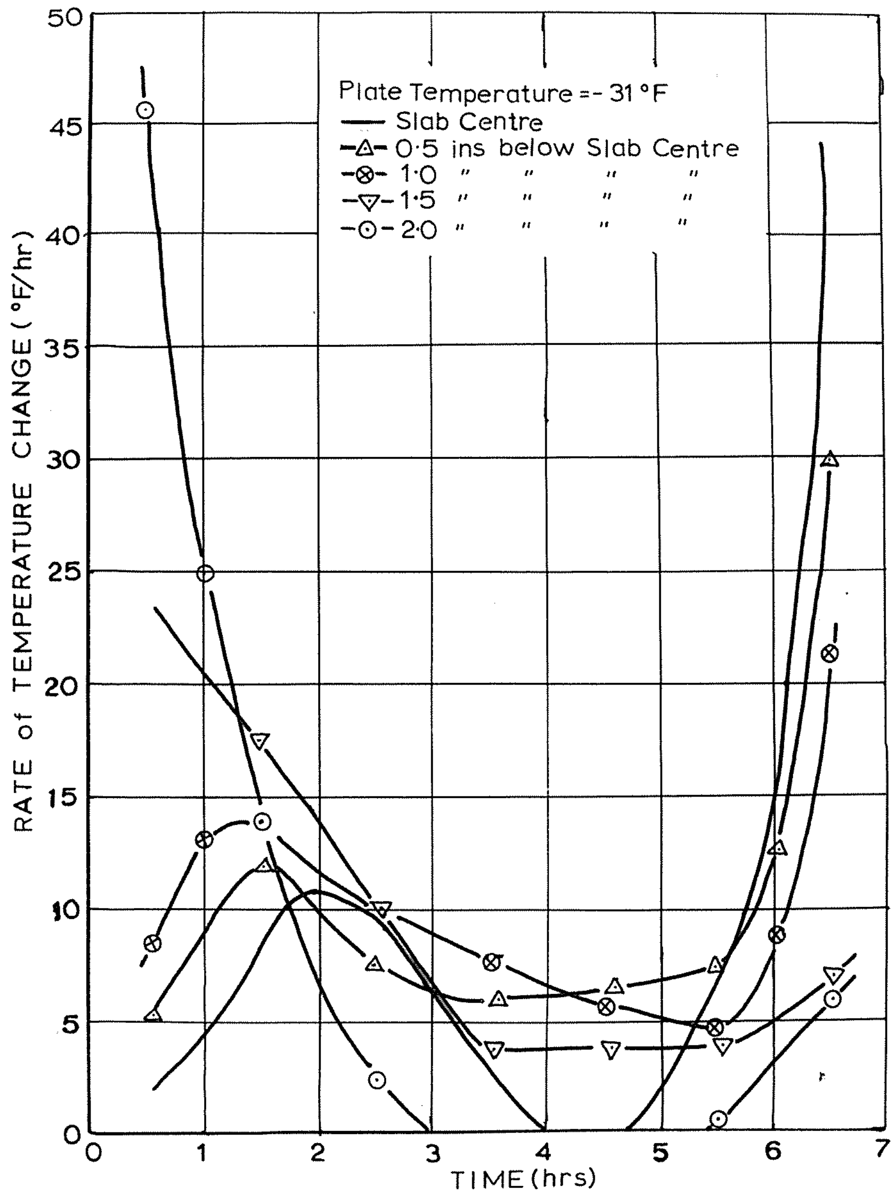


FIG. 30 RATE of TEMPERATURE CHANGE during the freezing of a 5ins thick slab – experimental –

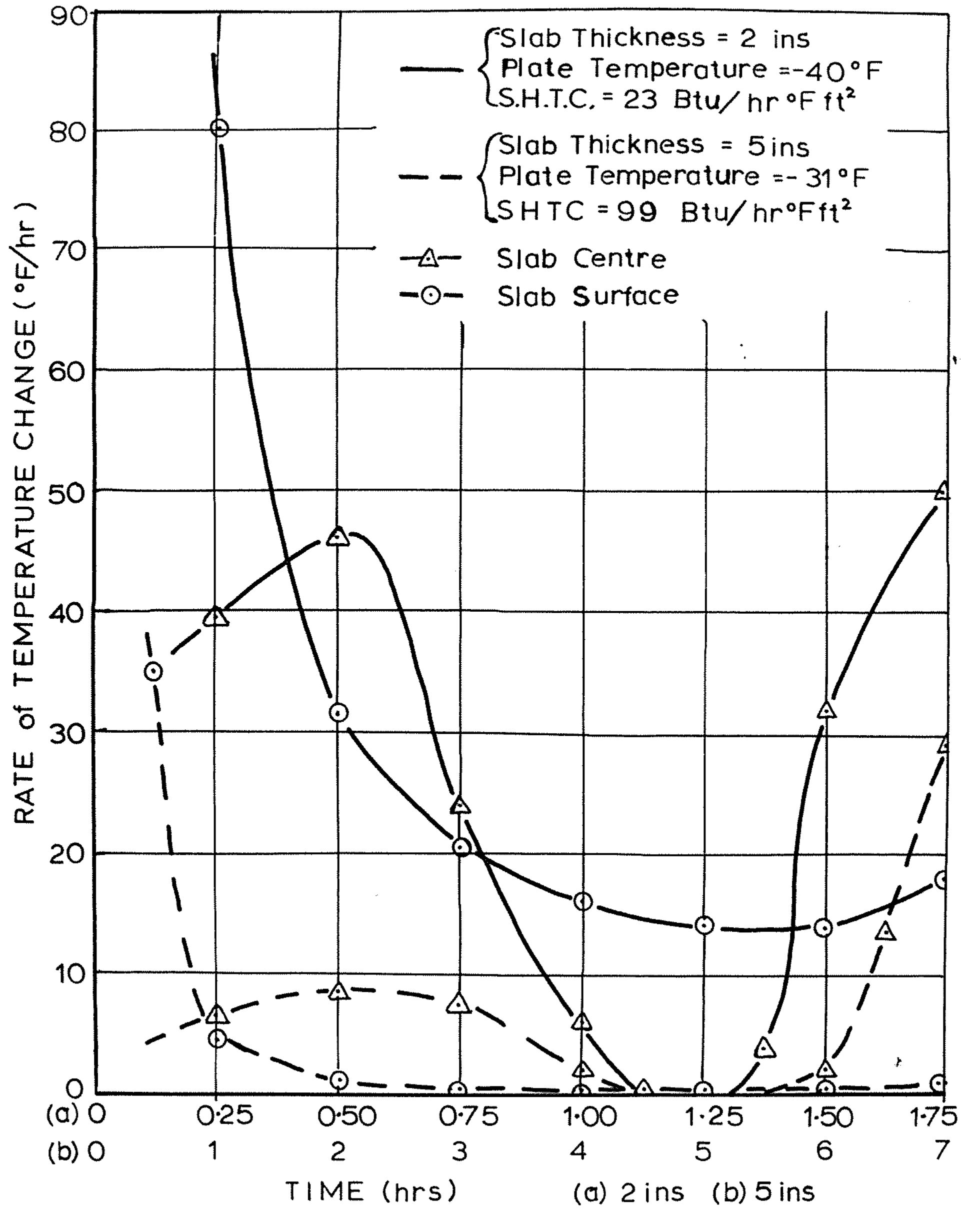


FIG. 31 RATE of TEMPERATURE CHANGE during the freezing of a slab —calculated—

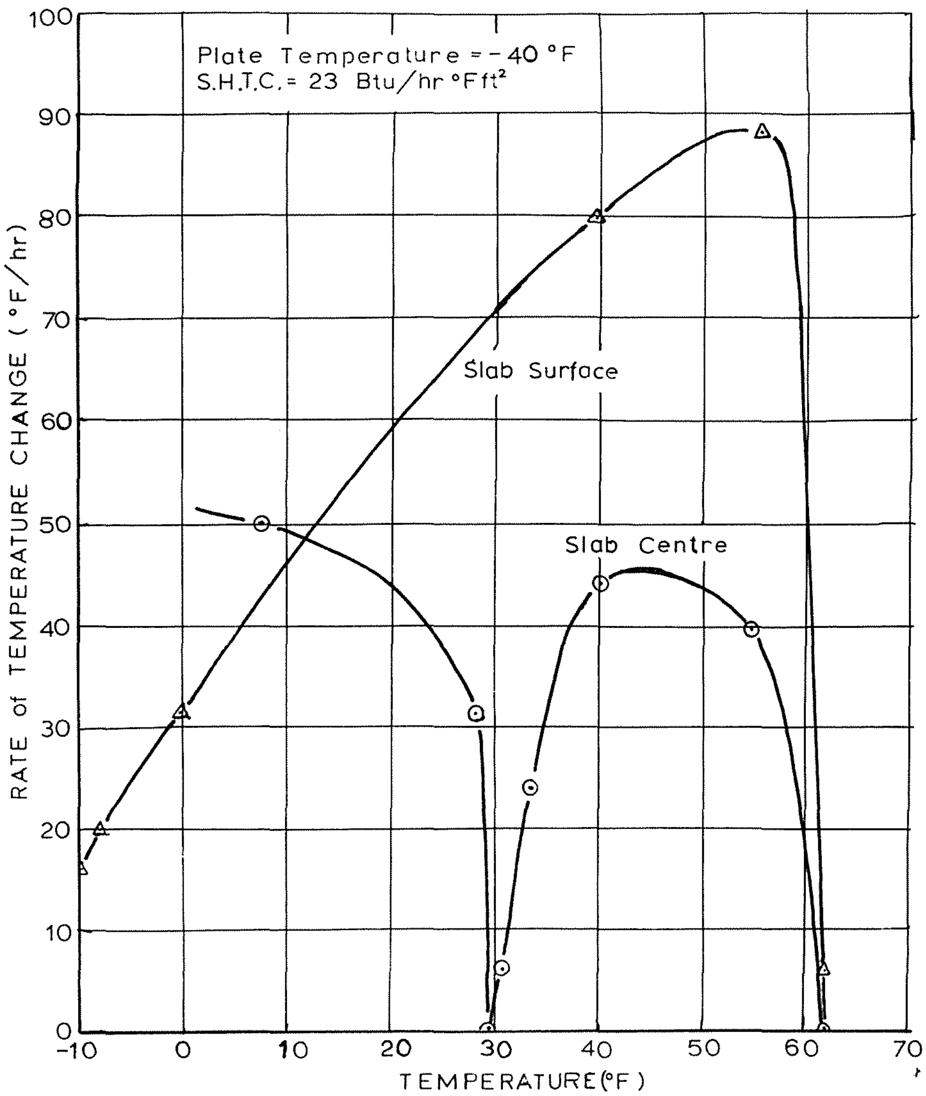


FIG. 32 RATE of TEMPERATURE CHANGE vs. TEMPERATURE for the freezing of a 2 ins thick slab — calculated —

changed as freezing proceeded. Hence the rates were different at different product temperatures as shown in Fig. 32 for the freezing of the 2 ins. slabs of minced lean beef under the conditions already specified. The rates were very high in the surface regions when the surface temperature was high but the rate decreased quite rapidly as the temperature was decreased. The slab centre was subjected to slower rates of temperature change than the surface and experienced a static period when the freezing point of the system was reached.

At present there is absence of knowledge which quantitatively relates freezing rates and product quality, freezing rates at specific temperatures and product quality but it is readily evident that these freezing rates may be obtained from the time-temperature profile curves as illustrated here.

7.4. Conclusions:

The accuracy of numerical predictions was determined by comparing the numerical solution and experimental freezing curves obtained under the same freezing conditions. It was found that these numerical freezing curve predictions were accurate when accurate parameter values were used in the numerical solution calculations. It was also found that the freezing time of a product could be simply and accurately predicted by using an equation of this type.

$$\theta = \left[1 + 0.019(T_1 + 10)\right] \frac{L\rho}{\Delta T} \left(\frac{1}{2} \frac{a}{h} + \frac{1}{8} \frac{a^2}{k} \right)$$

The rates of temperature change which occurred during the freezing of slabs of minced lean beef in a plate freezer were obtained from the appropriate time-temperature profiles. It was found that these rates varied as freezing proceeded and they were of a magnitude which Mazur (27) found gave extra cellular ice formation.

CHAPTER 8

SUMMARY

In view of the large quantities of foodstuffs now being preserved in the frozen state, it is important to be able to predict accurately the freezing time of a product. In this study the freezing curves for the one-dimensional freezing of a homogeneous product were predicted precisely by a numerical solution of the freezing problem which took into account variations in the specific heat and the thermal conductivity of the product with temperature. Precise freezing time predictions were available from these curves.

The accuracy of this prediction method was established when it was found that the calculated freezing curves closely approximated the experimental freezing curves obtained during the freezing of slabs of minced lean beef in a plate freezer, a system which closely approximates the one-dimensional freezing of a homogeneous product. In these correlations it was found that the accuracy of this prediction method depended very significantly upon the accuracy of the parameter values used in the calculations. It was thus necessary to obtain accurate values of these parameters which included the initial product temperature, the plate temperature, the slab thickness, the thermal properties of the minced beef and the surface heat transfer coefficient of the experimental system. The calculations in this type of numerical solution would be tedious but for the digital computer.

In these studies it was found that a surface heat transfer coefficient of approximately 100 Btu/hr ^{o}F ft^2 existed when the beef slab surfaces were in direct contact with the refrigerated plates but the coefficient was significantly affected by the nature of the contact surface. The extent of apparent air pocket formation in the contact surface appeared important but a more detailed study is required. A surface heat transfer coefficient of 8 Btu/hr ^{o}F ft^2 was found when the slab surfaces were initially covered with a layer of solid fiberboard 080.

It was found that the freezing time of a product, from an initial temperature T_1 down to $-10^{o}F$, could be simply and precisely predicted by using a modified form of Plank's equation for the freezing of a slab (32) namely

$$\theta = \left[1 + 0.019\ (T_1 + 10)\right] \frac{L\rho}{\Delta T} \left(\frac{a}{2h} + \frac{a^2}{8k} \right)$$

The rates of temperature change which occurred during the freezing of slabs of minced lean beef in a plate freezer were obtained from the appropriate time-temperature profiles. These rates varied as freezing proceeded and they were of a magnitude which Mazur (27) found gave extra cellular ice formation. This knowledge is of interest when the effect of freezing rate on product quality is considered.

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