TECHNICAL REPORT

A PRACTICAL METHOD OF PREDICTING SEA ICE FORMATION AND GROWTH

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ABSTRACT

A technique for predicting ice formation and growth is presented. The ice potential calculations originally discussed by Zubov and Defant form part of the method, as do the standard heat budget equations developed by various authors. In addition, new formulas are derived for computing ice growth in terms of known or predicted oceanographic and meteorological data. The method is applied to the problem of predicting the general features of the ice distribution in the Baffin Bay-Davis Strait area for the season 1952-53. It is pointed out that use of this method must be limited to open-sea areas where winter and not polar ice is the dominating feature. However, the technique has important applications to estimating the general ice features of such areas several months in advance.

FOREWORD

The increasing importance of defense installations in northern areas has increased greatly the responsibilities of the U. S. Navy in supplying bases in Arctic waters, where sea ice is often an operating obstacle. The Hydrographic Office is charged with the responsibility of developing and testing techniques for observing and forecasting sea ice conditions. Standardized techniques for observing, charting, and reporting sea ice are now in operational use by the Navy, as described in publications issued by the Hydrographic Office. Heretofore, techniques for forecasting the formation, growth, and movement of sea ice have not been published by this Office. This publication describes a method of long-range forecasting of ice formation and growth. Since this technique is still in the developmental stage, the Hydrographic Office welcomes comments as to its operational value.

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A. INTRODUCTION

The expanding program of ice observation and forecasting at the Hydrographic Office has emphasized the desirability of long-range ice forecasting. There are many phases of the ice program for which long range forecasts giving advance estimates of ice conditions of as much as 150 days are required. This paper deals with long-range forecasting of ice thickness in open seas whose salinity and density remain relatively constant, such as Baffin Bay and the Labrador Sea.

An operational method of forecasting for a long period must be easy to use, require a minimum number of involved calculations, and yield forecasts of reasonable accuracy. Most formulas previously developed have been complicated expressions which are not suited for operational use. In developing the following method, the goal has been to perfect a technique from which quantitative results can be derived with a minimum of computation and observation.

B. THE ICE POTENTIAL OF A WATER COLUMN

The severity of an ice season depends, among other things, upon the amount of thermal energy stored in the water mass and upon the rate at which convective mixing takes place. It is necessary to select a model of convective mixing which will explain the variation in the thermohaline conditions caused by heat removal and ice accretion. The method proposed by Defant (1949) and by Zubov (1938) of computing the ice potential and potential heat loss has been adopted as a basis for the present forecasting technique.

Before a forecast can be made, an analysis of the properties that inhibit ice formation and growth must be performed. Oceanographic measurements within the area in question must be secured in order to obtain information about salinity and thermal energy stored within the water mass. Unnecessary computation can be avoided by making the measurements at a time after the heat flux reverses, when thermal energy is being continually removed from the water. Otherwise the amount of heat which was added to the water column prior to the reversal of the heat flux would have to be computed before the method of Defant and Zubov could be utilized.

Establishing the ice potential of a given water column requires only the temperature and salinity at N levels within the column. The column is divided into (N-1) layers and the mean temperature ($\bar{T}_n$), salinity ($\bar{S}_n$), and density ($\bar{\sigma}_n$), are computed for each layer. The mixing model, as defined by the method of Defant and Zubov is constructed by finding the mean temperature and salinity of the surface and second layers, i.e.,

$$\frac{\bar{S}_1 + \bar{S}_2}{2} = \bar{S}_{1,2} \quad , \quad \frac{\bar{T}_1 + \bar{T}_2}{2} = \bar{T}_{1,2} \; .$$

The column is then said to be partially mixed down to the second level. Complete mising is achieved by cooling the partially mixed column until its density, $\sigma_{1, 2}$, equals that of the original second layer, σ_2. This mixing may be accomplished merely by changing the temperature of the partially mixed column, provided the water is not cooled below its freezing point. If the temperature change necessary for completely mixing the column requires a temperature below the freezing point, ice will form and the salinity of the remaining water in the column will be increased. The mixing process is carried out layer by layer until the potential heat loss is greater than the possible heat loss for a given ice season.

For convenience the expressions "partially mixed" and "completely mixed" have been used in connection with the ice potential computations. Two layers of water are termed "partially mixed" when the mixed column is defined completely by the means of the temperatures and salinities of the two original layers (i.e., no heat loss is involved). A "partially mixed" layer becomes "completely mixed" when the density of the partially mixed layer equals that of the original lower layer, with the density of the original lower layer remaining fixed throughout the process. In this latter case a heat loss is necessary, provided that the density distribution is stable. Temperature and salinity changes which result from this mixing model can be easily read from a T-S nomograph, or can be computed by use of standard hydrographic tables. (H.O. Pub. No. 615)

Complete mixing can be accomplished only by releasing q_T gram calories of sensible heat from the water column one square cm in cross section. Quantitatively, $q_{T(h)} = c \rho_w h \Delta T_w$ where c is the specific heat of sea water ρ_w is the density of sea water, h is the depth to which complete mixing reaches (or volume of h cm^3), and ΔT_w is the amount of heat lost in changing the partially mixed column to a completely mixed column. When it is necessary to change the salinity of the column in order to achieve complete mixing, latent heat is involved in the process as well as sensible heat. Since a known percentage of the salt is frozen out of the ice, it is possible to write an expression for the latent heat as a function of the salinity change. Consequently, the ice accretion corresponding to a given salinity change can be expressed mathematically. As written by Defant, the ice thickness is given by

$$\xi_i = \frac{h \Delta S}{C \rho_w b S} \tag{1}$$

where S is the salinity of the partially mixed column and b is the percentage of the salts frozen out of the ice. The latent heat can now be evaluated from the well-known formula $q_\xi (Z) = K \xi (Z)$, where K is the latent heat of fusion, which decreases with increasing salinity of the ice. The total potential latent heat is given by

$$\int_0^h q_\xi dz = Q_l (h) \tag{2}$$

As the mixing model is developed, each layer will yield a certain amount of potential heat loss, q_T, and eventually, when the temperatures are low and the densities are high, each layer will yield a certain mass of potential ice (ξ) associated with convective mixing down through the corresponding layer. Thus it is possible to construct the very useful "potential curve" (Figure 2) from corresponding

$$\int_0^h \xi dz = l_i(h) \quad \text{and} \quad Q_T(h) = \widetilde{Q}_T(h) - Q_o, \quad \text{where} \quad \widetilde{Q}_T = \int_0^h q_T dz. \quad (3)$$

The potential curve is plotted, Q_T starting from zero within the layer where ice first appears. The remainder of the $\widetilde{Q}_T, Q_o$, which is lost before ice is formed, determines the date of ice formation. The reason for taking Q_T as zero at this point becomes evident when one considers the lower limits of the integrals in equation (13). Obviously some question arises as to the exact quantity of heat that has been removed at the time ice is first formed. There is, of course, some error introduced, but it is not large as long as the water temperatures are near the freezing point and the water column is divided into layers of sufficiently small depth, for example five to ten meters. Recent work on the same type of model as Defant's has yielded exact values of the Q_T which must be removed before ice is formed, thus determining the proper point to start accumulating the Q_T for the potential curve (Brown, 1954).

In order to illustrate the computation of the ice potential and the drawing of the potential curve, a typical oceanographic station is used as an illustration. Station 37, at 66°N, 58°W, was occupied on 3 October 1952. A plot of the oceanographic variables at this station is given in Figure 1, and the complete numerical data are shown in Table 1.

TABLE 1
Oceanographic Data for Station #37
(66°N, 58°W), 3 October 1952

Depth m.	Temperature °C.	Salinity ‰	Density Anomaly (σ_t) gm/liter
0	0.56	32.37	25.98
5	0.10	32.36	26.00
10	0.61	32.39	25.99
20	0.73	32.47	26.05
30	-0.41	32.78	26.36
50	-1.65	33.08	26.64
75	-1.61	33.69	27.13
99	-2.13	33.69	27.14
148	-0.52	34.04	27.38
197	1.52	34.21	27.40
296	0.08	34.34	27.59
394	-1.71	34.52	27.81

FIG. 1 OCEANOGRAPHIC PLOT FOR STATION NO. 37, 66°N 58°W, 3 OCTOBER 1952.

From these data the ice potential has been calculated by the method of Defant and the results shown in Table 2A. Finally, the ice potential curve for Station 37 is shown in Figure 2. It will be noted that the ice potential curve is by no means a straight line or a smooth curve. In fact, for this station, the heat loss necessary to form a given amount of ice varies considerably. For this reason, the actual forecasting for this station is difficult, for a small additional heat loss at about 2 kg. cal. causes the formation of a large amount of ice. In this respect the example shown is not typical of many stations where the ice potential curve is quite regular and smooth; however, it is included to illustrate the kind of difficulties encountered in practice. In addition, the curve is atypical because Q_o, the heat loss necessary to bring about formation of ice was found exactly at 25 meters when the temperature of the completely mixed layer (1-4, Table 2B) first dropped to -1.8°C. In general, Q_o cannot be so easily determined.

C. METHOD OF COMPUTING DATE OF ICE FORMATION

There are two acceptable methods of computing the date of ice formation. Since the amount of heat that must be lost before ice is formed is known from the ice potential computations, it is only necessary to compute the time required to lose this heat. One method is to make actual observations of the heat loss per day per square cm. and thus to find the mean heat loss which is representative of a given area. The other method is to compute the total heat loss by consideration of the climatological data, the sun's altitude, and oceanographic data. For this purpose the only known formulas are those of Jacobs (1942), which yield rates of heat loss of the right order of magnitude in the Arctic, although they were specifically derived for middle latitudes.

Jacobs' formulas for computing heat losses are:

$$Q_{ab} = .025\ \bar{\alpha}\left[.29 + .71\left(1 - \frac{\bar{c}}{100}\right)\right](1 - r)\,t,\ t \text{ in minutes} \quad (4)$$

$$Q_b = .94\left[\text{eff. } Q_b\ (1 - .0083\bar{c})\right]t, \quad t \text{ in minutes} \quad (5)$$

$$Q_e = 145.4\ \bar{w}(e_w - e_a)\left[1 + .01\left\{\frac{T_w - T_a}{e_w - e_a}\right\}\right]t,\ t \text{ in days,} \quad (6)$$

where

Q_{ab} = total incoming radiation in gm. cal/cm.^{2}

Q_b = total back radiation in gm. cal/cm.^{2}

Q_e = total heat loss due to evaporation in gm. cal/cm.^{2}

$\bar{\alpha}$ = mean altitude of the sun in degrees,

$\bar{c}$ = mean cloud amount in percent,

$\bar{W}$ = mean wind velocity in knots,

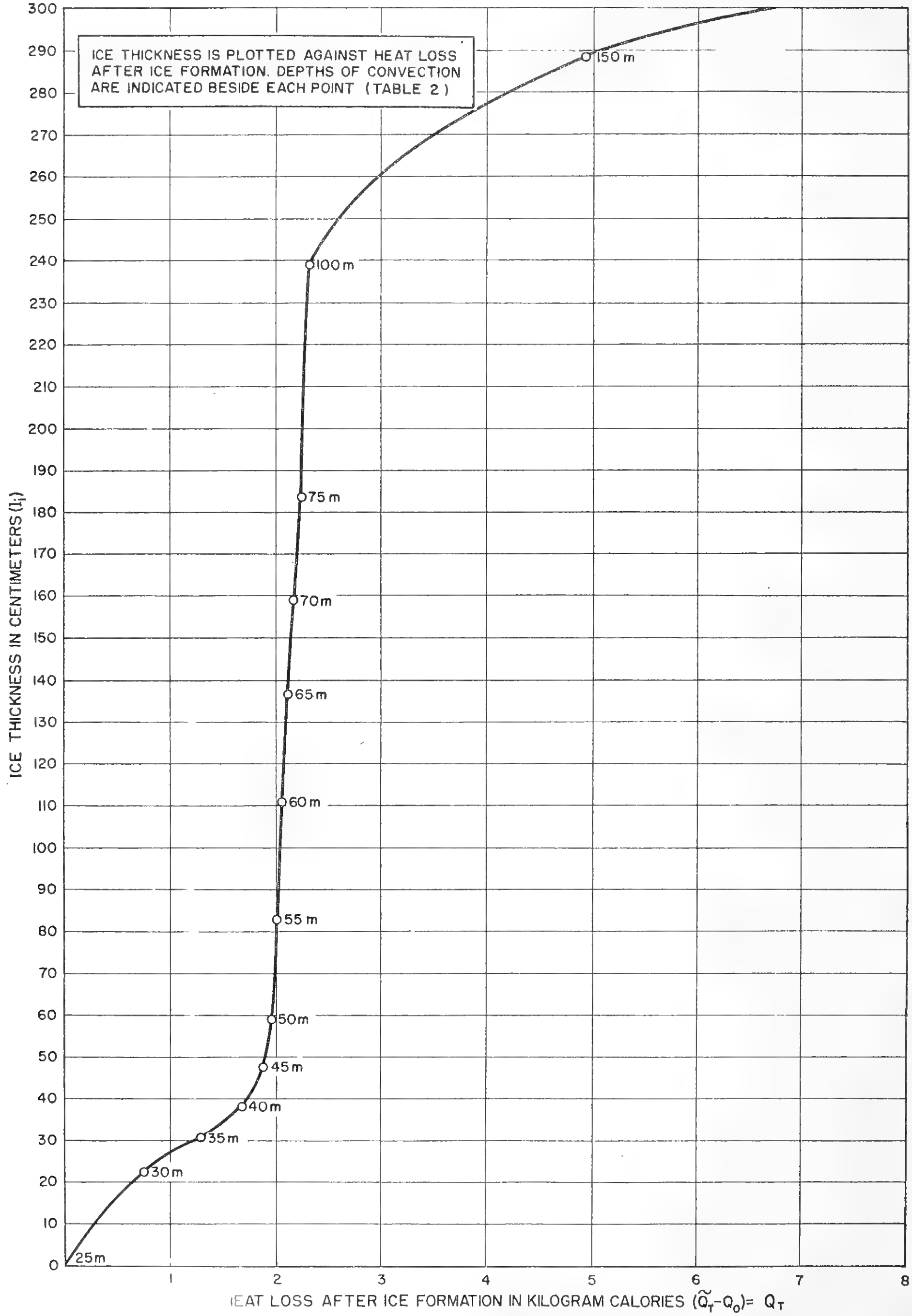

FIG. 2 ICE-POTENTIAL CURVE FOR STATION NUMBER 37.

e_w = vapor pressure of the water in inches Hg.,
e_a = vapor pressure of the air in inches Hg.,
T_w = temperature of the water in degrees F.,
T_a = temperature of the air in degrees F.
eff. Q_b (effective back radiation) = difference between temperature radiation of the sea surface and long-wave radiation from the atmosphere,
t = time in units designated above, and
r = fractional part of the incoming radiation reflected from the sea surface.

The ice potential computations determine the amount of sensible heat which must be removed from the water column prior to the initial formation of ice. For example, let this value be Q_p. Then setting $Q_p = Q_b - Q_e - Q_{ab}$ and solving for t gives the number of days between the time that the oceanographic measurements were madè and the time ice will form.

D. METHOD OF COMPUTING ICE GROWTH

From the time oceanographic observations are made until the time ice forms, it is assumed that the heat exchange results from incoming radiation, back radiation, and evaporation. After ice forms, the processes by which heat is removed from the water column are altered considerably. Any heat that is then removed from the water must be conducted through the solid layer of ice above it. Thus, the rate of further heat loss is determined by the temperature gradient through ice and snow. Hence, assuming steady-state conditions for finite increments of time,

$$\frac{d(Q_1+Q_T)}{dt} = k_i \frac{\Delta T_i}{l_i} = k_s \frac{\Delta T}{\bar{l}_s} \qquad (7)$$

where, Q_T is the amount of sensible heat loss (in kg. cal.),
Q_1 is the amount of latent heat loss (in kg. cal,),
k_1 is the heat conductivity coefficient of sea ice,
k_s is the heat conductivity coefficient of snow,
ΔT_i is the temperature difference between the upper surface of the ice and freezing point of sea water (in °C.),
ΔT_s is the temperature difference between the surface of the snow and the surface of the ice (in °C.),
l_i is the thickness of the ice in cm,
l_s is the thickness of the snow in cm, and
$\bar{l}_s$ is the mean snow cover over a finite period of time.

Since $\Delta T = \Delta T_i + \Delta T_s$, where ΔT is the temperature difference between the freezing point of sea water (taken at -1.8°C.) and the snow surface temperature, and from (7)

$$\frac{\Delta T_s}{\Delta T_i} = \frac{k_i \bar{l}_s}{k_s l_i} \qquad (8)$$

then $$\Delta T = \Delta T_l \left\{1 + \frac{k_l l_s}{k_s l_l}\right\} \quad \text{or} \quad \Delta T_l = \frac{\Delta T}{1 + \frac{k_l l_s}{k_s l_l}} \tag{9}$$

Then (7) becomes:

$$\frac{d(Q_1 + Q_T)}{dt} = \frac{k_l \Delta T}{l_l \left\{1 + \frac{k_l l_s}{k_s l_i}\right\}} \tag{10}$$

Substituting $Q_1 = \rho_i K l_i$ into (10) (ρ_o denotes ice density)

$$\rho_l K \frac{dl_l}{dt} + \frac{dQ_T}{dt} = \frac{k_i \Delta T}{l_l \left\{1 + \frac{k_l l_s}{k_s l_i}\right\}} \tag{11}$$

$$\rho_i K \left\{1 + \frac{k_l l_s}{k_s l_l}\right\} l_l \, dl_l + \left\{1 + \frac{k_i l_s}{k_s l_i}\right\} l_l \, dQ_T = k_l \Delta T dt \tag{12}$$

$$\rho_l K \int_0^{l_l(h)} l_l(Z) dl_i(Z) + \frac{\rho_i K k_l}{k_s} \int_0^{l_l(h)} l_s dl_i(Z) + \int_0^{Q_T(h)} l_l(Z) dQ_T(Z) +$$

$$\frac{k_l}{k_s} \int_0^{Q_T(h)} l_s dQ_T(Z) = k_i \int_{t_o}^{t} \Delta T dt \tag{13}$$

$$\frac{\rho_l K}{2} l_l^2(h) + \frac{\rho_i K k_l}{k_s} \bar{l}_s l_i(h) + \int_0^{Q_T(h)} l_l(Z) dQ_T(Z) + \frac{k_i}{k_s} \bar{l}_s Q_T(h) = k_i \int_{t_o}^{t} (T_F - T) dt. \tag{14}$$

The right-hand expression in equation 14 is usually denoted by the title "degree-days of frost." A degree-day of frost is defined as a day with a mean temperature 1-degree Centigrade below the freezing point of sea water. While the freezing temperature of sea water varies with salinity, it is here assumed to be -1.8°C. A degree-day of frost is then 1 day with a mean temperature of -2.8°C. Degree-days of frost usually are accumulated for forecasting over periods of 15 or 30 days. By giving the following values to some of the terms in equation 14:

$$\rho_i = 0.9$$

$$K = .080 \frac{\text{Kg Cal}}{\text{gm}}$$

$$k_i = .389 \frac{\text{Kg Cal}}{\text{cm °C day}}$$

$$k_s = .062 \frac{\text{Kg Cal}}{\text{cm °C day}},$$

the formula can be used directly to forecast the ice in terms of degree-days of frost

$$\int_{t_0}^{t} (T_F - T)\,dt.$$

Thus, for a given value of $\bar{l}_s$ all terms in the equation are known except l_i and Q_T. A given l_i and likewise the corresponding Q_T, can be selected from the potential curve. By substituting l_i and Q_T into equation (14) and by evaluating the area under the potential curve between the proper limits for the expression

$$\int_{0}^{Q_T(h)} l_i(Z)\,dQ_T(Z)$$

the number of degree-days of frost required to form l_i centimeters of ice can be computed.

To eliminate the necessity of computation, the end results of the derivation have been presented in the form of tables (Tables 3-12). In addition the integral

$$\int_{0}^{Q_T(h)} l_i(Z)\,dQ_T(Z)$$

had to be evaluated by approximation methods. It was found from the majority of potential curves that the integral could be approximated as

$$\frac{l_i}{2} Q_T(h),$$

The error introduced was found to be small unless the water temperature was unusually high, and in most cases ice will not form under such conditions. Since the potential curve $l_i(Q_T)$ must always be plotted, it is readily apparent when the above approximation is invalid; in this situation the formula can be used. In order to facilitate substitution of the actual integral for the approximation, an auxiliary table (Table 13) is included which gives the degree-days of frost associated with various values of l_i and Q_T. If the potential curve is very irregular, Table 13 is entered, and by comparison with the degree-day figure computed from an average l_i, one can determine the amount of error introduced into the total. Most frequently this will be found to be small, since the potential term is only one of four separate factors contributing to the total; however, the actual value can be added or subtracted and a more accurate figure secured.

The form of equation 14 which was used in the tables is

$$\int_{t_0}^{t}(T_F - T)\,dt = \frac{1}{k_i}\left[\frac{\rho_i K}{2} l_i^2 + \left\{\frac{\rho_i K k_i l_s}{k_s} + \frac{Q_T}{2}\right\} l_i + \frac{k_i l_s}{k_s} Q_T\right]. \qquad (15)$$

The degree-days of frost for fixed l_s = 0, 2.5, 5, 7.5, 10, 15, 20, 30, 40, and 50 cm. are given in Tables 3 to 12. The concept of degree-days has an advantage over one of calendar days because of its versatility as far as forecasting is concerned. An ice forecast in days is difficult because it requires a forecast of air temperatures as well as ice growth, while the degree-day forecast permits ice growth forecasts which fit all conceivable temperature variations.

E. USE OF THE ICE GROWTH TABLES IN FORECASTING

Forecasting the ice growth in a given area requires the following information: (1) oceanographic data taken after the water mass begins to cool and prior to ice formation, (2) the date of ice formation, and (3) an expression relating ice growth to degree-days of frost for the given area. With this information the forecaster can then proceed to make a forecast for the entire season. The procedure is as follows: (1) the ice potential of each oceanographic station is calculated and the ice potential curve (example, Figure 2) is drawn; (2) from available meteorological and oceanographic data, the date of ice formation is determined; and (3) the forecast is made in terms of degree-days of frost.

Since the calculation of the ice potential, the date of first ice formation, and the ice potential curve have been previously explained, the remaining discussion will describe the preparation of an actual forecast. As before, Station #37 is used as an example. The ice potential curve for this station is given in Figure 2. In order to draw the ice forecast curves for this station it is necessary to read the ice thickness figures corresponding to integral values of Q_T from the ice potential curve. The degree-days of frost corresponding to each combination of l_i and Q_T values are read from each of the tables 3 to 12. A plot of ice thickness vs degree-days of frost is made from each set of values obtained from the graphs, and a smooth curve is drawn for each value of snow depth (l_s). An example of a completed forecast is given in Figure 3. In Figure 3, $Q_T = 1$ corresponds to an ice thickness of 27 cm. and $Q_T = 2$ to an ice thickness of 72 cm. on the ice potential curve of Figure 2. To convert the completed forecast into a time forecast the meteorologist must provide temperature and snow depth forecasts in order to secure an ice thickness forecast of 120 to 150 days for this station.

Now let us suppose that the date of first ice formation at Station #37 is 12 November and that the meteorologist provides a forecast, including the following data for the succeeding months:

Period	Mean Temperature (°C)	Degree-Days of Frost	Snow Depth (cm.)
12 - 15 Nov.	-5.8	16	0
16 - 30 Nov.	-4.8	45	0
1 - 15 Dec.	-8.8	105	2.5
16 - 31 Dec.	-7.8	96	2.5
1 - 15 Jan.	-9.8	120	7.5
16 - 31 Jan.	-18.8	272	7.5

The ice thickness for any given date may be found from the above data and the forecast curve.

During the period when the snow depth is zero, the growth of ice will be along the upper curve on Figure 3; on 30 November, the final day with no snow, the total of degree-days of frost is 16 + 45 or 61 and the ice thickness will be 17 cm. (point A on Figure 3).

During the month of December the ice grows under a snow depth of 2.5 cm. from a starting point of 17 cm. This point is marked A'. During December a total of 105 plus 96 or 201 degree-days of frost is counted, so that it is necessary to follow the curve $l_s = 2.5$ for 201 degree-days of frost beyond point A', or to point B. At point B, reached 31 December, the ice thickness will be 35 cm.

Similarly, during January the ice grows under a snow depth of 7.5 cm. for 120 plus 272 or 392 degree-days beyond the point B' corresponding to an ice thickness of 35 cm. On 31 January the point C is reached, and the ice thickness will be 53 cm. This constitutes an operational forecast, as the user of the forecast can determine the ice thickness on any day between 12 November and 31 January by counting the number of degree-days of frost and noting the snow depth applicable to the situation.

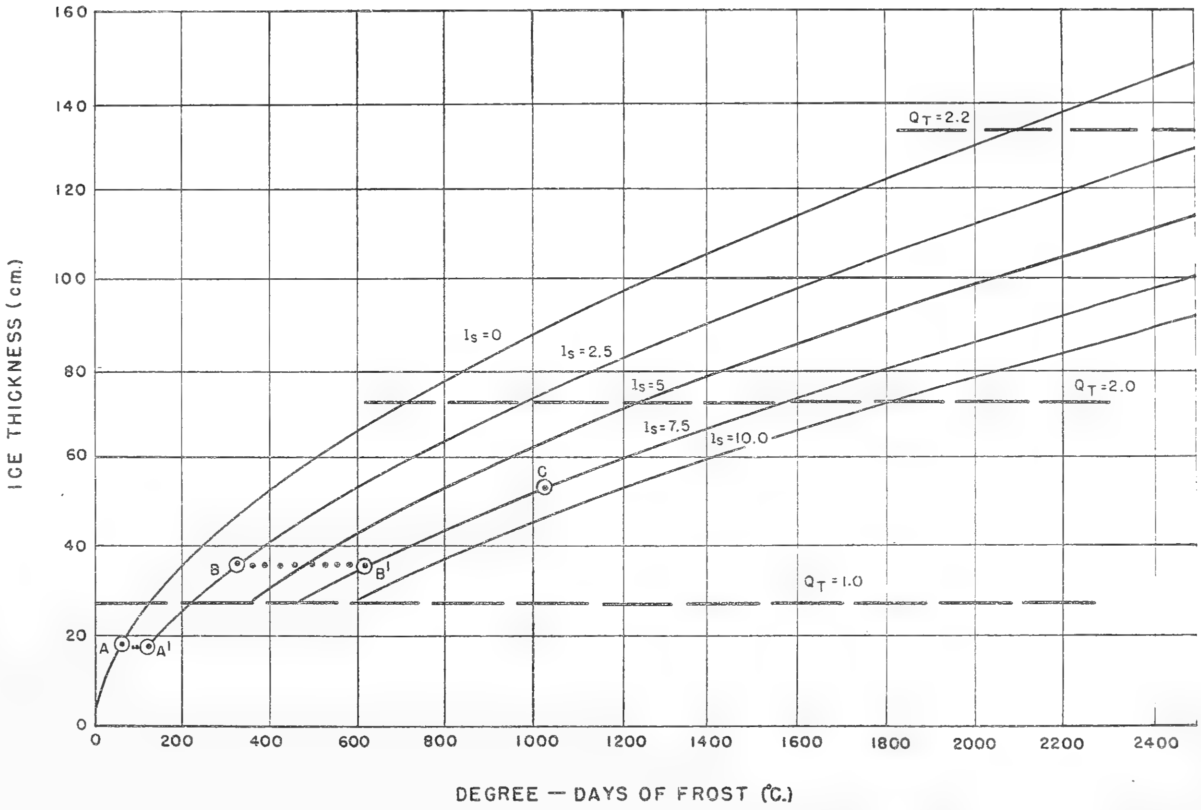

FIG. 3. ICE GROWTH FORECAST FOR STATION # 37

F. BAFFIN BAY-DAVIS STRAIT LONG-RANGE ICE FORECAST FOR SEASON 1952-53.

During early autumn, 1952, oceanographic observations were taken at the locations shown on Figure 4. The method explained previously was employed to forecast the ice formation and growth of these locations. The dates of ice formation were computed and are shown beside each station. Since the thermohaline structure at some of the stations was such that no ice would be formed, it was possible to delineate the theoretical extreme ice boundary shown as a heavy line in Figure 4. This boundary agrees very well with the boundary which was actually observed in late March and early April 1953, (shown as a dashed line in Figure 4) except for the occurrence of ice south of Stations 39 and 40. It is possible that ice which was observed at these two stations was not formed there, but had drifted from nearby areas of ice formation. The dispersion of ice near the observed boundary in this area indicates that the ice actually was formed outside the area.

CONCLUSIONS

The methods of Zubov and Defant for ice potential calculation have proved in practice to give reasonable answers for open seas and for inshore areas where local variations in the physical properties of the water are not large. In harbors and areas where runoff is important, changes in salinity and density are so rapid that it is difficult to attach a meaning to an average value of these parameters. Hence any ice potential calculation based on one or a few observations in a harbor may give a potential ice growth which is unreasonably high or low for a single season.

The forecast of ice growth based on the ice potential can be used only during the period when ice thickness is increasing. No theory has been included which accounts for decreasing ice thicknesses during the breakup period. Indeed, no mathematical theory has yet been developed for the breakup of ice.

Many refinements of the method presented in this paper are possible. Some of them are discussed in a paper by Brown (1954). The method described here was used to forecast during the 1952-53 ice season; the forecast proved to be satisfactory. The most important advancement discussed in this report is the use of the ice potential as a basis for forecasting ice growth.

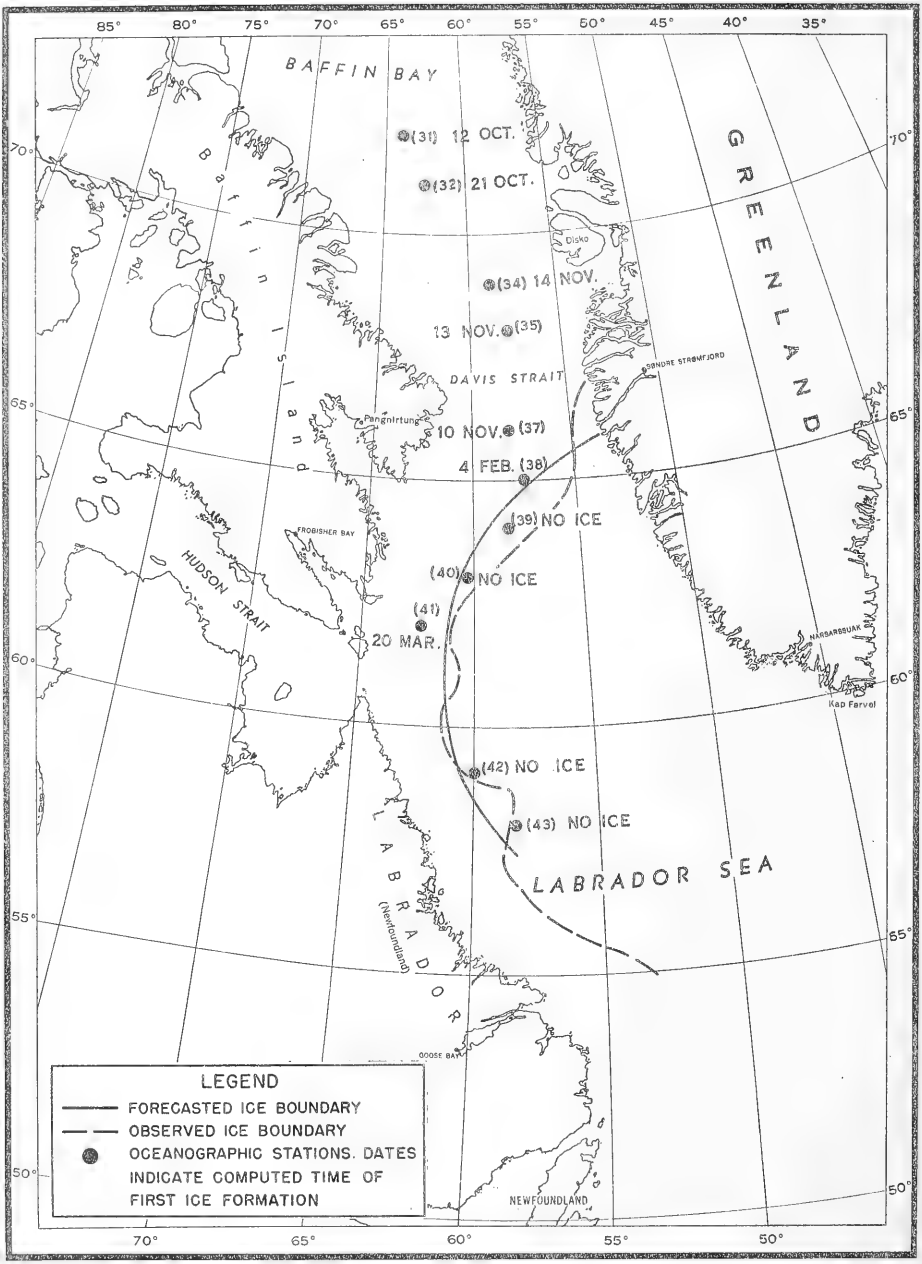

FIG. 4. FORECASTED AND OBSERVED ICE BOUNDARIES IN BAFFIN BAY AND DAVIS STRAIT FOR THE SEASON 1952-1953

TABLE 2 A
ICE POTENTIAL CALCULATIONS FOR STATION #37
(66°N,58°W), 3 OCTOBER 1952

Depth Meters	T°C	S °/oo	σ_t
0	.56	32.38	25.98
5	.10	32.36	26.00
10	.61	32.39	25.99
15	.67	32.41	26.00
20	.73	32.47	26.05
25	.15	32.62	26.20
30	-.41	32.78	26.36
35	-.86	32.86	26.43
40	-1.18	32.94	26.48
45	-1.50	33.01	26.54
50	-1.65	33.08	26.64
55	-1.65	33.20	26.76
60	-1.62	33.36	26.88
65	-1.62	33.50	26.98
70	-1.61	33.60	27.07
75	-1.61	33.69	27.13
80	-1.72	33.69	27.14
85	-1.80	33.69	27.14
90	-1.80	33.69	27.14
95	-1.80	33.69	27.14
100	-1.80	33.70	27.14
150	-0.51	34.06	27.38
200	1.50	34.21	27.40
300	0.06	34.35	27.60
400	-1.75	34.53	27.82

Layer No.	Depth (Meters)	Mean Values T°C	S °/oo	σ_t
1	0-10	.42	32.38	25.99
2	10-15	.54	32.40	26.00
3	15-20	.70	32.44	26.02
4	20-25	.44	32.54	26.12
5	25-30	-.13	32.70	26.28
6	30-35	-.64	32.82	26.40
7	35-40	-1.02	32.90	26.45
8	40-45	-1.34	32.98	26.51
9	45-50	-1.58	33.04	26.59
10	50-55	-1.65	33.14	26.70
11	55-60	-1.64	33.28	26.82
12	60-65	-1.62	33.43	26.93
13	65-70	-1.62	33.55	27.02
14	70-75	-1.61	33.64	27.10
15	75-80	-1.66	33.69	27.14
16	80-85	-1.76	33.69	27.14
17	85-90	-1.80	33.69	27.14
18	90-95	-1.80	33.69	27.14
19	95-100	-1.80	33.70	27.14
20	100-150	-1.16	33.88	27.26
21	150-200	.50	34.14	27.39
22	200-300	.78	34.28	27.50
23	300-400	-.84	34.44	27.71

TABLE 2 B

Layer	Depth h (m)	Before Mixing T °C	Before Mixing S °/oo	After Mixing	After Mixing T °C	After Mixing S °/oo	ΔT	q_T	$\tilde{Q}_T$	ΔS	ξ_i	l_i	Q_T
1-2	15	.46	32.39	26.00	.45	32.39	-.01	-.01	-.01				
1-3	20	.51	32.40	26.02	.30	32.40	-.21	.38	.39	0			
1-4	25	.33	32.44	26.12	-1.80	32.44	-2.13	4.79	5.18	0			
1-5	30	-1.52	32.48	26.28	-1.80	32.70	-.28	.76	5.94	.22	22.4	22.4	.76
1-6	35	-1.63	32.72	26.40	-1.80	32.79	-.17	.54	6.48	.07	8.2	30.6	1.30
1-7	40	-1.70	32.80	26.45	-1.80	32.86	-.10	.36	6.84	.06	8.0	38.6	1.66
1-8	45	-1.75	32.87	26.51	-1.80	32.93	-.05	.20	7.04	.06	9.0	47.6	1.86
1-9	50	-1.78	32.94	26.59	-1.80	33.01	-.02	.09	7.13	.07	11.7	59.3	1.95
1-10	55	-1.79	33.02	26.70	-1.80	33.15	-.01	.05	7.18	.13	23.8	83.1	2.00
1-11	60	-1.79	33.16	26.82	-1.80	33.30	-.01	.05	7.23	.14	27.7	110.8	2.05
1-12	65	-1.79	33.31	26.93	-1.80	33.43	-.01	.06	7.29	.12	25.6	136.4	2.11
1-13	70	-1.79	33.44	27.02	-1.80	33.54	-.01	.06	7.35	.10	23.0	159.4	2.17
1-14	75	-1.79	33.55	27.10	-1.80	33.65	-.01	.07	7.42	.10	24.5	183.9	2.24
1-19	100	-1.79	33.53	27.14	-1.80	33.70	-.01	.09	7.51	.17	55.4	239.3	2.33
1-20	150	-1.59	33.76	27.26	-1.80	33.86	-.21	2.83	10.34	.10	48.7	288.0	5.16
1-21	200	-1.22	33.93	27.39	-1.80	34.02	-.58	10.44	20.78	.09	58.2	346.2	15.60
1-22	300	-.94	34.11	27.50	-1.80	34.15	-.86	23.22	44.00	.04	38.7	384.9	38.82

TABLE 3

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESS AND HEAT LOSSES FOR SNOW COVER = 0 cm.

Ice Thickness in cm. (I_T)	Heat Loss kg. cal. (Q_T) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0																			
5	2	9	15	22	28	34	41	47	54	60	67	73	80	86	92	99	131	163	195
10	9	22	35	48	61	74	86	99	112	125	138	151	163	176	189	202	266	330	395
15	21	40	59	79	98	117	136	156	175	194	214	233	252	271	291	310	406	503	599
20	37	63	88	114	140	166	191	217	243	268	294	320	346	371	397	423	551	680	808
25	58	90	122	154	186	218	251	283	315	347	379	411	443	476	508	540	700	861	1022
30	83	122	160	199	238	276	315	353	392	430	469	508	546	585	623	662	852	1047	1240
35	113	158	203	248	293	338	383	428	473	518	563	608	653	698	743	788	1013	1238	1463
40	148	200	251	302	354	405	457	508	559	611	662	714	765	816	868	919	1176	1434	1690
45	187	245	303	361	419	477	534	592	650	708	766	824	882	939	997	1955	1344	1633	1923
50	231	296	360	424	488	553	617	681	746	810	874	938	1003	1067	1131	1195	1517	1838	2159
55	280	351	421	492	563	633	704	775	846	916	987	1058	1128	1199	1270	1340	1694	2047	2401
60	333	410	487	565	642	719	796	873	950	1027	1104	1182	1259	1336	1413	1490	1876	2261	2647
65	391	474	558	642	725	809	892	976	1059	1143	1226	1310	1394	1477	1561	1644	2062	2480	2897
70	454	544	633	723	813	903	993	1083	1173	1263	1353	1443	1533	1623	1713	1803	2253	2703	3153
75	521	617	713	810	906	1003	1099	1195	1292	1388	1485	1581	1677	1774	1870	1967	2449	2931	3413
80	592	695	798	901	1004	1106	1209	1312	1415	1518	1622	1723	1826	1929	2032	2135	2649	3163	3677
85	669	778	887	996	1106	1215	1324	1433	1543	1652	1761	1870	1980	2089	2198	2307	2854	3400	3946
90	750	865	981	1097	1212	1328	1444	1559	1675	1791	1906	2022	2138	2254	2369	2485	3063	3642	4220
95	835	957	1079	1202	1324	1446	1568	1690	1812	1934	2056	2178	2300	2423	2545	2667	3277	3888	4498
100	925	1054	1182	1311	1440	1568	1697	1825	1954	2082	2211	2339	2468	2596	2725	2853	3496	4139	4781
110	1120	1261	1403	1544	1685	1827	1968	2110	2251	2392	2534	2675	2816	2958	3099	3241	3948	4654	5362
120	1333	1487	1641	1795	1950	2104	2259	2412	2566	2721	2875	3029	3184	3338	3492	3646	4417	5189	5960
130	1564	1731	1898	2065	2232	2400	2567	2734	2901	3068	3235	3402	3569	3736	3902	4070	4906	5741	6577
140	1814	1994	2174	2354	2534	2714	2894	3074	3254	3433	3613	3793	3973	4153	4333	4513	5413	6313	7212
150	2092	2275	2468	2661	2854	3046	3239	3432	3625	3818	4010	4203	4396	4589	4782	4974	5938	6902	7866
160	2369	2575	2780	2986	3192	3398	3603	3809	4014	4220	4426	4631	4837	5043	5248	5454	6482	7511	8539
170	2674	2893	3112	3330	3548	3767	3986	4204	4423	4641	4860	5078	5297	5515	5734	5952	7045	8137	9230
180	2998	3230	3461	3693	3924	4155	4387	4618	4849	5081	5312	5544	5775	6006	6238	6468	7626	8783	9939
190	3341	3585	3829	4074	4318	4562	4806	5050	5295	5539	5783	6027	6272	6516	6760	7004	8225	9446	10667
200	3702	3959	4216	4473	4730	4987	5244	5501	5758	6015	6274	6530	6787	7044	7301	7558	8853	10129	
210	4031	4351	4621	4891	5161	5431	5701	5971	6241	6510	6780	7050	7320	7590	7860	8130	9480		
220	4479	4762	5045	5328	5610	5893	6176	6459	6741	7024	7307	7590	7872	8155	8438	8721	10135		
230	4896	5191	5487	5782	6078	6374	6669	6965	7261	7556	7852	8148	8443	8739	9034	9330			
240	5331	5639	5948	6256	6564	6873	7182	7490	7798	8107	8415	8724	9032	9341	9649	9958			
250	5784	6105	6427	6748	7070	7391	7712	8034	8355	8676	8998	9319	9640	9962	10283	10604			
260	6256	6590	6924	7259	7593	7927	8261	8595	8930	9264	9598	9932	10266	10600					
270	6746	7094	7441	7788	8135	8462	8829	9176	9523	9870	10217	10564							
280	7256	7615	7976	8335	8695	9055	9415	9775	10135	10495									
290	7783	8156	8528	8901	9274	9647	10020	10392											
300	8329	8715	9100	9486	9871	10257													

TABLE 4

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 2.5 cm.

Heat Loss kg. cal. (Q_T)

Ice Thickness in cm. (l_i)

l_i cm	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	0	40	81	121	161	202	242	282	323	363	403	444	484	524	564	605	806	1008	1210
5	17	64	110	157	204	250	297	344	391	433	484	531	578	624	671	718	952	1186	1419
10	38	91	144	198	251	304	357	410	464	517	570	623	676	730	783	836	1102	1368	1634
15	64	124	184	243	303	362	422	482	541	601	660	720	780	839	899	956	1256	1554	1852
20	95	161	227	293	359	425	491	557	623	689	755	821	888	954	1020	1086	1416	1746	2076
25	130	203	275	348	420	493	565	638	710	782	855	927	1000	1072	1145	1217	1580	1942	2304
30	170	249	328	407	486	565	644	723	802	880	959	1048	1117	1196	1275	1354	1748	2142	2537
35	215	300	386	471	556	642	727	812	898	983	1063	1153	1239	1324	1409	1495	1921	2348	2774
40	264	356	448	539	631	723	815	906	998	1090	1182	1273	1365	1457	1548	1640	2099	2558	3016
45	318	416	514	612	711	809	907	1005	1103	1202	1300	1398	1496	1594	1692	1790	2281	2772	3263
50	377	481	586	687	795	900	1004	1109	1213	1318	1423	1537	1632	1736	1841	1945	2468	2991	3514
55	440	551	662	773	884	995	1106	1217	1328	1439	1550	1661	1772	1883	1994	2105	2660	3215	3770
60	507	625	742	860	977	1095	1212	1330	1447	1564	1632	1799	1917	2034	2152	2269	2856	3444	4031
65	580	704	827	951	1075	1199	1323	1447	1571	1694	1818	1942	2166	2190	2314	2438	3057	3676	4296
70	657	787	917	1048	1178	1308	1438	1569	1699	1829	1960	2090	2220	2351	2481	2611	3263	3914	4566
75	738	875	1012	1148	1285	1422	1559	1695	1832	1969	2106	2242	2379	2516	2652	2789	3473	4156	4840
80	825	968	1111	1254	1397	1540	1684	1827	1970	2113	2256	2399	2542	2686	2829	2972	3688	4403	5119
85	915	1065	1214	1364	1514	1163	1813	1962	2112	2262	2411	2561	2710	2860	3010	3159	3907	4655	5353
90	1011	1167	1323	1479	1635	1791	1947	2103	2259	2415	2571	2727	2883	3039	3195	3351	4131	4911	5691
95	1111	1273	1436	1598	1761	1923	2086	2248	2410	2573	2735	2898	3060	3223	3385	3547	4360	5172	5984
100	1215	1384	1553	1722	1891	2060	2229	2398	2567	2735	2904	3073	3242	3411	3580	3743	4593	5437	6281
110	1439	1621	1803	1984	2166	2348	2529	2711	2893	3075	3256	3438	3620	3802	3983	4155	5073	5982	6891
120	1681	1876	2070	2265	2459	2654	2848	3043	3238	3432	3627	3821	4016	4210	4405	4599	5572	6545	7518
130	1941	2149	2356	2564	2771	2978	3186	3393	3601	3808	4016	4223	4430	4638	4845	5053	6090	7127	8164
140	2220	2441	2661	2881	3102	3322	3542	3762	3983	4203	4423	4643	4864	5084	5304	5524	6626	7727	8829
150	2518	2751	2984	3217	3450	3683	3916	4150	4383	4616	4849	5082	5315	5548	5782	6015	7130	8346	9512
160	2834	3080	3326	3572	3818	4064	4310	4556	4802	5048	5294	5539	5786	6031	6277	6523	7753	8983	10213
170	3168	3427	3686	3945	4203	4462	4721	4980	5239	5493	5756	6015	6274	6533	6792	7050	8345	9639	
180	3522	3794	4065	4337	4609	4880	5151	5424	5696	5967	6239	6511	6782	7054	7325	7597	8956	10314	
190	3892	4177	4461	4747	5031	5315	5600	5884	6169	6453	6738	7022	7307	7592	7877	8160	9583		
200	4232	4530	4877	5175	5472	5769	6067	6364	6662	6959	7256	7554	7851	8148	8446	8743	10230		
210	4691	5001	5311	5622	5932	6242	6552	6863	7173	7483	7793	8104	8414	8724	9034	9345			
220	5113	5441	5764	6087	6410	6733	7056	7380	7703	8026	8349	8672	8995	9318	9641	9964			
230	5563	5899	6235	6571	6907	7243	7579	7915	8251	8587	8923	9259	9595	9931	10267	10603			
240	6027	6376	6725	7074	7423	7771	8120	8469	8818	9167	9515	9864	10213	10562					
250	6510	6872	7233	7595	7957	8318	8680	9042	9403	9765	10126	10483							
260	7011	7385	7760	8134	8509	8883	9258	9632	10007	10381									
270	7530	7918	8305	8692	9080	9467	9855	10242											
280	8068	8469	8869	9269	9669	10070	10470												
290	8625	9038	9451	9864	10277														
300	9200	9626	10052	10478															

TABLE 5

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 5 cm.

Ice Thickness in cm. (I_t)	Heat Loss in kg. cal. (Q_T)																		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	0	81	161	242	323	403	484	564	645	726	806	887	968	1048	1129	1210	1613	2016	2419
5	31	118	206	292	380	467	554	641	728	815	902	989	1076	1163	1250	1337	1773	2208	2644
10	67	161	254	348	441	535	628	722	815	909	1002	1096	1189	1283	1376	1470	1937	2405	2872
15	108	208	308	408	508	608	708	807	907	1007	1107	1207	1307	1407	1507	1607	2106	2606	3106
20	153	259	366	472	578	685	791	898	1004	1110	1217	1323	1429	1536	1642	1748	2280	2812	3344
25	203	316	429	542	654	767	880	993	1106	1218	1331	1444	1556	1669	1782	1895	2459	3023	3587
30	258	377	496	615	734	854	973	1092	1211	1330	1450	1569	1688	1807	1926	2046	2642	3238	3834
35	316	442	568	693	819	945	1070	1196	1322	1447	1573	1698	1824	1950	2075	2201	2829	3457	4086
40	380	512	644	776	909	1041	1173	1305	1437	1569	1701	1833	1965	2097	2229	2361	3022	3682	4342
45	449	587	726	864	1003	1141	1280	1418	1557	1695	1834	1972	2110	2249	2388	2526	3218	3911	4603
50	522	667	812	956	1101	1246	1391	1536	1681	1826	1971	2116	2261	2406	2550	2695	3420	4144	4869
55	599	751	902	1053	1205	1356	1507	1659	1810	1961	2113	2254	2415	2567	2718	2869	3626	4383	5140
60	682	839	997	1155	1313	1470	1628	1786	1944	2106	2259	2417	2575	2733	2890	3048	3837	4626	5415
65	768	932	1097	1261	1425	1589	1754	1918	2082	2246	2410	2574	2739	2903	3067	3231	4052	4873	5694
70	860	1031	1201	1372	1542	1713	1884	2054	2225	2396	2566	2737	2907	3078	3249	3419	4272	5126	5979
75	956	1133	1310	1487	1664	1841	2018	2195	2372	2550	2726	2904	3081	3258	3435	3612	4497	5382	6268
80	1057	1240	1424	1607	1791	1974	2158	2341	2525	2708	2892	3075	3258	3442	3625	3809	4726	5644	6561
85	1162	1352	1542	1732	1922	2112	2302	2491	2681	2871	3061	3251	3441	3631	3821	4011	4960	5910	6859
90	1272	1468	1665	1861	2058	2254	2450	2646	2843	3039	3235	3432	3628	3824	4021	4217	5199	6180	7162
95	1387	1590	1792	1995	2198	2400	2603	2806	3009	3212	3414	3617	3820	4023	4225	4428	5442	6456	7469
100	1506	1715	1924	2134	2343	2552	2761	2970	3180	3389	3598	3807	4016	4225	4434	4644	5690	6736	7781
110	1758	1980	2203	2425	2647	2869	3091	3313	3535	3757	3979	4201	4423	4645	4867	5089	6199	7309	8420
120	2029	2134	2499	2734	2969	3204	3439	3674	3908	4143	4378	4613	4848	5083	5313	5553	6727	7902	9076
130	2319	2486	2814	3062	3310	3558	3805	4053	4301	4548	4796	5044	5292	5539	5787	6035	7274	8512	9751
140	2627	2807	3148	3408	3669	3930	4190	4451	4712	4972	5233	5493	5754	6014	6275	6536	7839	9142	10445
150	2953	3227	3500	3774	4047	4320	4594	4867	5141	5414	5688	5961	6235	6508	6782	7055	8422	9790	
160	3298	3584	3871	4157	4443	4730	5016	5302	5589	5875	6161	6448	6734	7020	7306	7593	9024	10456	
170	3662	3961	4260	4559	4858	5157	5457	5756	6055	6354	6653	6952	7252	7551	7850	8149	9645		
180	4044	4356	4668	4980	5292	5604	5916	6228	6540	6852	7164	7476	7788	8100	8412	8724	10284		
190	4444	4769	5094	5419	5744	6068	6393	6718	7043	7368	7692	8018	8342	8667	8992	9317			
200	4863	5201	5538	5876	6214	6552	6889	7227	7565	7902	8240	8578	8916	9253	9591	9929			
210	5301	5651	6002	6352	6703	7053	7404	7755	8105	8456	8806	9157	9507	9858	10208	10559			
220	5757	6120	6484	6847	7210	7574	7937	8300	8664	9027	9391	9754	10118	10481					
230	6231	6607	6984	7360	7736	8112	8489	8865	9241	9618	9994	10370							
240	6724	7113	7502	7892	8281	8670	9059	9448	9837	10226	10615								
250	7236	7638	8040	8442	8844	9246	9648	10050	10452										
260	7766	8180	8595	9010	9425	9840	10254												
270	8314	8742	9170	9597	10025	10453													
280	8881	9322	9763	10203															
290	9467	9920	10374																
300	10071	10537																	

TABLE 6

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 7.5 cm.

Ice Thickness in cm. (I_i)	Heat Loss in kg. cal. (Q_T) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	0	121	242	363	484	605	726	847	968	1089	1210	1331	1452	1573	1694	1814	2419	3024	3629
5	46	173	301	428	555	683	810	938	1065	1192	1320	1447	1574	1702	1829	1957	2594	3231	3868
10	96	230	364	498	632	765	899	1033	1167	1301	1434	1568	1702	1836	1970	2104	2773	3442	4111
15	151	292	432	572	712	853	993	1133	1273	1414	1554	1694	1834	1975	2115	2255	2956	3658	4359
20	211	358	504	651	798	944	1091	1238	1385	1531	1678	1825	1971	2118	2265	2411	3145	3878	4611
25	276	429	582	735	888	1041	1194	1347	1500	1653	1806	1960	2113	2266	2419	2572	3338	4103	4868
30	345	504	664	823	983	1142	1302	1461	1621	1780	1940	2099	2259	2418	2578	2738	3535	4333	5130
35	418	584	750	916	1082	1248	1414	1580	1746	1912	2078	2244	2410	2576	2742	2908	3737	4567	5397
40	496	669	841	1014	1186	1358	1531	1603	1876	2048	2220	2393	2565	2738	2910	3082	3944	4806	5668
45	579	758	937	1116	1295	1473	1652	1831	2010	2189	2367	2546	2725	2904	3083	3261	4156	5050	5944
50	667	852	1037	1223	1408	1593	1778	1964	2149	2334	2519	2704	2890	3075	3260	3445	4372	5298	6224
55	759	951	1142	1334	1526	1717	1909	2101	2292	2484	2676	2867	3059	3250	3442	3634	4592	5550	6509
60	856	1054	1252	1450	1648	1846	2044	2242	2440	2639	2837	3035	3233	3431	3629	3827	4818	5808	6798
65	957	1162	1366	1571	1775	1980	2184	2389	2593	2798	3002	3207	3411	3616	3820	4025	5048	6070	7092
70	1063	1274	1485	1696	1907	2118	2329	2540	2751	2962	3173	3384	3594	3806	4016	4227	5282	6337	7391
75	1174	1391	1608	1826	2043	2261	2473	2695	2913	3130	3348	3565	3782	4000	4217	4434	5521	6603	7695
80	1289	1513	1737	1960	2184	2408	2632	2856	3079	3303	3527	3751	3975	4198	4422	4646	5765	6884	8003
85	1409	1639	1869	2100	2330	2560	2790	3020	3251	3431	3711	3941	4172	4402	4632	4862	6013	7164	8316
90	1534	1770	2007	2243	2480	2737	2953	3190	3427	3663	3900	4136	4373	4610	4846	5083	6266	7450	8633
95	1563	1906	2149	2392	2635	2878	3121	3364	3607	3850	4093	4336	4580	4823	5066	5309	6524	7740	8955
100	1796	2046	2295	2545	2794	3044	3293	3543	3792	4042	4292	4541	4790	5040	5289	5539	6786	8034	9281
110	2078	2340	2603	2865	3127	3390	3652	3914	4177	4439	4702	4964	5226	5489	5751	6013	7325	8637	9949
120	2378	2653	2928	3203	3479	3754	4029	4304	4579	4855	5130	5405	5680	5956	6231	6506	7882	9258	10634
130	2696	2984	3272	3560	3849	4137	4425	4713	5001	5289	5577	5865	6153	6441	6729	7017	8458	9898	
140	3033	3334	3635	3936	4237	4538	4839	5140	5441	5742	6042	6343	6644	6945	7246	7547	9052	10556	
150	3389	3703	4016	4330	4644	4958	5271	5595	5899	6213	6525	6840	7154	7463	7782	8095	9664		
160	3763	4089	4416	4743	5069	5396	5722	6049	6376	6702	7029	7356	7682	8009	8335	8662	10295		
170	4155	4495	4834	5174	5513	5852	6192	6532	6871	7210	7550	7889	8229	8568	8908	9247			
180	4566	4919	5271	5623	5976	6328	6680	7032	7385	7737	8090	8442	8794	9146	9499	9851			
190	4996	5361	5726	6091	6156	6822	7187	7552	7917	8232	8648	9013	9378	9743	10108	10473			
200	5444	5822	6200	6578	6956	7334	7712	8090	8468	8846	9224	9602	9980	10358					
210	5910	6301	6692	7083	7474	7865	8256	8646	9037	9423	9819	10210	10601						
220	6395	6799	7203	7606	8010	8414	8818	9222	9625	10029	10433								
230	6399	7315	7732	8149	8565	8982	9398	9815	10232										
240	7421	7350	8280	8709	9139	9568	9998	10427											
250	7962	8404	8846	9288	9731	10173	10615												
260	8520	3976	9431	9886	10341														
270	9098	9566	10034	10502															
280	9694	10175																	
290	10309																		
300																			

TABLE 7

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 10 cm.

Ice Thickness in cm. (I_i)	Heat Loss in kg. cal. (q_T)																		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	0	161	323	484	645	806	967	1129	1290	1452	1613	1774	1936	2097	2258	2419	3226	4032	4839
5	60	228	396	564	731	899	1067	1234	1402	1570	1738	1905	2073	2241	2408	2576	3415	4253	5092
10	125	300	474	648	822	996	1170	1344	1518	1693	1867	2041	2215	2389	2563	2738	3608	4478	5350
15	195	376	556	737	917	1098	1278	1459	1640	1820	2001	2181	2362	2542	2723	2904	3806	4709	5612
20	269	456	643	830	1017	1204	1391	1578	1765	1952	2139	2326	2513	2700	2887	3074	4009	4944	5879
25	348	542	735	928	1122	1315	1509	1702	1896	2089	2282	2476	2669	2863	3056	3250	4217	5184	6151
30	432	632	831	1031	1231	1431	1631	1831	2030	2230	2430	2630	2830	3030	3230	3430	4429	5428	6427
35	520	725	932	1139	1345	1551	1757	1964	2170	2376	2583	2789	2995	3201	3408	3614	4645	5677	6708
40	612	825	1038	1251	1463	1676	1889	2101	2314	2527	2740	2952	3165	3378	3590	3803	4867	5930	6994
45	710	929	1148	1367	1587	1806	2025	2244	2463	2682	2901	3120	3340	3559	3778	3997	5093	6188	7284
50	812	1038	1263	1489	1714	1940	2165	2391	2616	2842	3068	3293	3519	3744	3970	4195	5323	6451	7579
55	919	1151	1383	1615	1847	2078	2310	2542	2774	3006	3238	3470	3702	3934	4166	4398	5553	6718	7878
60	1030	1268	1507	1745	1984	2222	2460	2699	2937	3176	3414	3652	3891	4129	4368	4606	5793	6990	8182
65	1146	1391	1636	1880	2125	2370	2615	2860	3104	3349	3594	3839	4084	4329	4574	4818	6043	7267	8491
70	1266	1518	1769	2020	2272	2523	2774	3025	3276	3528	3779	4030	4282	4533	4784	5035	6292	7548	8804
75	1392	1649	1907	2165	2422	2680	2938	3195	3453	3711	3968	4226	4484	4742	4999	5257	6545	7834	9122
80	1521	1785	2050	2314	2578	2842	3106	3370	3634	3898	4162	4427	4691	4955	5219	5483	6804	8124	9445
85	1656	1926	2197	2467	2738	3008	3279	3550	3820	4091	4361	4632	4902	5173	5443	5714	7067	8419	9772
90	1795	2072	2349	2626	2903	3180	3457	3734	4011	4288	4564	4842	5118	5396	5672	5949	7334	8719	10104
95	1938	2222	2505	2789	3072	3355	3639	3922	4206	4489	4772	5056	5339	5623	5906	6189	7606	9023	
100	2087	2376	2666	2956	3246	3536	3826	4115	4405	4695	4985	5275	5565	5854	6144	6434	7883	9332	
110	2397	2700	3003	3305	3608	3910	4213	4516	4819	5121	5424	5727	6029	6332	6635	6937	8151	9964	
120	2726	3042	3357	3673	3988	4304	4619	4935	5250	5566	5881	6197	6512	6828	7144	7459	9037	10614	
130	3074	3402	3730	4059	4387	4716	5044	5372	5701	6029	6358	6686	7014	7343	7671	8000	9641		
140	3440	3781	4122	4463	4805	5146	5487	5828	6170	6511	6852	7193	7535	7876	8217	8558	10264		
150	3824	4178	4532	4886	5181	5595	5949	6303	6657	7011	7365	7719	8073	8427	8782	9136			
160	4227	4594	4961	5328	5695	6062	6429	6796	7163	7530	7897	8264	8631	8998	9365	9732			
170	4649	5029	5409	5788	6168	6548	6929	7307	7687	8067	8447	8827	9206	9586	9966	10346			
180	5089	5482	5874	6267	6660	7052	7445	7837	8230	8623	9015	9408	9801	10193	10586				
190	5547	5953	6358	6764	7170	7575	7980	8386	8791	9197	9602	10008	10414						
200	6022	6441	6859	7278	7696	8114	8533	8951	9369	9788	10206								
210	6520	6951	7382	7814	8245	8676	9107	9538	9970	10401									
220	7034	7478	7922	8366	8810	9254	9698	10142	10586										
230	7567	8024	8480	8937	9394	9851	10308												
240	8118	8588	9057	9527	9997	10356													
250	8687	9170	9653	10135	10621														
260	9275	9771	10266																
270	9882	10390																	
280	10507																		

TABLE 8

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 15 cm.

Heat Loss in kg. cal. (q_T)

Ice Thickness in cm. (1_i)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	0	212	424	726	968	1210	1452	1694	1936	2177	2419	2661	2903	3145	3387	3629	4839	6049	7259
5	89	338	586	834	1083	1331	1580	1828	2076	2325	2573	2821	3070	3318	3566	3815	5057	6298	7540
10	183	439	693	943	1202	1453	1712	1967	2222	2476	2731	2986	3241	3495	3750	4005	5279	6553	7827
15	282	543	805	1085	1346	1599	1849	2111	2372	2633	2894	3155	3417	3673	3939	4200	5506	6812	[illegible]
20	395	653	921	1188	1456	1724	1991	2259	2527	2794	3062	3330	3597	3865	4132	[illegible]	5738	7076	[illegible]
25	493	767	1042	1348	1622	1864	2133	2412	2686	2960	3231	3508	3782	4056	4330	4604	5975	7345	[illegible]
30	606	886	1167	1447	1728	2008	2239	2569	2850	3130	3411	3691	3972	4252	4533	4813	6216	7621	9022
35	723	1010	1297	1629	1916	2159	2445	2732	3018	3305	3592	3880	4166	4453	4740	5027	6462	7896	9331
40	845	1138	1432	1725	2018	2312	2605	2898	3192	3485	3778	4072	4365	4659	4952	5245	6712	8179	9645
45	971	1271	1571	1928	2228	2470	2770	3070	3370	3669	3969	4269	4569	4869	5168	5468	6967	8466	[illegible]
50	1102	1409	1715	2021	2327	2634	2940	3246	3552	3858	4164	4471	4777	5083	5389	5695	7226	8755	[illegible]
55	1238	1551	1863	2247	2559	2801	3114	3426	3739	4052	4364	4677	4990	5302	5615	5927	7491	9054	
60	1378	1697	2016	2336	2656	2974	3293	3612	3931	4250	4569	4888	5207	5526	5845	6164	7760	9355	
65	1523	1849	2174	2583	2909	3151	3476	3802	4127	4453	4778	5104	5429	5755	6080	6406	8033	9660	
70	1673	2005	2337	2669	3000	3333	3664	3996	4328	4660	4992	5324	5656	5988	6320	6652	8311	9971	
75	1827	2165	2504	2938	3277	3519	3857	4195	4534	4872	5210	5549	5887	6225	6564	6902	8591	10237	
80	1986	2330	2675	3020	3365	3710	4054	4399	4744	5089	5434	5779	6123	6468	6812	7157	8881		
85	2149	2500	2852	3312	3663	3905	4256	4608	4959	5310	5661	6013	6364	6715	7066	7417	9173		
90	2317	2675	3033	3390	3749	4106	4463	4821	5178	5536	5894	6251	6609	6966	7324	7682	9470		
95	2490	2854	3218	3704	4068	4310	4674	5038	5402	5766	6130	6494	6858	7223	7587	7951	9771		
100	2667	3039	3403	3779	4149	4520	4890	5260	5631	6002	6372	6742	7113	7484	7854	8224	10077		
110	3036	3419	3803	4196	4569	4953	5336	5719	6102	6486	6869	7252	7636	8019	8402	8786			
120	3423	3819	4215	4611	5008	5404	5800	6196	6592	[illegible]	[illegible]	7781	8177	8573	8969	9366			
130	3728	[illegible]	4647	[illegible]	5465	5874	6283	6692	7101	7510	7919	8328	8737	9146	9555	9964			
140	4253	4674	[illegible]	[illegible]	[illegible]	6362	6784	7206	7628	8050	8472	8893	9315	9737	10159	10581			
150	4695	[illegible]	5565	5999	6434	6869	7304	7738	8173	8608	9043	9477	9912	10347					
160	[illegible]	[illegible]	6052	[illegible]	[illegible]	7394	7842	8289	8737	9185	9632	10080	10527						
170	5626	[illegible]	6557	7017	[illegible]	7938	8399	8859	9320	9780	10240								
180	6134	[illegible]	[illegible]	7554	8027	8501	8974	9447	9920	[illegible]									
190	6651	7137	7623	8109	8595	9082	9565	10054	10540										
200	7136	7685	[illegible]	8633	[illegible]	9631	10130												
210	7739	8251	8763	9275	9787	10299													
220	[illegible]	8836	9381	[illegible]	[illegible]														
230	8902	9440	9977	10515															
240	9511	10062	10612																
250	10139																		

TABLE 9

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 20 cm.

Ice Thickness in cm. (l_i)	Heat Loss kg. cal. ([illegible]) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
0	[illegible]	323	645	968	1290	1613	1936	2253	2581	2903	3226	3548	3871	4191	4516	4839	6452	8064	[illegible]
5	118	447	776	1105	1434	1763	2092	2422	2750	3079	3408	3738	4066	4395	4724	5054	6690	8341	[illegible]
10	242	577	912	1245	1583	1919	2254	2590	2925	3260	3596	3931	4267	4602	4938	5273	6950	8627	10304
20	502	850	1198	1546	1895	2243	2591	2940	3288	3636	3984	4333	4681	5029	5378	5726	7467	9209	
30	780	1141	1502	1864	2225	2586	2947	3308	3669	4030	4392	4753	5114	5475	5836	6197	8003	9809	
40	1077	1451	1825	2199	2573	2947	3321	3695	4069	4443	4817	5191	5565	5939	6313	6687	8557	10427	
50	1393	1780	2156	2552	2940	3327	3714	4101	4457	4874	5261	5648	6035	6422	6808	7195	9130		
60	1727	2126	2526	2926	3325	3725	4125	4525	4924	5324	5724	6123	6523	6923	7322	7722	9731		
70	2079	2492	2904	3317	3730	4142	4555	4967	5380	5792	6205	6617	7030	7412	7855	8268	10330		
80	2540	2966	3391	3717	4242	4667	5093	5515	5944	6369	6794	7220	7645	8101	8496	8922			
90	2840	3278	3716	4155	4593	5031	5470	5903	6345	6784	7222	7661	8099	8537	8976	9414			
100	3243	3699	4150	4601	5052	5504	5955	6406	6857	7308	7759	8210	8661	9112	9563	10015			
110	3675	4139	4603	5066	5530	5994	6452	6922	7386	7850	8314	8778	9242	9705	10170				
120	4120	4596	5073	5550	6027	6504	6981	7458	7934	8411	8888	9365	9842	10318					
130	4563	5073	5563	6052	6542	7032	7522	8011	8501	8990	9480	9979	10460						
140	5066	5568	6071	6573	7066	7578	8081	8583	9086	9588	10091	10593							
150	5566	6082	6597	7112	7628	8143	8658	9174	9689	10205									
160	6035	6614	7142	7570	8197	8726	9255	9783	10311										
170	6522	7154	7725	8246	8787	9308	9870	10411											
180	7179	7733	8287	8841	9395	9949	10593												
190	7754	8321	8887	9454	10020	10588													
200	8347	8927	9506	10036															
210	8959	9550	10144																
220	9539	10194																	
230	10236																		

TABLE 10

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 30 cm.

Ice Thickness in cm. (I_i)	Heat Loss kg. cal. (Q_T)																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20
0	0	184	968	1452	1936	2419	2903	3387	3871	4355	4839	5323	5806	6290	6774	7258	9677
5	176	667	1157	1644	2138	2628	3113	3609	4099	4589	5080	5570	6060	6550	7041	7531	9982
10	358	854	1351	1848	2344	2841	3338	3835	4341	4828	5325	5822	6313	6815	7312	7808	10292
20	734	1243	1753	2262	2772	3282	3771	4301	4810	5320	5830	6339	6849	7358	7868	8377	
30	1128	1651	2173	2696	3218	3741	[illegible]	4736	5303	5830	6353	6875	7398	7920	8442	8965	
40	1542	2077	2612	3147	3683	4218	4653	5239	5824	6359	6894	7430	7965	8500	9036	9571	
50	1973	2522	3070	3618	4166	4714	5262	5810	6353	6906	7455	8003	8551	9099	9647	10195	
60	2424	2984	3545	4106	4662	5228	5739	6350	6912	7472	8033	8594	9155	9716	10277		
70	2892	3466	4040	4614	5188	5762	6335	6909	7483	8057	8631	9204	9778	10352			
80	3379	3966	4553	5140	5726	6313	6900	7436	8073	8660	9246	9833	10420				
90	3885	4485	5084	5684	6283	6883	7432	8082	8682	9281	9881	10480					
100	4409	5022	5634	6247	6859	7422	8084	8696	9309	9921	10534						
110	4952	5577	6203	6828	7453	8078	[illegible]	9329	9954	10579							
120	5513	6151	6789	7429	8066	8704	9342	9950	10618								
130	6093	6744	7395	8046	8697	9348	9999	10650									
140	6691	7355	8019	8683	9347	10012	10674										
150	7308	7985	8661	9338	10015												
160	7943	8633	9322	10012													
170	8597	9300	10002														
180	9270	9985															
190	9960	10688															
200	10670																

TABLE 11

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 40 cm.

Ice Thickness in cm. (I_T)	Heat Loss kg. cal. (Q_T) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	0	645	1290	1936	2581	3226	2871	4516	5161	5806	6452	7097	7742	8387	9032	9677
5	235	886	1538	2189	2841	3492	4144	4796	5447	6099	6750	7402	8054	8705	9357	10008
10	474	1132	1790	2448	3106	3764	4422	5080	5738	6396	7054	7712	8370	9028	9686	
20	966	1637	2308	2979	3649	4320	4991	5662	6333	7004	7675	8346	9016	9687	10358	
30	1477	2161	2844	3528	4212	4895	5579	6263	6947	7630	8314	8998	9681	10365		
40	2006	2703	3399	4096	4792	5489	6186	6882	7579	8275	8972	9669	10365			
50	2554	3264	3973	4682	5392	6101	6811	7520	8229	8939	9648	10358				
60	3120	3843	4565	5287	6009	6732	7454	8176	8899	9621	10343					
70	3705	4440	5175	5910	6646	7381	8116	8851	9586	10321						
80	4308	5056	5804	6552	7300	8048	8796	9544	10292							
90	4930	5691	6452	7213	7974	8734	9495	10256								
100	5571	6344	7118	7892	8665	9439	10213									
110	6230	7016	7803	8589	9376	10162										
120	6907	7706	8506	9305	10104											
130	7603	8415	9227	10040												
140	8317	9142	9967													
150	9050	9888	10726													
160	9802	10652														
170	10571															

TABLE 12

DEGREE-DAYS OF FROST ASSOCIATED WITH GIVEN ICE THICKNESSES AND HEAT LOSSES FOR SNOW COVER = 50 cm.

Ice Thickness in cm. (I_I)	Heat Loss kg. cal. (Q_T)													
	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	0	806	1612	2419	3226	4032	4839	5645	6452	7258	8064	8871	9677	10484
5	293	1105	1918	2731	3344	4357	5170	5983	6796	7608	8421	9234	10047	
10	590	1409	2228	3048	3867	4686	5506	6325	7144	7964	8783	9602		
20	1198	2030	2837	3695	4527	5359	6191	7023	7856	8688	9520	10352		
30	1825	2670	3515	4360	5205	6050	6895	7740	8585	9430	10275			
40	2471	3328	4186	5044	5902	6760	7618	8476	9334	10191				
50	3135	4005	4876	5747	6618	7488	8359	9230	10100					
60	3817	4701	5584	6468	7351	8235	9118	10002						
70	4518	5414	6311	7207	8104	9000	9896							
80	5238	6147	7056	7965	8875	9784	10693							
90	5975	6898	7820	8742	9664	10586								
100	6732	7667	8602	9537	10472									
110	7507	8455	9403	10350										
120	8300	9261	10222											
130	9112	10086												
140	9943													
150	10792													

TABLE 13

DEGREE-DAYS OF FROST FOR DIFFERING HEAT LOSS AND ICE THICKNESS $\left(\frac{QT\ l_i}{2k_i}\right)$

Ice Thickness (cm)	Heat Loss (Kg. Cal.)														
l_i cm.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
5	6	13	19	26	32	39	45	51	58	64	71	77	84	90	96
10	13	26	39	51	64	77	90	103	116	129	141	154	167	180	193
20	26	51	77	103	129	154	180	206	231	257	283	308	334	360	386
30	39	77	116	154	193	231	270	308	347	386	424	462	501	540	578
40	51	103	154	207	257	308	360	411	463	514	566	617	668	720	771
50	64	129	193	257	321	386	450	514	578	643	707	771	835	900	964
60	77	154	231	308	386	463	540	617	694	771	848	925	1003	1080	1157
70	90	180	270	360	450	540	630	720	810	900	990	1080	1170	1260	1350
80	103	206	308	411	514	617	720	823	925	1029	1131	1234	1337	1440	1542
90	116	231	347	463	578	694	810	925	1041	1157	1272	1388	1504	1620	1735
100	129	257	386	514	643	771	900	1029	1157	1285	1414	1542	1671	1799	1928
110	141	283	424	566	707	848	990	1131	1272	1414	1555	1697	1838	1979	2121
120	154	308	463	617	771	925	1080	1234	1388	1542	1697	1851	2005	2159	2314
130	167	334	501	668	835	1003	1170	1337	1504	1671	1838	2005	2172	2339	2506
140	180	360	540	720	900	1080	1260	1440	1620	1799	1979	2159	2339	2519	2699
150	193	386	578	771	964	1157	1350	1542	1735	1928	2121	2314	2506	2699	2892
160	206	411	617	823	1029	1234	1440	1645	1851	2057	2262	2468	2674	2879	3085
170	219	437	656	874	1093	1311	1530	1748	1967	2185	2404	2622	2841	3059	3278
180	231	463	694	925	1157	1388	1620	1851	2082	2314	2545	2776	3008	3239	3470
190	244	488	733	977	1221	1465	1710	1954	2198	2442	2686	2931	3175	3419	3663
200	257	514	771	1028	1285	1542	1799	2057	2314	2571	2828	3085	3342	3599	3856
210	270	540	810	1080	1350	1620	1889	2159	2429	2699	2969	3239	3509	3779	4049
220	283	566	848	1131	1414	1697	1979	2262	2545	2828	3111	3393	3676	3959	4242
230	296	591	887	1183	1478	1774	2069	2365	2661	2956	3252	3548	3843	4139	4434
240	308	617	925	1234	1542	1851	2159	2468	2776	3085	3393	3702	4010	4319	4627
250	321	643	964	1285	1607	1928	2249	2570	2892	3213	3535	3856	4177	4499	4820
260	334	668	1003	1447	1671	2005	2339	2674	3008	3342	3676	4010	4344	4679	5013
270	347	694	1041	1388	1735	2082	2429	2776	3123	3470	3817	4165	4512	4859	5206
280	360	720	1080	1440	1799	2159	2519	2879	3239	3599	3959	4319	4679	5039	5398
290	373	746	1118	1491	1864	2237	2609	2982	3355	3728	4100	4473	4856	5219	5591
300	386	771	1157	1542	1928	2314	2699	3085	3470	3856	4242	4627	5013	5398	5784

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