ADDENDUM:

Subsequent to the publication of this report, BERG2 has been modified based upon the recommendations of Zarling (1). These alterations allow better representation of the environmental parameters affecting a problem and increase the accuracy of the model.

These changes require two additional input fields to the program's location screen. An example of the newly designed screen is shown below. The additional fields provide specification of the design freezing and thawing indices. These indices are used by the model to determine the average surface temperature differential, v_s, defined by eq. 8 of this report. These design indices are also used in eq. 1 to estimate the maximum depth of freeze or thaw.

The mean freezing and thawing indices are used to calculate the length of the freeze and thaw season at the soil surface and to determine the mean annual soil surface temperature (MASST). The season lengths are used in the derivation of v_s, eq. 8. The initial ground temperature is assumed to equal the MASST. This value is used to calculate the variable v_o as defined by eq. 12 in the report.

```
      FAIRBANKS          ANCHORAGE          JUNEAU             McKINLEY PARK
      NORTHWAY           DILLINGHAM         POINT BARROW       BETHEL
      KOTZEBUE           GULKANA            CENTRAL            USER INPUT

   LOCATION NAME .........................FAIRBANKS
   THAW N FACTOR .........................1.7
   FREEZE N FACTOR .......................1
   DESIGN AIR THAWING INDEX °DAY .........4000
   DESIGN AIR FREEZING INDEX °DAY ........6900
   MEAN AIR THAWING INDEX °DAYS ..........3500
   MEAN AIR FREEZING INDEX °DAY ..........5600
   MEAN ANNUAL AIR TEMP. °F ..............26.2
   AMPL. OF AIR TEMP. SINE WAVE ..........38.7

   DESIGN SURFACE THAWING INDEX °DAYS .....6800
   DESIGN SURFACE FREEZING INDEX °DAYS ....6900
   MEAN SURFACE THAWING INDEX °DAYS .......5950      THAW SEASON   FREEZE SEASON
   MEAN SURFACE FREEZING INDEX °DAYS ......5600         LENGTH         LENGTH
   MEAN ANNUAL SURFACE TEMP. °F ...........33      AIR  165.2          199.8
   AMPL. OF SURFACE TEMP. SINE WAVE .......49.7   SURF  184.7          180.3

  INPUT FIRST LETTER OF DESIRED LOCATION
  OR USE CURSOR CONTROL KEYS TO MOVE CURSOR AND CHANGE DATA

  F1-COLOR  F2-SAVE  F3-LOAD  F4-DISK    S-SOILS  R-RUN  L-NEW SCREEN  Q-QUIT
```

BERG2 Location Screen

BERG2
MICRO-COMPUTER ESTIMATION OF FREEZE AND THAW DEPTHS AND THAW CONSOLIDATION

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ABSTRACT

The BERG2 microcomputer program uses a methodology similar to the Modified Berggren method (Aldrich and Paynter, 1953) to estimate the freeze and thaw depths in layered soil systems. The program also provides an estimate of the thaw consolidation in ice rich soils. BERG2 differs from the original Modified Berggren method since it uses the actual frozen and unfrozen material thermal properties instead of average values. This approach improves the accuracy of the predictions.

BERG2 provides an improved user interface over the original BERG program, (Braley, 1984). It also requires less input as a result of the ability to compute many of climatic parameters from the more common data. As a result the user required input is significantly reduced.

This manual provides the user information concerning the use of BERG2, its strengths and its limitations. It also provides a discussion of the equations used in development of the program for those who wish a better understanding of the analysis process.

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INTRODUCTION

The Modified Berggren method as presented by Aldrich and Paynter (1953) and later expanded by the Department of Army and Air Force (1966) and by Sanger (1963) to include layered soil systems is widely used by engineers and designers in estimating the depth of maximum freeze or thaw. The usefulness of this method for the design of highways, airport runways, utilidors, and building foundations prompted Aitken and Berg (1968) to simplify the calculation process by developing a digital computer model of this method. Due to the proliferation of desk top microcomputers and the availability of these devices to many engineers and designers, a computer model of the Berggren method, BERG Version 1.0, was written for use with IBM PC compatible machines, Braley (1984).

BERG2 was developed from the original BERG program to include several new features and to improve on the calculation method used for determining the depth of freeze or thaw. A major addition is the capability of estimating thaw consolidation for saturated soils. Significant changes were made to simplify and enhance the input and manipulation of data in the model and the program is now compiled to speed execution on IBMPC/XT/AT and compatible microcomputers with and without math co-processors.

In presenting their modified Berggren method, Aldrich and Paynter used average values of the frozen and thawed specific heats and the frozen and thawed thermal diffusivities in order to simplify the calculation process. In BERG2 this simplification has been removed and the actual frozen and thawed properties are used during the calculation process.

This report will discuss the methods used in this model to estimate the depth of freeze or thaw in multilayer soil systems and instruct the user in the input of data and the application of the model. For a more complete discussion of the derivation and theoretical basis of the modified Berggren method, the reader is referred to the work of Aldrich and Paynter (1953), the Department of Army and Air Force's 1966 work describing a standard hand calculation method, and Lunardini (1981). The calculation method used in BERG2 is presented by Zarling (1989).

BERG2 is supplied in an executable form for operation on IBM PC's, XT's and AT's or compatible microcomputers with or without math co-processors. To initiate operation of the program, type in BERG2 with the program residing in the current disk drive and, if applicable, current directory. Upon execution of the program a title screen will appear. Pressing any key will clear this screen and bring up the location screen, the first of the data input and editing screens.

- **THE LOCATION SCREEN**

This screen (Fig. 1) allows input and modification of the climatic data affecting the problem under consideration. The bottom line indicates special keys which may be used in conjunction with this screen. Keys F1 - F4 are used to toggle the screen between B/W and color -[F1]-, save the current data from all input screens to disk -[F2]-, retrieve previously saved data sets from disk -[F3]-, and alter the disk drive used for data storage and retrieval -[F4]-. Keys S, R, L and Q are used to switch to the soil data input screens 'S', run the calculation

```
              FAIRBANKS           PRUDHOE+BARROW
              ANCHORAGE           BETHEL
              JUNEAU+KODIAK       KOTZEBUE
              NOME                GLENNALLEN
              TOK                 FT. YUKON
              DELINGHAM           USER INPUT

LOCATION NAME.................. FAIRBANKS
THAW N FACTOR.................. 1.9
FREEZE N FACTOR................ 1
AIR THAWING INDEX °DAYS........ 3500
AIR FREEZING INDEX °DAYS....... 6400
MEAN ANNUAL AIR TEMP. °F....... 24.1
AMPL. OF AIR TEMP. SINE WAVE... 41.8

SURFACE THAWING INDEX °DAYS.... 6650        THAW SEASON   FREEZE SEASON
SURFACE FREEZING INDEX °DAYS... 6400           LENGTH         LENGTH
MEAN ANNUAL SURFACE TEMP. °F... 32.7      AIR   160.3          204.7
AMPL. OF SURF TEMP. SINE WAVE.. 56.2  SURFACE   183.9          181.1

INPUT FIRST LETTER OF DESIRED LOCATION (Y FOR FT. YUKON)
OR USE CURSOR CONTROL KEYS TO MOVE CURSOR AND CHANGE DATA
F1-COLOR  F2-SAVE  F3-LOAD  F4-DISK   S-SOILS  R-RUN  L-NEW SCREEN  Q-QUIT
```

Figure 1. BERG2 location screen.

for the currently specified data 'R', refresh the current location screen 'L', and exit the program 'Q'.

At the top of this screen are the names of eight locations for which default surface N-factors and air thawing and freezing indices are stored within the program. Each of these locations are selected by typing in the first letter of the name, except for Fort Yukon where "Y" is used. The program allows modification to the climatic data for these default locations. However, these values will be reset to the defaults if the user returns to the location screen from one of the soil screens or if a freeze and thaw depth calculation is performed. To prevent this from occurring, the user must select the user input location "U". Following this selection the location name will appear on the screen in reverse video, and alterations may be made to this name and the climatic parameters without the program subsequently resetting them. Any character data entered on the location name line are considered to be part of the location name and not letters for selecting a new location or program control.

To modify the data on the screen, move the cursor to the data to be altered using the cursor control keys and the new value input. The backspace and delete keys may aid in this editing. Following the alteration of data on the screen, moving the cursor to another line will store the new value in the program memory.

The user may modify the location name, when the location is specified as user input, the user must supply the surface thaw and freeze N-factors, air thawing and freezing indices, mean annual air temperature (MAAT), or amplitude of the air temperature sine wave. The program calculates the other parameters shown on this screen (surface thawing and freezing indices, mean annual soil surface temperature (MASST), amplitude of the surface temperature sine wave, and thaw and freeze season lengths for air and the surface). This information is presented as an aid to the user.

These calculated values are determined from the surface N factors and either the air thawing and freezing indices or MAAT and amplitude of the air temperature sine wave. A change to either of the air indexes prompts the program to recalculate the MAAT and the amplitude of the air temperature sine wave as well as the surface parameters and season lengths. Alteration of either the MAAT or the amplitude of the air temperature sine wave results in recalculation of the air thawing and freezing indices, the soil surface parameters, and the season lengths.

```
   LAYER NUMBER  2  OF  6

1:GRAVEL 2:SAND 3:SILT 4:ASPHALT 5:CONCRETE 6:INSULATION 7:USER MATERIAL

MATERIAL NUMBER....................... 7
THICKNESS OF LAYER (FT)............... 1.6
...........THAW CYCLE.................
FROZEN % MOISTURE..................... 2.1
FROZEN DENSITY OF LAYER (LB/FT^3)..... 155
FROZEN HEAT CAPACITY (BTU/FT^3-F°).... 27.98
FROZEN CONDUCTIVITY (BTU/FT-HR-F°).... 1.68
LATENT HEAT (BTU/FT^3)................ 469
THAWED % MOISTURE..................... 2.1
THAWED DENSITY OF LAYER (LB/FT^3)..... 155
THAWED HEAT CAPACITY (BTU/FT^3-F°).... 29.61
THAWED CONDUCTIVITY (BTU/FT-HR-F°).... 1.85
............FREEZE CYCLE..............
LATENT HEAT OF FUSION (BTU/FT^3)...... 469
FROZEN DENSITY (LB/FT^3).............. 155
FROZEN HEAT CAPACITY (BTU/FT^3-F°).... 27.98
FROZEN CONDUCTIVITY (BTU/FT-HR-F°).... 1.68

USE F1 - F8 TO SELECT A LAYER #, USE F10 TO SET TOTAL # OF LAYERS = LAYER #
OR MOVE CURSOR TO MODIFY DATA              L-LOCATION  R-RUN  Q-QUIT
```

Figure 2. BERG2 soils screen.

- **THE SOIL SCREENS**

Typing an "S" from the location output screen calls up the soil screens, as shown in Fig. 2. These screens allow the user to describe the physical and thermal properties of the material layers for the problem being analyzed. The methods used when editing values on these screens are the same as for the location screen.

The user may describe up to eight layers. Each layer may be called by pushing the corresponding "F" key 1-8. The current and total number of layers defined for the problem are indicated in the upper left corner of the screen. If the user wishes to reduce the number of layers defined for a problem, the soils screen corresponding to the bottom layer of the new problem is selected and the F10 key pressed.

The soil screen contains a list of six default material types and a seventh user defined material. The material type is selected by entering the material number on the line provided. For the first three of these materials (gravel, sand, and silt) the program will compute the thermal properties based upon input values of moisture content and dry density. These calculated thermal properties may be modified by the user. However, if the moisture content or dry density is subsequently altered, the thermal properties will be recalculated by the program.

To accommodate the calculation of thaw consolidation, there are three sets of properties input for each layer. These are the pre-thaw cycle frozen soil properties, the thawed soil properties, and the post-thaw cycle frozen soil properties. The program first calculates the thaw depth using the pre-thaw cycle frozen soil properties and the thawed soil properties. The freeze depth is computed using the thawed soil properties and the post-thawed cycle frozen soil properties. When a layer of material is non-consolidating, the frozen and thawed moisture contents and dry densities are the same for both phases. In this case when changes are made to any of the moisture contents or dry densities specified on the soil screen, the other moisture contents and dry densities for the layer are changed to the same value by the program. For a layer which may undergo thaw consolidation, the moisture content and dry density of the material may change during the thaw cycle resulting in differing moisture content, dry density and thermal properties for the subsequent freeze cycle. Input fields are provided on the soils screens for these parameters.

Thaw consolidation for a layer is selected by the user inputting the moisture content or dry density so that the 98% saturation level for the layer is exceeded. The program will then prompt the user to determine if the layer is to be consolidated. If consolidation is selected, the program will adjust the density to achive a 98% saturation level based upon the specified moisture content. The user may then alter the pre- and post-thaw cycle moisture contents to reflect the desired change in moisture content during thaw. With each modification of the moisture content, the program will alter the densities to maintain a 98% saturation level before and after thaw. These densities may not be changed as it is assumed that the soil is consolidating from a frozen soil at 98% saturation to a thawed soil at the same level of saturation.

If consolidation is not selected by the user when prompted then the default moisture contents, dry densities, and thermal properties for the material type chosen will be restored to the layer. Thaw consolidation may only be selected for material numbers 1-3 (gravel, sand, and silt).

Having completed the entry of the layered material properties, the user may wish to return to the location screen by typing "L" and saving the data set to disk; or "R" may be typed and the thaw depth, freeze depth, and the amount of consolidation calculated.

• EXECUTION AND OUTPUT

Having initiated the analysis sequence by typing "R" from the location screen or a soils screen, the current screen will clear and layer numbers will be displayed as the program calculates the thawing index required for the thaw front to penetrate each layer. When the thawing index required to penetrate a layer exceeds the input surface index for the selected location, the front is known to be contained somewhere in this layer. At this point, an iteration process is initiated to find the depth within the layer at which the input and calculated indices are similar. During the iteration process, the input surface index and calculated index are displayed. Once these two numbers are approximately equal, plus or minus 10 ^{o}F-days, the screen is again cleared and a similar calculation sequence is undertaken to determine the depth of maximum freeze. The output screen is then displayed, as shown in Fig. 3.

LOCATION	THAW N	FREZ N	MAAT	THAW °F DAY	FREZ °F DAY	THAW DAYS	FREZ DAYS
FAIRBANK	1.90	1.00	24	3500	6400	160	205

THAW CYCLE		1	2	3	4	5	6
	FROZEN % MOIS.	0.0	2.1	2.8	6.5	4.6	5.2
	FROZEN DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	LATENT HEAT	0	469	609	1217	808	869
	FROZEN HEAT CAP	28.00	27.98	27.78	26.33	23.55	22.74
	FROZEN COND.	0.86	1.68	1.78	1.11	0.71	0.61
	THAWED % MOIS.	0.0	2.1	2.8	6.5	4.6	5.2
	THAWED DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	THAWED HEAT CAP	28.00	29.61	29.90	30.55	26.35	25.75
	THAWED COND.	0.86	1.85	1.92	0.88	0.55	0.54
	INITIAL THICK	0.40	1.60	3.00	12.00	2.00	1.00
	AMOUNT THAWED	0.40	1.60	3.00	10.41	0.00	0.00
	CONSOLIDATION	----	----	----	----	----	----
	FINAL THICK	0.40	1.60	3.00	12.00	2.00	1.00

FREEZE CYCLE		1	2	3	4	5	6
	LATENT HEAT	0	469	609	1217	808	869
	FROZEN DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	FROZEN HEAT CAP	28.00	27.98	27.78	26.33	23.55	22.74
	FROZEN COND.	0.86	1.68	1.78	1.11	0.71	0.61
	INITIAL THICK	0.40	1.60	3.00	12.00	2.00	1.00
	AMOUNT FROZEN	0.40	1.60	3.00	11.16	0.00	0.00

ESTIMATED THAW=15.41 FREEZE=16.16 PRINT LOCATION SOIL QUIT

Figure 3. BERG2 output screen.

The output screen displays the surface N-factors, MAAT, air thawing and freezing indices and season lengths, and the soil properties for each layer of the analysis. The amount of each layer which is frozen, thawed, and consolidated is also shown. The total depth of freeze and thaw and the amount of consolidation for the entire layered system is indicated at the bottom of the screen. While viewing this screen it may be sent to a printer by typing "P". The user may now choose to return to the location screen, soil screen, or exit the program.

- **EXAMPLE SOLUTION**

To demonstrate the use of BERG2 for the estimation of the depth of thaw, an example problem has been taken from the Department of Army and Air Force's manual (1966). In this example, the depth of thaw beneath an asphalt concrete pavement located in Thule, Greenland is estimated. The environmental data for the problem are:

Mean annual air temperature (MAAT) = 12 °F
Air thawing index (ATI) = 780 °F Days
Surface thawing n-factor (N_t) = 2.0
Thaw season length (t_t) = 105 Days

The relevant parameters for the pavement structure are shown in Table 1.

Table 1. Material properties used in the example problem.

Layer	Thickness feet	Material	Dry unit weight lb./ft^3	% Moisture
1	.4	Asphalt	138	--
2	1.6	Gravel	155	2.1
3	3	Gravel	151	2.8
4	1	Silt	130	6.5
5	2	Silt	122	4.6
6	1	Silt	116	5.2

Upon entering BERG2 and clearing the title screen, the location screen is displayed (Fig. 4). Modification of this screen for the example problem requires the following steps.

```
            FAIRBANKS          PRUDHOE+BARROW
            ANCHORAGE          BETHEL
            JUNEAU+KODIAK      KOTZEBUE
            NOME               GLENNALLEN
            TOK                FT. YUKON
            DELINGHAM          USER INPUT

LOCATION NAME .................. FAIRBANKS
THAW N FACTOR .................. 1.9
FREEZE N FACTOR ................ 1
AIR THAWING INDEX °DAYS ........ 3500
AIR FREEZING INDEX °DAYS ....... 6400
MEAN ANNUAL AIR TEMP. °F ....... 24.1
AMPL. OF AIR TEMP. SINE WAVE ... 41.8

SURFACE THAWING INDEX °DAYS .... 6650           THAW SEASON  FREEZE SEASON
SURFACE FREEZING INDEX °DAYS ... 6400              LENGTH        LENGTH
MEAN ANNUAL SURFACE TEMP. °F ... 32.7          AIR    160.3         204.7
AMPL. OF SURF TEMP. SINE WAVE .. 56.2      SURFACE    183.9         181.1

INPUT FIRST LETTER OF DESIRED LOCATION (Y FOR FT. YUKON)
OR USE CURSOR CONTROL KEYS TO MOVE CURSOR AND CHANGE DATA
```

Figure 4. BERG2 location screen prior to editing.

1. Select a location name. Because this is not one of the default locations given in the list, "U" is input allowing for the creation of a new user-input location.

2. Type the name of the location, "THULE", is typed in the location name field provided and press the enter key.

3. Input the thaw season N-factor of 2 and press the enter key.

4. Move the cursor to the input field for the air thawing index, ATI by using the down cursor or enter keys.

5. The ATI of 780 is typed here and the enter key pressed.

6. Now enter the air freezing index, AFI. The program calculates the mean annual air temperature, MAAT, and the thaw season length, t_t, based on the ATI and AFI. Since the desired MAAT is known, estimated values of AFI are entered until the computed MAAT agrees with the desired value. In this case, an AFI of 8080 was found to be appropriate. Note that an alternate iterative process could be carried out using the MAAT and the amplitude of the air temperature sine wave to deter-

```
            FAIRBANKS            PRUDHOE+BARROW
            ANCHORAGE            BETHEL
            JUNEAU+KODIAK        KOTZEBUE
            NOME                 GLENNALLEN
            TOK                  FT. YUKON
            DELINGHAM            USER INPUT

LOCATION NAME.................. THULE
THAW N FACTOR.................. 2
FREEZE N FACTOR................ 1
AIR THAWING INDEX °DAYS........ 780
AIR FREEZING INDEX °DAYS....... 8080
MEAN ANNUAL AIR TEMP. °F....... 12
AMPL. OF AIR TEMP. SINE WAVE... 31.6

SURFACE THAWING INDEX °DAYS.... 1561            THAW SEASON   FREEZE SEASON
SURFACE FREEZING INDEX °DAYS... 8080               LENGTH         LENGTH
MEAN ANNUAL SURFACE TEMP. °F... 14.1          AIR   102.7          262.3
AMPL. OF SURF TEMP. SINE WAVE.. 37.1      SURFACE   124.1          240.9

INPUT FIRST LETTER OF DESIRED LOCATION (Y FOR FT. YUKON)
OR USE CURSOR CONTROL KEYS TO MOVE CURSOR AND CHANGE DATA
```

Figure 5. BERG2 location screen after editing.

mine the ATI and t_t. In this latter case, the known value for the MAAT, 12 °F, would have been entered in the appropriate field and the amplitude of the air temperature sine wave adjusted until the desired value of ATI and t_t were computed.

Following the six steps above the location screen should look like Fig. 5.

Once the environmental data for this problem are entered, type "S" to select a soil modification screen. Fig. 6 shows the default layer definition screen for the first layer of the problem. Modification of this screen requires the following steps for this test case:

1. The material number is changed from 1 to 4, indicating that this layer consists of asphalt, and press the enter key.

2. Enter the thickness of the asphalt pavement, .4 ft, followed by the enter key.

Fig. 7 shows the soils screen for the first layer following these modifications. For this test case, the default thermal properties for asphalt will be used with no further modifications.

```
    LAYER NUMBER  1  OF  1

1:GRAVEL 2:SAND 3:SILT 4:ASPHALT 5:CONCRETE 6:INSULATION 7:USER MATERIAL

MATERIAL NUMBER ....................... 1
THICKNESS OF LAYER (FT) ............... 1
...........THAW CYCLE .................
FROZEN % MOISTURE ..................... 2.5
FROZEN DENSITY OF LAYER (LB/FT^3) ..... 130
FROZEN HEAT CAPACITY (BTU/FT^3-F°) .... 23.73
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ..... .84
LATENT HEAT (BTU/FT^3) ................ 468
THAWED % MOISTURE ..................... 2.5
THAWED DENSITY OF LAYER (LB/FT^3) ..... 130
THAWED HEAT CAPACITY (BTU/FT^3-F°) .... 25.35
THAWED CONDUCTIVITY (BTU/FT-HR-F°) .... 1.13
............FREEZE CYCLE ..............
LATENT HEAT OF FUSION (BTU/FT^3) ...... 468
FROZEN DENSITY (LB/FT^3) .............. 130
FROZEN HEAT CAPACITY (BTU/FT^3-F°) .... 23.73
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ..... .84

USE F1 - F8 TO SELECT A LAYER #, USE F10 TO SET TOTAL # OF LAYERS = LAYER #
OR MOVE CURSOR TO MODIFY DATA              L-LOCATION  R-RUN  Q-QUIT
```

Figure 6. Soils screen for layer 1 prior to editing.

```
    LAYER NUMBER  1  OF  1

1:GRAVEL 2:SAND 3:SILT 4:ASPHALT 5:CONCRETE 6:INSULATION 7:USER MATERIAL

MATERIAL NUMBER ....................... 4
THICKNESS OF LAYER (FT) ............... .4
...........THAW CYCLE .................
FROZEN % MOISTURE ..................... 0
FROZEN DENSITY OF LAYER (LB/FT^3) ..... 138
FROZEN HEAT CAPACITY (BTU/FT^3-F°) .... 28
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ..... .86
LATENT HEAT (BTU/FT^3) ................ 0
THAWED % MOISTURE ..................... 0
THAWED DENSITY OF LAYER (LB/FT^3) ..... 138
THAWED HEAT CAPACITY (BTU/FT^3-F°) .... 28
THAWED CONDUCTIVITY (BTU/FT-HR-F°) ..... .86
............FREEZE CYCLE ..............
LATENT HEAT OF FUSION (BTU/FT^3) ...... 0
FROZEN DENSITY (LB/FT^3) .............. 138
FROZEN HEAT CAPACITY (BTU/FT^3-F°) .... 28
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ..... .86

USE F1 - F8 TO SELECT A LAYER #, USE F10 TO SET TOTAL # OF LAYERS = LAYER #
OR MOVE CURSOR TO MODIFY DATA              L-LOCATION  R-RUN  Q-QUIT
```

Figure 7. Soils screen for layer 1 after modification.

Press the "F2" key to display the layer definition screen for the second layer. The unmodified input screen for this layer is identical to that for layer one, with the exception of the layer number indicated at the top of the screen. Modification of this screen for solving the example problem requires three steps:

1. Move the cursor to the input field provided for layer thickness using the cursor control keys or the enter key,. Change this field to 1.6 ft as dictated by the problem, and the press enter key.

2. The cursor is now located in the frozen % moisture input field. Change this number to 2.1 and press the enter key. Following the movement of the cursor to the next line, the other material properties shown on the screen are recalculated by the program based upon the input percentage moisture and the current density shown on the screen.

3. Finally, change the frozen density of the layer to 155.

Following Step 3, the screen should appear as in Fig. 8. The material's heat capacities, thermal conductivities, and latent heat of fusion are determined by the program. The calculated values for these parameters are used in this example.

Alteration of the material properties for layers 3 - 6 would be performed using the same process:

1. Select the layer by pressing the corresponding "F" key.

2. Select the material type, gravel for Layer 3, silt for Layers 4-6.

3. Enter the moisture contents and densities as described in Table 3.

Following the completion of the material property definition, "R" is typed to run the example problem. The output screen for this example is shown in Fig. 9.

```
   LAYER NUMBER  2  OF  2

1:GRAVEL 2:SAND 3:SILT 4:ASPHALT 5:CONCRETE 6:INSULATION 7:USER MATERIAL

MATERIAL NUMBER ........................1
THICKNESS OF LAYER (FT) ................1.6
...........THAW CYCLE .................
FROZEN % MOISTURE ......................2.1
FROZEN DENSITY OF LAYER (LB/FT^3) .....155
FROZEN HEAT CAPACITY (BTU/FT^3-F°) ....27.98
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ....1.68
LATENT HEAT (BTU/FT^3) ................469
THAWED % MOISTURE ......................2.1
THAWED DENSITY OF LAYER (LB/FT^3) .....155
THAWED HEAT CAPACITY (BTU/FT^3-F°) ....29.61
THAWED CONDUCTIVITY (BTU/FT-HR-F°) ....1.85
............FREEZE CYCLE ..............
LATENT HEAT OF FUSION (BTU/FT^3) ......469
FROZEN DENSITY (LB/FT^3) ..............155
FROZEN HEAT CAPACITY (BTU/FT^3-F°) ....27.98
FROZEN CONDUCTIVITY (BTU/FT-HR-F°) ....1.68

USE F1 - F8 TO SELECT A LAYER #, USE F10 TO SET TOTAL # OF LAYERS = LAYER #
OR MOVE CURSOR TO MODIFY DATA              L-LOCATION  R-RUN  Q-QUIT
```

Figure 8. Soils screen for layer 2 after modification.

LOCATION	THAW N	FREZ N	MAAT	THAW °F DAY	FREZ °F DAY	THAW DAYS	FREZ DAYS
THULE	2.0	1.00	12	780	8080	103	262

		1	2	3	4	5	6
THAW CYCLE	FROZEN % MOIS.	0.0	2.1	2.8	6.5	4.6	5.2
	FROZEN DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	LATENT HEAT	0	469	609	1217	808	869
	FROZEN HEAT CAP	28.00	27.98	27.78	26.33	23.55	22.74
	FROZEN COND.	0.86	1.68	1.78	1.11	0.71	0.61
	THAWED % MOIS.	0.0	2.1	2.8	6.5	4.6	5.2
	THAWED DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	THAWED HEAT CAP	28.00	29.61	29.90	30.55	26.35	25.75
	THAWED COND.	0.86	1.85	1.92	0.88	0.55	0.54
	INITIAL THICK	0.40	1.60	3.00	1.00	2.00	1.00
	AMOUNT THAWED	0.40	1.60	3.00	1.00	0.78	0.00
	CONSOLIDATION	----	----	----	----	----	----
	FINAL THICK	0.40	1.60	3.00	1.00	2.00	1.00
FREEZE CYCLE	LATENT HEAT	0	469	609	1217	808	869
	FROZEN DENS.	138.0	155.0	151.0	130.0	122.0	116.0
	FROZEN HEAT CAP	28.00	27.98	27.78	26.33	23.55	22.74
	FROZEN COND.	0.86	1.68	1.78	1.11	0.71	0.61
	INITIAL THICK	0.40	1.60	3.00	1.00	2.00	6.12
	AMOUNT FROZEN	0.40	1.60	3.00	1.00	2.00	6.00

THAW= 6.78 ESTIMATED FREEZE=14.00

Figure 9. BERG2 output screen for example problem.

FREEZE AND THAW DEPTH CALCULATION

BERG2 estimates the depth of freeze or thaw in a non-homogenous soil system by determining the portion of the air freezing or thawing index, AFI or ATI, required to move the freezing or thawing isotherm through each layer. The sum of the depths of these layers is the total depth of freeze or thaw. This method differs from the Modified Berggren method in that actual rather than of average thermal diffusivities and heat capacities are used in determining a layer's thermal resistance and the λ'coefficient. The equation used to determine the partial index required to penetrate the 'ith' layer is:

$$AFI_i \left(\text{or } ATI_i \right) = \frac{L_i d_i}{24 \lambda'^2_i N} \left(\sum_{n=1}^{i-1} R_n + \frac{R_i}{2} \right) \tag{1}$$

where:

L_i = Latent heat (Btu / ft^3)
d_i = layer thickness (ft)
λ' = lambda' coefficient
R_i = thermal resistance (hr • ^{o}F / Btu)
N = surface N-factor
AFI;ATI = air freezing and thawing indices (^{o}F-Day)

and:

$$R_i = \frac{d_i}{K_i} \tag{2}$$

where:

K_i = thermal conductivity (Btu / hr • ft • ^{o}F)

The frozen or thawed thermal conductivity is used during calculation of freeze and thaw depth, respectively. When the effects of thaw consolidation are taken into account, the expression for R_i becomes:

$$R_i = \frac{d_i \left(1 - \varepsilon_i \right)}{K_i} \tag{3}$$

where ε_i is the thaw strain of layer i.

BERG2 successively calculates and sums the partial index, AFI_i or ATI_i, for each layer defined by the user. When the summation of the partial indices exceeds the surface index defined for the problem the phase change front is located within the current Layer i. The program then adjusts the apparent thickness of the ith Layer, recalculates the partial index for that layer, and again sums the partial indices of all Layers 1 thru i. This process of adjusting the apparent layer thickness and summing the partial indices continues until the summation of the partial indices is within plus or minus 10 °F-Days of the surface index (Fig.10). The depth of the bottom of the current layer's apparent thickness is the depth of freeze or thaw.

The λ'coefficient used in BERG2 is similar to the λ coefficient in Aldrich and Paynter's (1953) Modified Berggren method. The calculation of λ'differs from that of λ in that actual frozen and thawed heat capacities and thermal diffusivities are used in place of the average values.

The λ' coefficient for a layer of a multilayer soil system is determined using:

$$\lambda_i' = \gamma_i \sqrt{2/STE_i} \tag{4}$$

The constant γ_i is defined below. STE, the Stephan number is defined as:

$$STE_i \equiv \overline{C}_i v_s / \overline{L}_i \tag{5}$$

where:

v_s is the average surface temperature differential.

and:

$$\overline{C}_i = \frac{\sum_{i=1}^{n} C_i d_i}{\sum_{i=1}^{n} d_i} \tag{6}$$

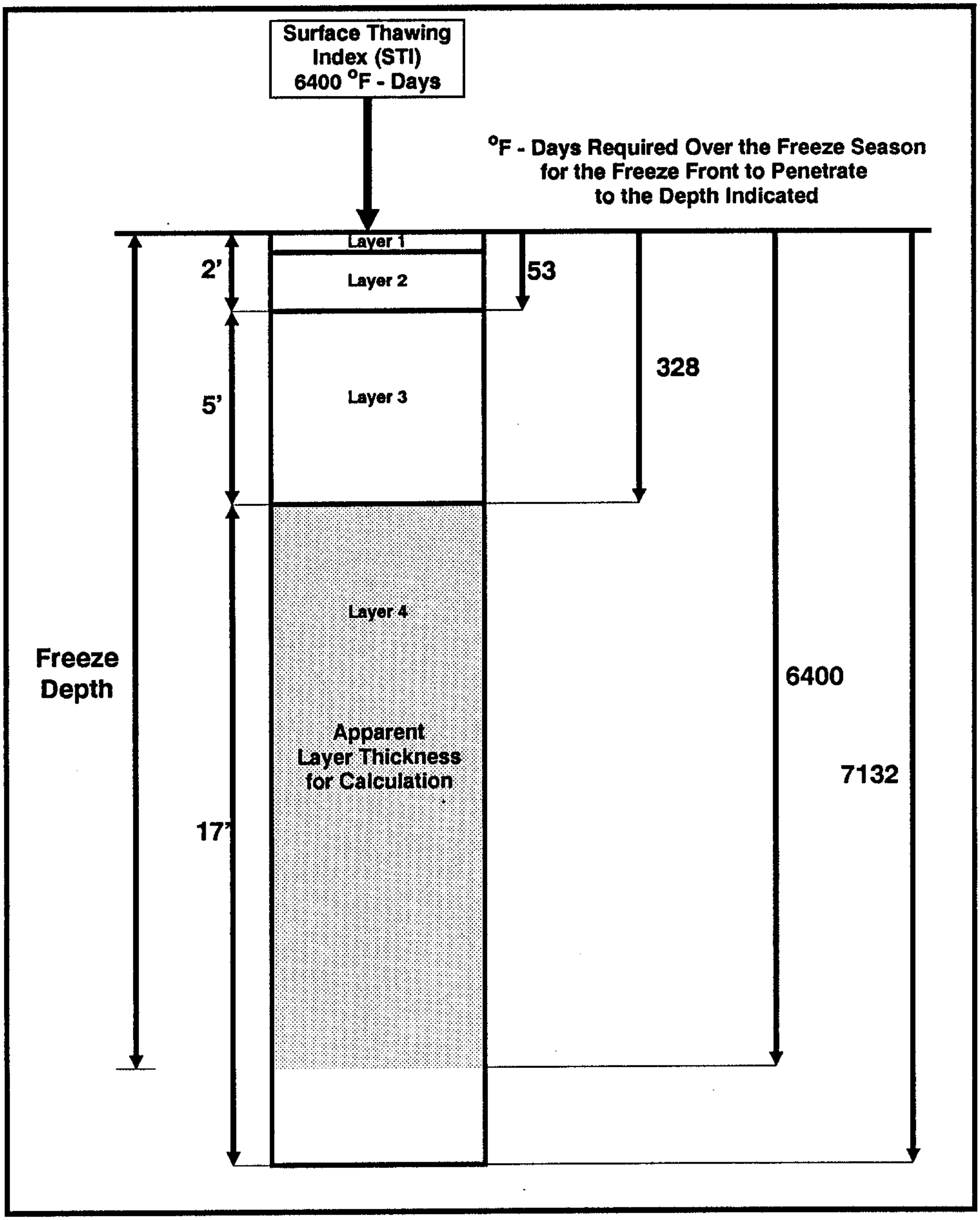

Figure 10. BERG2 freeze depth calculation.

$$\overline{L}_i = \frac{\sum_{i=1}^{n} L_i d_i}{\sum_{i=1}^{n} d_i} \tag{7}$$

where:

d_i = thickness of the ith layer
C_i = volumetric heat capacity (Btu / ft^3 • ^{o}F)
L_i = latent heat of fusion (Btu / ft^3)

The frozen or thawed heat capacity is used during the calculation of freeze or thaw depth respectively. The average surface temperature differential is determined from:

$$v_s = N\, AI / t \tag{8}$$

where:

N = surface N-factor
t = season length (days)
AI = air index (^{o}F-days)

N, t, and AI used during the thaw cycle are N_t,t_t, and ATI while for a freeze cycle these are N_f, t_f, and AFI.

The parameter γ, in equation 4, is determined for the freeze cycle using:

$$\frac{e^{-\gamma^2}}{\operatorname{erf}\gamma} - \left(\frac{K_u}{K_f}\right)\frac{v_o}{v_s}\,\frac{\sqrt{\overline{\alpha}_f/\alpha_u}\; e^{-(\overline{\alpha}_f/\alpha_u)\gamma^2}}{\operatorname{erf} c\,(\gamma\sqrt{\overline{\alpha}_f/\alpha_u})} = \frac{\gamma\sqrt{\pi}}{STE_f} \tag{9}$$

and for the thaw cycle:

$$\frac{e^{-\gamma^2}}{\operatorname{erf}\gamma} - \left(\frac{K_f}{K_u}\right)\frac{v_o}{v_s}\,\frac{\sqrt{\overline{\alpha}_u/\alpha_f}\; e^{-(\overline{\alpha}_u/\alpha_f)\gamma^2}}{\operatorname{erf} c\,(\gamma\sqrt{\overline{\alpha}_u/\alpha_f})} = \frac{\gamma\sqrt{\pi}}{STE_u} \tag{10}$$

Equations 9 or 10 are solved iteratively to determine a value of γ of acceptable accuracy. The subscripts u and f indicate unfrozen and frozen properties respectively. The other variables in Eqs. 9 and 10 are:

$$\alpha_f = K_f / C_f$$

$$\alpha_u = K_u / C_u$$

$$\bar{\alpha}_f = \bar{K}_f / \bar{C}_f$$

$$\bar{\alpha}_u = \bar{K}_u / \bar{C}_u$$

Calculation of $\bar{C}_i$ is shown by Eq. 6. $\bar{K}_i$ is calculated similarly using:

$$\bar{K}_i = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{K_i}} \qquad (11)$$

"v_o" is the absolute difference between the initial ground temperature, T_o, and the fusion temperature, T_f.

$$v_o = |T_o - T_f| \qquad (12)$$

In practice, T_o is assumed to be equal to the mean annual soil surface temperature, MASST.

As indicated by Eq. 12, BERG2 calculates both the depth of freeze and the depth of thaw using the same value of v_o. In a location where T_o is greater than T_f, the calculation of the thaw depth is meaningless because the entire soil regime will be thawed during the thaw cycle. Similarly in an area where T_o is less than T_f, permafrost will exist and the calculation of the depth of freeze will be meaningless.

- **FREEZING AND THAWING INDICES AND SURFACE N-FACTORS**

The freezing and thawing indices for air, AFI, and ATI are calculated using;

$$\mathrm{AFI} = \int_{t_2}^{t_1+365} (T_f - T_a)\, dt \tag{13}$$

$$\mathrm{ATI} = \int_{t_1}^{t_2} (T_a - T_f)\, dt \tag{14}$$

where

t_1 = beginning of thaw season (Julian Day)
t_2 = end of thaw season (Julian Day)
T_f = freezing temperature (32 °F)
T_a = air temperature (°F)

When using BERG2 for engineering design purposes, the design AFI and ATI should be used. The design AFI is defined as the average AFI for the three years having the greatest AFI in the latest 30 years of record. The design ATI is similarly defined using the average of the three years having the greatest ATI. Figures A.1 and A.2 show the design and mean AFI for the North American continent. Figures A.3 - A.6 show the design and mean AFI and ATI for Alaska.

The surface N-factors for a location are calculated using:

$$N_t = \mathrm{STI} / \mathrm{ATI} \tag{15}$$

$$N_f = \mathrm{SFI} / \mathrm{AFI} \tag{16}$$

where STI and SFI represent the surface thawing and freezing indices respectively. In contrast to the air indices which are determined from generally available meteorological records, the surface indices and thus the surface N-factors require site and surface specific temperature measurements. N-factors have been determined for many different surfaces, and a compilation of these was prepared by Lunardini (1978). A condensed version of this work is given in Tables A.1 and A.2.

- **SOIL SURFACE SEASON LENGTHS AND TEMPERATURES**

Because the soil surface freezing and thawing season lengths, t_f and t_t, and the MASST are not known for many locations, these values are calculated within the model based upon a sinusodial approximation of annual variation in air and surface temperatures. Dependent upon the data available to the user, they may elect to determine these sine waves in two manners. The first of these is by inputting the surface N-factors and the ATI and AFI. The second would be to input the MAAT and the amplitude of the air temperature sine wave, A_a. In both cases the model will calculate the other neccesary parameters for determing the sine wave.

If the surface N-factors and the ATI and AFI are defined by the user, then the STI, SFI, MASST, and t_t and t_f for the soil surface are determined as follows.

The surface thawing and freezing indexes, STI and SFI are determined from:

$$STI = N_t \times ATI \tag{17}$$

$$SFI = N_f \times AFI \tag{18}$$

and

$$MASST = T_f + (STI - SFI)/365 \tag{19}$$

The amplitude of the surface temperature sine wave, A_s, is found through an iterative calculation process. A_s is first estimated using:

$$A_{est} = \frac{\frac{\pi\, STI}{365} - (MASST - 32)\cos^{-1}\left(\frac{32 - MASST}{A_{seed}}\right)}{\left[1 - \left(\frac{32 - MASST}{A_{seed}}\right)^2\right]^{.5}} \tag{20}$$

Where A_{seed} is a first guess of the A_s. The cosine argument in this and subsequent equations is expressed in radians. This calculated value of A_{est} is then compared to A_{seed}. If these two values are not equal to the nearest hundredth, A_{seed} is set equal to A_{est} and the process is repeated.

Having arrived at an acceptable value of A_s, t_t and t_s for the soil surface are then calculated.

$$t_t = \cos^{-1}\left(\frac{32 - MASST}{A_s}\right)\left(\frac{365}{\pi}\right) \tag{21}$$

$$t_f = 365 - t_t$$

If the surface N-factors, MAAT, and A_a are input, then the ATI and AFI are calculated directly from:

$$ATI = \frac{365}{\pi}\left[\left(MAAT - 32\right)\left(\pi - \cos^{-1}\left(\frac{32 - MAAT}{A_a}\right)\right) + A_a\left(1 - \left(\frac{32 - MAAT}{A_a}\right)^2\right)^{.5}\right] \tag{22}$$

$$AFI = \frac{365}{\pi}\left[\left(32 - MAAT\right)\left(\pi - \cos^{-1}\left(\frac{32 - MAAT}{A_a}\right)\right) + A_a\left(1 - \left(\frac{32 - MAAT}{A_a}\right)^2\right)^{.5}\right] \tag{23}$$

Having solved for ATI and AFI, then STI, SFI, MASST, A_s, and the surface t_t and t_f are calculated by performing the calculation sequence beginning with Eq. 17.

- **ERROR FUNCTION CALCULATION (erf)**

A polynomial estimation of the error function is used to determine erf(x). This is:

$$erf = 1 - \left[1/\left(1 + A_1 X + A_2 X^2 + A_3 X^3 + A_4 X^4 + A_5 X^5 + A_6 X^6\right)^{16}\right] \tag{24}$$

where:

$A_1 = .0705230784$
$A_2 = .0422820123$
$A_3 = .0092705272$
$A_4 = .0001520143$
$A_5 = .0002765672$
$A_6 = .000043063$

The error function complement is defined as:

$$erfc(x) = 1 - erf(x) \tag{25}$$

- **SOIL THERMAL PROPERTIES**

Based upon the user specified soil moisture contents and densities, BERG2 has the capability of calculating the thermal conductivity, heat capacity, and latent heat for silt, gravel, and sand.

The equations used for determining the thermal conductivity for unsaturated soils were derived by Kersten (1949). For coarse grained soils (gravel and sand):

$$K_f = \left[.076\,(10)^{.013\,\gamma_d} + .032\,(10)^{.0146\,\gamma_d}\,w \right] / 12 \tag{26}$$

$$K_u = \left[\left(.7 \log(w) + .4 \right) 10^{.01\,\gamma_d} \right] / 12 \tag{27}$$

For fine grained soils (silt and clay):

$$K_f = \left[.01\,(10)^{.022\,\gamma_d} + .085\,(10)^{.008\,\gamma_d}\,w \right] / 12 \tag{28}$$

$$K_u = \left[\left(.91 \log(w) - .2 \right) 10^{.01\,\gamma_d} \right] / 12 \tag{29}$$

where:

γ_d = dry density of soil (lb / ft^3)
w = percentage moisture content by weight

K is expressed in units of Btu / hr $\cdot$ft $\cdot$ ^{o}F.

The equations for coarse grained soils are valid for moisture contents down to 1%. Those for fine grained soils are valid down to 7%. Kersten did not test soils to full saturation; however, he did extrapolate the data to this point. The degree of accuracy of these equations was given as plus or minus 25%.

The conductivity of frozen fine grained materials at saturation, such as ice-rich permafrosts, is estimated using an equation set forth by Lunardini (1981). This is:

$$K_f = \left[\left(1.007\,(1.0054)^{w/100} \right)^{\gamma_d} \right] .5778 \qquad (\text{Btu / hr} \cdot \text{ft} \cdot {}^{o}\text{F}) \tag{30}$$

The equations used to calculate the frozen and unfrozen heat capacity are respectively:

$$C_f = \gamma_d(c + .5(w/100)) \qquad (Btu / ft^3 \cdot {}^oF) \tag{31}$$

$$C_u = \gamma_d(c + 1.0(w/100)) \qquad (Btu / ft^3 \cdot {}^oF) \tag{32}$$

where:

c = specific heat of dry soil, .17 Btu/lb ^oF
w = percentage moisture by weight

The equation used to calculate the latent heat of the soil is:

$$L = 144\, \gamma_d\, (w / 100) \qquad (Btu / ft^3) \tag{33}$$

- **CONSOLIDATION**

The amount a layer of soil consolidates following the thaw cycle is proportional to the thaw strain, ε in equation 3, of that layer.

$$d_2 = \varepsilon d_1 \tag{34}$$

where:

d_1 is the initial thickness of the layer
d_2 is the post-thaw thickness of the layer

Thaw strain is calculated using:

$$\varepsilon = (e_f - e_u) / (1 + e_f) \tag{35}$$

The frozen and thawed void ratios, e_f and e_u, are determined using:

$$e = m\, G / s \tag{36}$$

where:

m = fractional moisture content by weight
G = specific gravity of the solids, 2.65 (lb / ft^3)
s = degree of saturation

It is assumed that thaw consolidation occurs at a degree of saturation of .98. The void ratio of the unfrozen soil is then found using:

$$e_u = m_u G / .98 \tag{37}$$

Since in a frozen soil it is assumed that the volume of the liquid fraction increases 1.1 times due to freezing, the frozen void ratio at .98 saturation is:

$$e_f = 1.1 \frac{m_f G}{.98} \tag{38}$$

The model only determines consolidation for a frozen soil with an s of .98 consolidating to a thawed soil with s equal to .98. Once thaw consolidation calculation is selected for a layer, (see user manual for this selection), the model backcalculates the frozen and unfrozen densities for an s equal to a .98 based on the user input moisture contents. The model performs this task as follows.

Expressing the void ration in terms of density gives:

$$e = G\,(\gamma_w/\gamma_d) - 1 \tag{39}$$

where:

γ_w is the density of water (62.4 lb/ft^3)
γ_d is the dry density of soil solids (lb/ft^3)

Combining Eqs. 37 and 39 while substituting the known values for γ_w and G yields an expression for unfrozen soil density in terms of unfrozen moisture content.

$$\gamma_{du} = 165.36/(2.7m_u + 1) \tag{40}$$

For the frozen case, Eqs. 38 and 39 are combined.

$$\gamma_{df} = 165.36/(2.97m_f + 1) \tag{41}$$

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Table A.1. N-Factors, Asphalt Paved Surfaces.

Location	N - Factors		Air Indices (°F-Day)	
	Freeze	Thaw	Freeze	Thaw
Fairbanks, Alaska	.78	2.11	5042	3055
	.65	2.28	5042	3055
	.72	2.15	5042	3055
	--	1.96	--	3320
	--	.98*	--	3320
	--	1.15*	--	2720
	--	1.39	--	2720
Chitina, Alaska	1.0	1.73	5400	2400
Sudbury, Ont.	.58	--	2600	--
Laksolv, Norway	1.26	--	1908	--
Os, Norway	1.02	--	2034	--
Amli, Norway	2.48	--	342	--
Amli, Norway	1.9	--	234	--

* Painted white

Table A.2. N-Factors, Non-Paved Surfaces

Location	Surface Type	N-Factors		Air Indices (°F-Day)	
		Freeze	Thaw	Freeze	Thaw
Fairbanks, Alaska	spruce/brush/moss over peat soil	.29	.37	5042	3055
	trees & brush cleared moss over peat soil	.25	.73	5042	3055
	vegetation and 16" of soil stripped clean	.33	1.22	5042	3055
	gravel	.76	1.99	5042	3055
	gravel	.63	2.01	5042	3055
	gravel colored dark	--	1.4	--	3320
	gravel	--	1.5	--	2680
	gravel colored dark	--	1.27	--	2720
Chitina, Alaska	gravel	1.0	1.47	5400	2400
Lakselv, Norway	sandy soil w/.66' snow	.49	--	1908	--
Os, Norway	sandy soil w/1.9' snow	.02	--	2034	--
Amli, Norway	sandy soil w/.66' snow	.53	--	342	--
Amli, Norway	sandy soil w/.33' snow	1.39	--	234	--

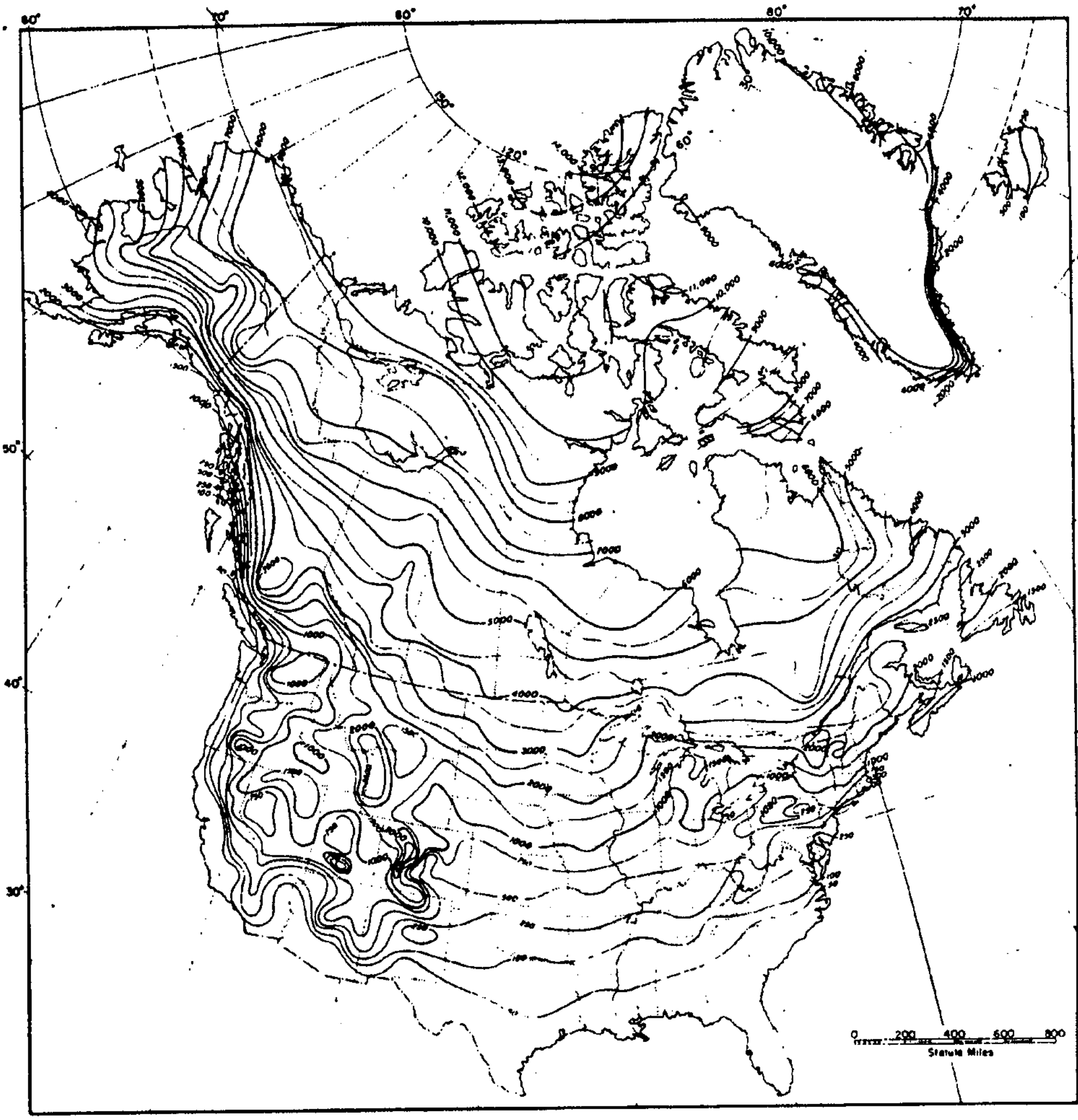

Figure A.1. Design air freezing indices for North America.
(from Joint Department of the Army and Air Force USA, 1985)

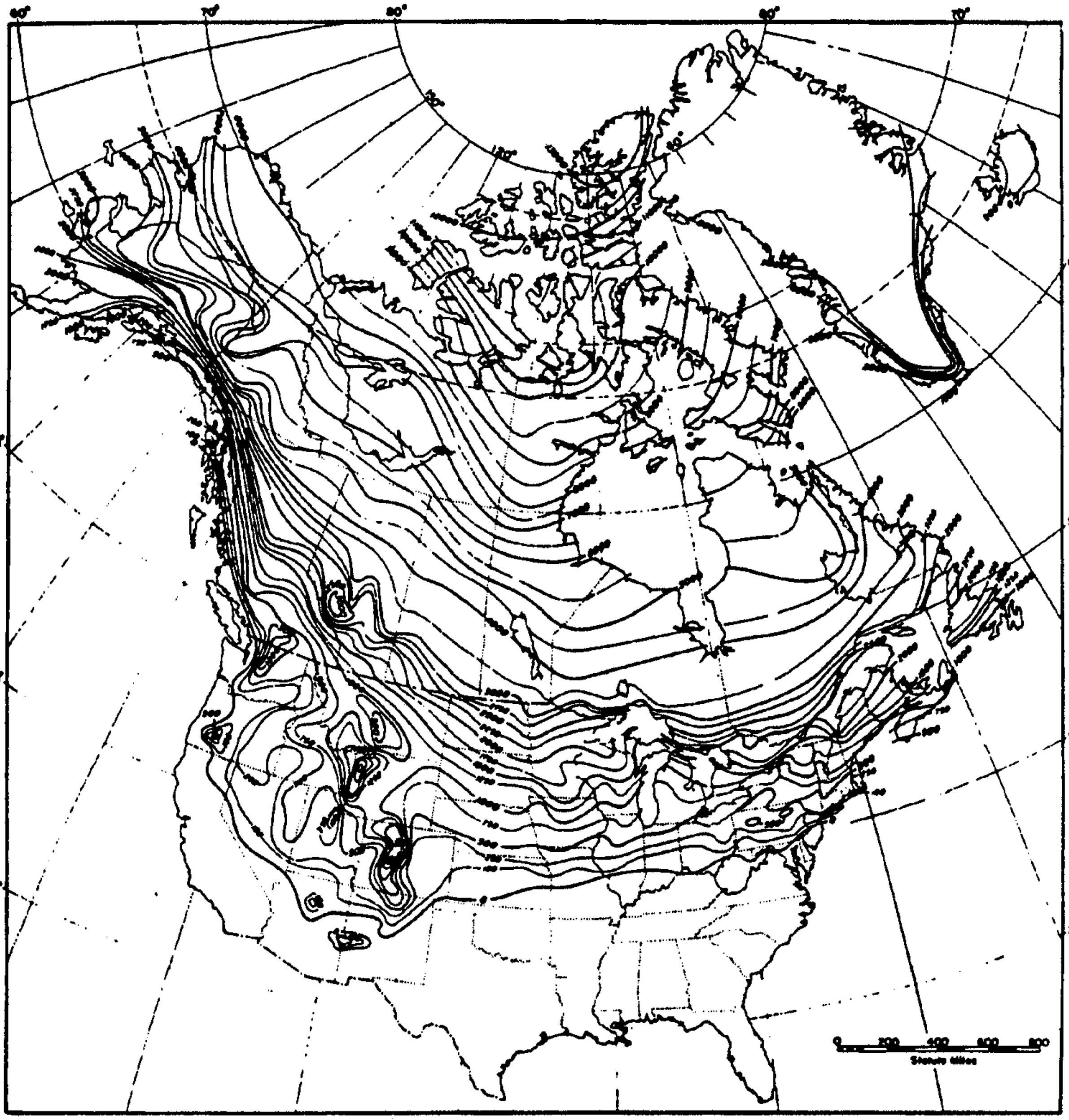

Figure A.2. Mean air freezing indices for North America.
(from Joint Department of the Army and Air Force USA, 1985)

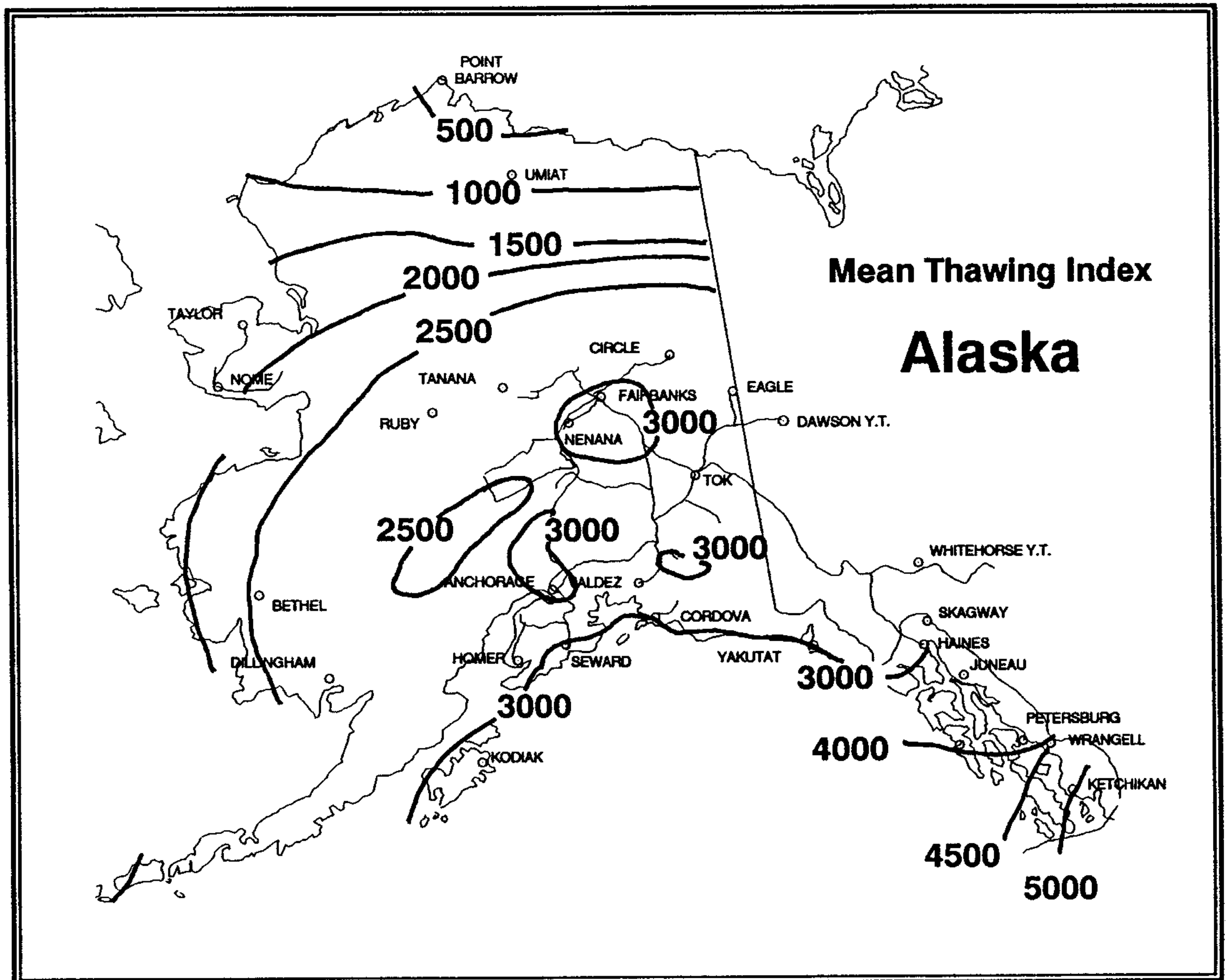

Figure A.3. Hartman (1978)

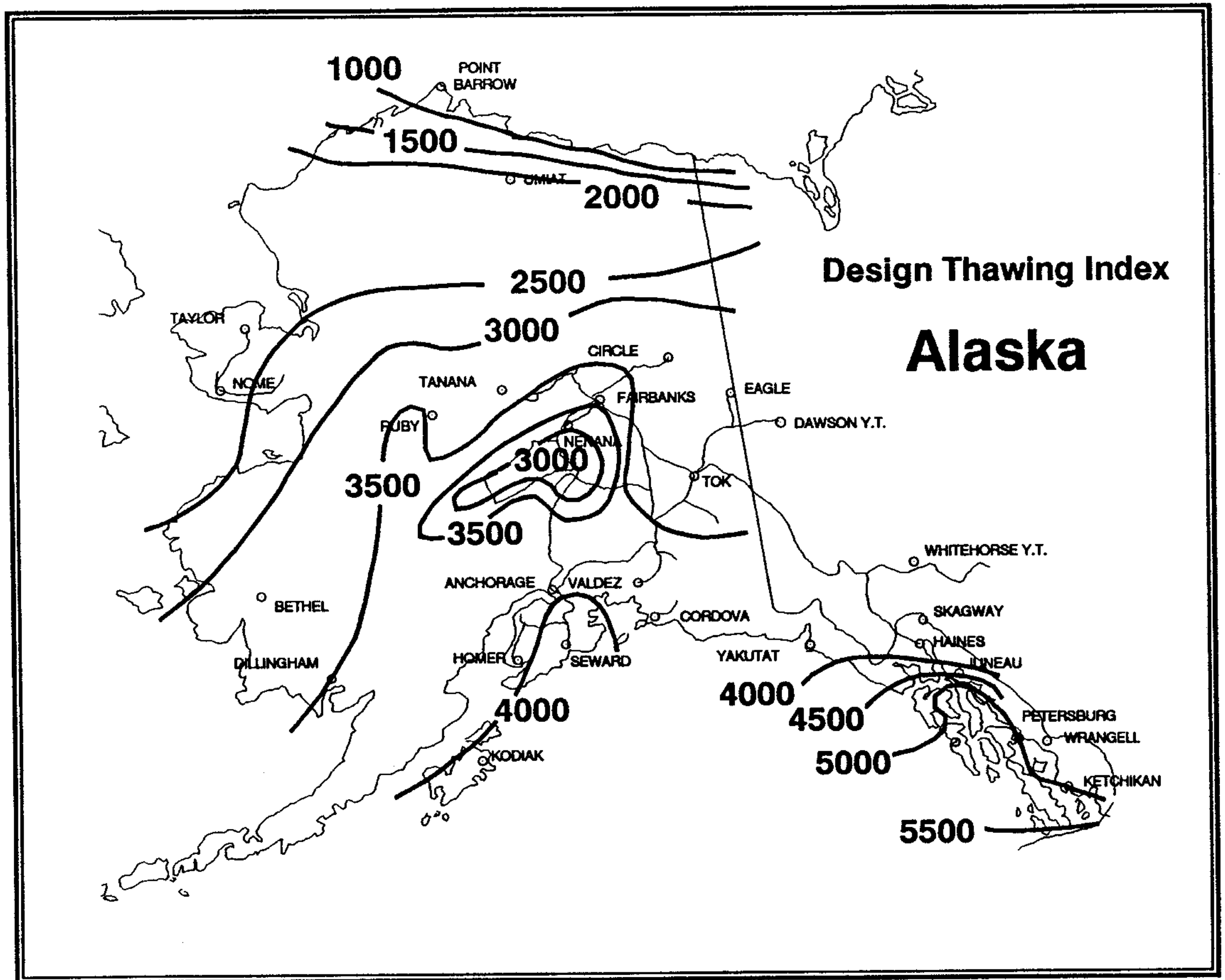

Figure A.4. Hartman (1978)

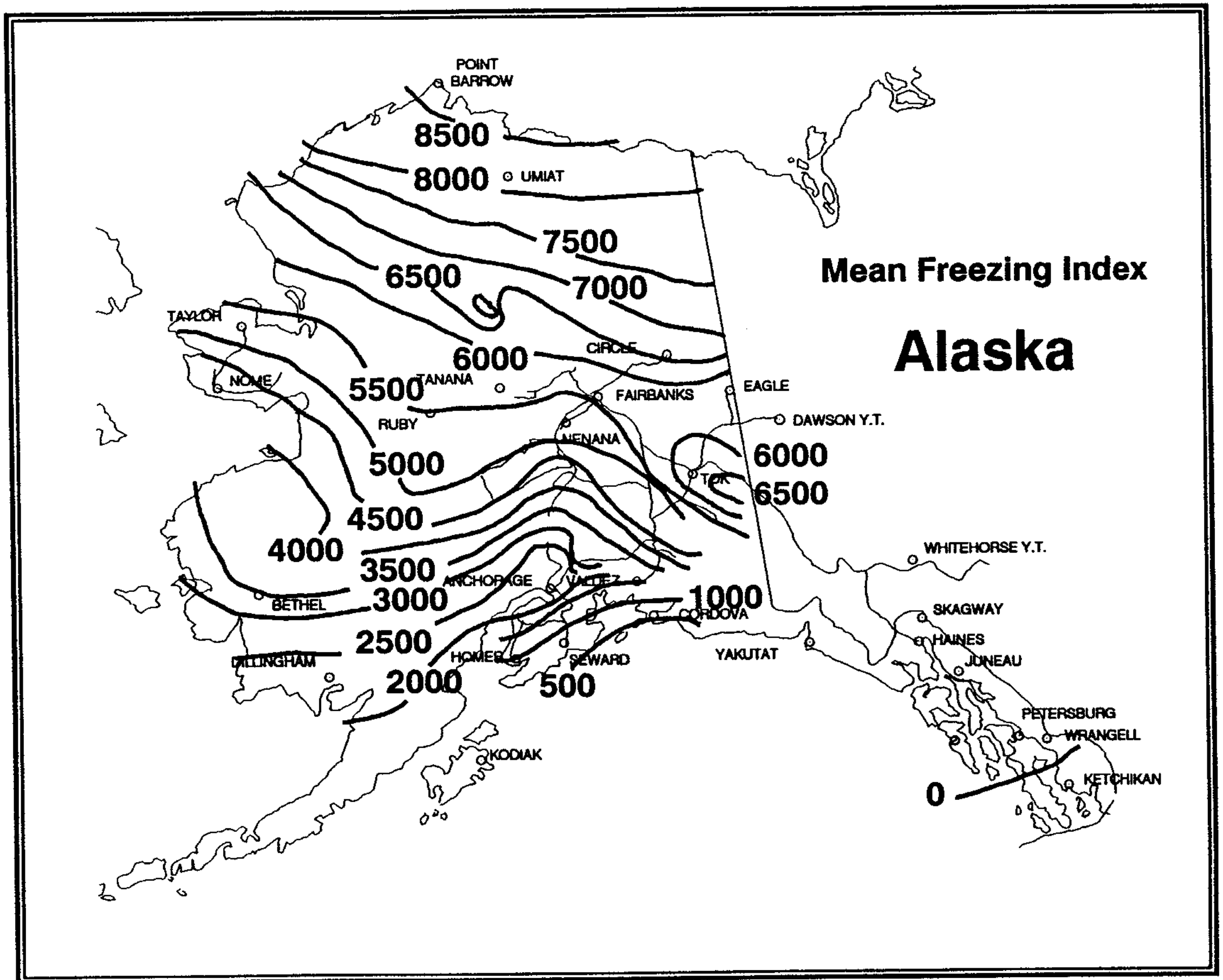

Figure A.5. Hartman (1978)

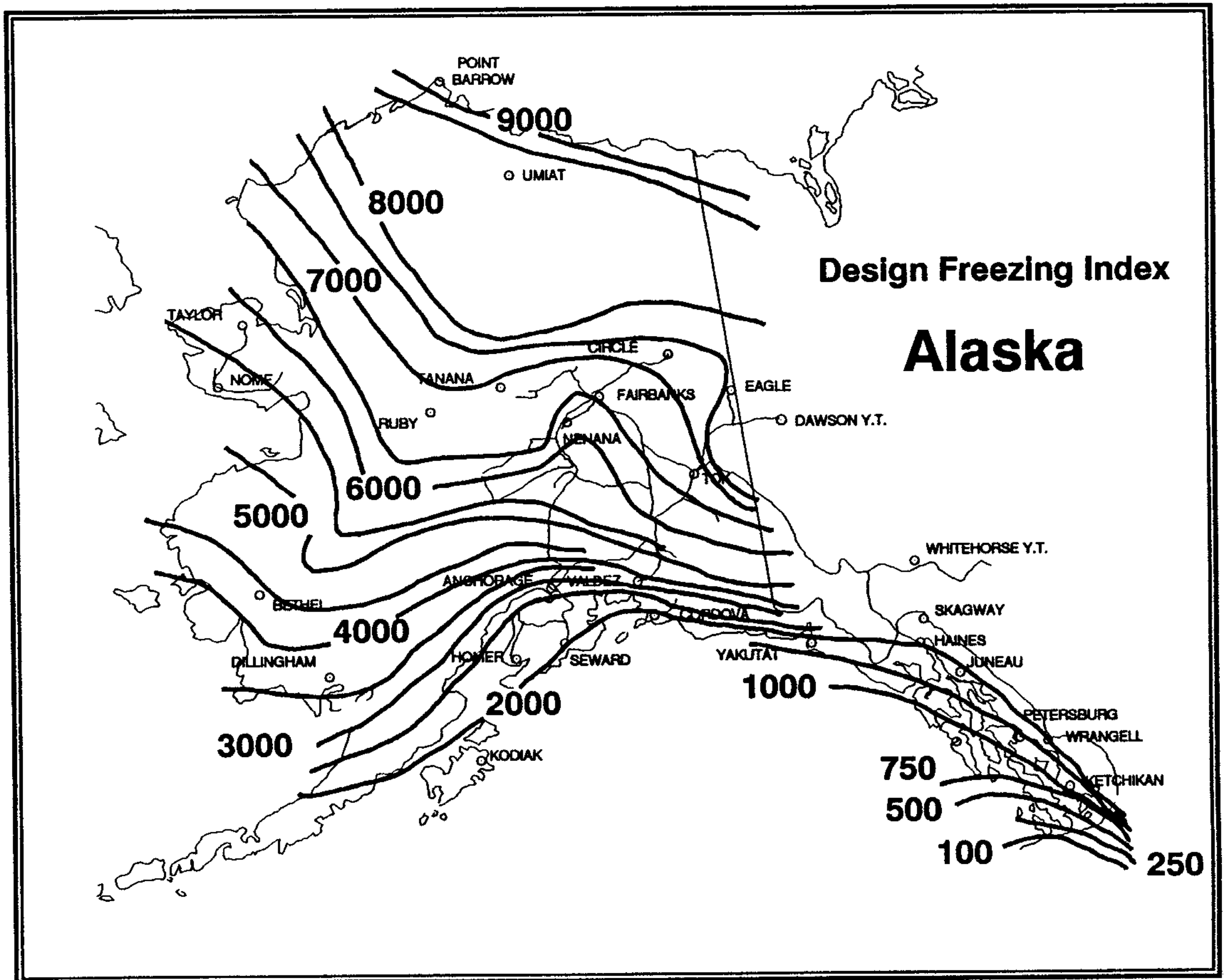

Figure A.6. Hartman (1978)