DESIGN AIDS FOR THERMAL ANALYSIS

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The purpose of the "Design Aids for Thermal Analysis" study was to obtain the license to operate the "GEOGRD, GEODYM and GEOPLT" series of computer programs from Resource Management Associates of Lafayette, CA and to make them usable to Alaska Department of Transportation and Public Facilities (DOT&PF) engineers for use in analysis of road sections in Alaska. Though very effective and sophisticated, these programs require considerable time and expertise to be used properly.

This report presents a summary of the programs and their capabilities, and provides simplified input nstructions as well as some guidance regarding the less well known input parameters. In addition, the use of the program to solve surface energy balance calculations is described in detail, and the appropriate **SOLMET** input parameters are provided for 17 sites in Alaska. The original documentation for the programs is also included. The source code for the program is licensed from Resource Management Associates and therefore cannot be included in this report.

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FINAL REPORT

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Prepared for

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ABSTRACT

The purpose of the "Design Aids for Thermal Analysis" study was to obtain the license to operate the "GEOGRD, GEODYN and GEOPLT" series of computer programs from Resource Management, Associates of Lafayette, California and to make them usable to Alaska Department of Transportation and Public Facilities (DOT&PF) engineers for use in analysis of road sections in Alaska. The programs were purchased and installed on the University of Alaska VAX 11/730 for verification, testing, and possible modification for ease of use by DOT&PF. It was determined that the programs are very powerful and flexible and will do many problems that other commercially available programs will not. Coupled with this power and flexibility, is the inherent complexity of use and necessity for large amounts of computer time.

It is neither a design tool for the beginner nor a design tool that can be used at a moment's notice to obtain rapid answers. It is the author's opinion that an engineer who is reasonably familiar with the program and the problem will spend several days of his time and several hundreds of dollars in computer time in getting the desired results. It is possible, however, for the engineer with the time, patience and know-how to do some very sophisticated analyses with the programs,

This report presents a summary of the programs and their capabilities, and provides simplified input instructions as well as some guidance regarding the less well known input parameters. In addition, the use of the program to solve surface energy balance calculations is described in detail, and the appropriate SOLMET input parameters are provided for 17 sites in Alaska, The original documentation for the programs is also included. The source code for the program is licensed from Resource Management Associates and therefore cannot be included in this report.

I. INTRODUCTION

1.1 Background

In December of 1983, the Alaska Department of Transportation and Public Facilities (DOT&PF), Research Section awarded a contract to the Institute of Northern Engineering (INE) at the University of Alaska-Fairbanks (UAF) to study several of the heat flow computer models that were available on DOT&PF computers to determine which one would be the most appropriate for use in studying the thermal regime under roads in Alaska. The Geophysical Intitute at the University of Alaska was under a complimentary contract and by the spring of 1983 had limited the possible programs for consideration to two: GEODYN by Resource Management Associates and the Guymond model by Prof. Gary Guymond at the University of California. DOT&PF revised our scope of work to obtain the license for the GEODYN model and to verify its validity instead of looking at several different programs. The license for GEODYN was obtained in the late summer of 1984, and validation started in accordance with the revised proposal dated April 2, 1984.

1.2 Purpose

The purpose of the revised project was to do the following:

* Obtain the licence to run the GEODYN computer model and install it on the University of Alaska Engineering VAX 11/730 and the DOT&PF IBM computers.
* Check the program against the Neumann solution and the modified Berggren solution.
* **Estimate the cost of running the program**
* **Implement a surface energy balance algorithm in the program that can be used to study Alaskan roads.**
* **Compare the results of** calculations **with** field **data existing** in **the DOT&PF files.**
* Make the program user friendly by writing a clearly stated users manual or by writing a more user-friendly front end, whichever appears to be the most appropriate.

1.3 Scope

The study addressed each of the topics in the outline, but the level of effort on the individual tasks was shifted due to factors that became apparent during the work. Extensive effort was required to install the program and to develop new input instructions that are correct and easy to follow. The work required to compare the results to theoretical solutions was minimal. The RMA documentation contains the Neumann comparison. It was decided early in the contract that it was neither practical, nor in DOT&PF's best interest, to try to simplify the input to the program. To simplify the input, the program would

Loose much of its power and versatility for little increase in usability. Comparing the program calculations with field data from DOT & PF files was not done because none of the instrumented field sites had sufficiently well developed data to make a comparison meaningful. The effort to be expended on the surface energy balance calculations was shifted from one of program development to one of providing simplified data for input. Part of the agreement with RMA included their adding a surface energy balance model to the program. Program run time determination became a mute point once it was decided that the program was more of a research tool than a production calculation tool. It was not meaningful to define the run time in general terms without a standard cross section and standard temperature regime. Run time calculations are not specifically included in the report but it is sufficient to say that they are not excessive for a sophisticated finite element model.

2. PROGRAM FEATURES

2.1 Program Flow

There are three *programs* that act in series to Process the input data, calculate temperature fields at various times and output results. The first, GEOGRD, generated a finite element mesh from a relatively simple set of input parameters and optimizes the element numbering for efficient calculation by GEODYN. The second, **GEODYN**, calculates the temperature of each node in the finite element mesh as a function of time.. the Third, GEOPLT, takes the output from GEODYN and draws an isothermal contour plot throughout the finite element mesh, The basic use of each program is given **below**. A complete description of each program is given in the operating instructions (Appendices F, G and H) provided **by** RMA Associates.

The programs will use either SI units or English units. The programs are capable of handling two dimensional problems or axisymmetric problems.

2.2 Input/Output

We have found many serious errors in the operating instructions provided by RMA in the operating instructions (Appendices F, G and H) and have rewritten them, The corrected input instructions are included in Appendices C, D and E. A brief description of the forms of the input are given below. The output is also described in general terms below. The output is self explanatory once the user finds the right files.

2.2.1 GEOGRD

The program GEOGRD takes input in one of three forms and generates a mesh for finite element analysis. GEOGRD can use the definitions for individual nodes and elements or the boundary of a quadrilateral or triangular area to be filled with quadrilateral or triangular elements from input file IN.DAT which is read from the standard input device. GEOGRD is also capable of using the output from a previous GEOGRD run from the **file**, LUNIT.DAT, on input device **LUNIT** and modifying **it** to add elements, delete elements or subdivide elements. If requested, GEOGRD will renumber the elements **so** that GEODYN computer time will be minimized.

Nodes are defined by X **and** *Y* coordinates for two dimensional problems or r and z coordinated for axisymmetric problems. The dimensions input may be modifyed by scaling parameters used by GEOGRD when plotting **or** by GEODYN for calculations.

The program generates **two** output files and a plot of the completed grid. The file OUT.DAT on the standard output device contains a regurgitation of the input data, and the calculated node and element definitions of the completed mesh in one of several levels of user-specified detail. The file LUNIT.DAT on output device LUNIT, contains an unformatted listing of the node and element data for use by GEODYN or a future run of GEOGRD, It also contains the renumbered mesh if appropriate. All GEODYN calculations will be performed in the renumbered format. All output will be created using the original numbering system. The program will generate a plot of the entire mesh or any subset of the mesh. The plotting is intended to be performed on-line, the plot file is not saved.

2.2.2 GEODYN

GEODYN does the numerical calculations to determine the temperature field as a function of time. It takes the initial temperature distribution throughout the mesh and calculates the temperature at specified times considering various time dependent thermal input applied throughout the mesh.

GEODYN can read the mesh from one of three files. It can read the output of GEOGRD from file LUNIT.DAT on input device LUNIT. It can read the output from a restart file IT-DAT on input device LI. The restart file IT.DAT was created on output device IT by a previous GEODYN run. Or it can generate a new grid, one element at a time, from input specifications defined in file IN.DAT on the standard input device. It is also capable of modifying a grid by adding elements, subtracting elements or subdividing elements input by one of the previous methods-

The initial temperature field can be established by input parameters to the program from file IN.DAT on the standard input device or by input from a restart file IT.DAT on input device IT. Input through file IN.DAT can take several forms: 1) a constant temperature field, 2) a constant temperature field modified at one or more nodes or, 3) the temperatures may be distributed by a polynomial which has a specified value at the X or Y axis and is asymptotic to some temperature at an infinite distance from the X or Y axes.

GEODYN considers heat conduction through the soil and heat carried through the soil by groundwater flow. The velocity of the groundwater flow is contained in file IN.DAT.

External thermal conditions are controlled through data in file IN.DAT. The external conditions can consist of a specified temperature at any node, a specified thermal flux across any element face, or the results of a thermal energy balance calculation on any surface element face.

The temperature at any node can be held constant for any length of time, can be changed to a new constant value at any time, can be varied linearly with time over any time interval, or can be varied sinusoidally throughout a year. The temperature variations are expected to be variations throughout a year, but it is possible to look at daily or even hourly variations with all but the sinusoidal input mode, if desired,

A specified thermal flux can be applied to any element face for any specified time, it can be changed to a new value at any time, or it can be varied linearly with time over any specified time interval,

A surface energy balance calculation can be specified on any number of element faces. The meteorological conditions for the surface energy balance are initially input as average values inserted on a month by month basis. The surface characteristics are initialized at the beginning of the problem. Most of the input values can be changed at any of the element faces at any time, The input parameters include:

1. Short wave solar radiation, albedo, and view factor,
2. Long wave radiation emissivity.
3, Air temperature.
4. Wind speed and surface roughness,
5. Cloud cover.
6. Evapotranspiration flux.
7. Snow depth and density,

The soil property input to GEODYN includes the frozen and unfrozen thermal conductivities in the horizontal and vertical directions, the frozen and unfrozen heat capacities and the latent heat of fusion. The latent heat is lost or gained over a temperature range through a mathematical relationship which was developed to model the relationship between unfrozen water content and temperature, Freezing starts at 32 degrees F, but it is possible to lower the freezing temperature by an appropriate choice of input parameters,

The output from GEOGRD goes to one or more of three output files. File OUT.DAT is output to the the standard output device. It contains the node, element and mesh data, and the temperature of each node at specified times in several levels of user-controlled detail, This file is intended for screen or paper output and is always produced, In the RMA version, it is formatted for a wide carriage printer. In the UAF version, it is formatted for screen output.

The file IS5.DAT is output to device IS5. It contains an unformatted version of the node locations and the calculated temperatures at all nodes at each time requested in the file IN.DAT. This information is stored for use by program GEOPLT to produce plotted output and is produced only if requested.

The file IT.DAT is output to device IT. It contains an unformatted version of the node and element data along with the final temperatures at each node. These data are used as input to restart GEODYN from the ending point and are only produced if requisted.

2.2.3 GEOPLT

GEOPLT uses the output from GEODYN to develop isothermal contour plots at any or all of the time steps calculated. Input is from the file IN.DAT on the standard input device and file LUG.DAT on input device LUG. Plotting information such as the plotting scales, the time steps to be considered and the contouring interval to be used are input in file IN.DAT. File LUG.DAT was generated by GEODYN and contains the node locations and the temperatures for every time step specified in running that program. Note that the name of the file IS5.DAT output by GEODYN on output device IS5 must be renamed to LUG.DAT and put on input device LUG for use in GEOPLT.

The output from GEOPLT is primarily in the form of isothermal contour plots. The plotting is expected to be on-line, so no plot files are saved. There is also a short output file OUT.DAT on the standard output device which contains error messages and error tracing information.

2.3 Restart Capabilities

It is possible to stop the program at the end of any time step and restart it again after changing selected input parameters. This feature allows an incremental approach to changes in the surface conditions such as the construction of a building, the addition of snow or clearing. In addition, certain subsurface changes can also be accounted for such as thaw consolidation or the insertion of refrigeration devices.

2.4 Hardware Requirements

The programs were developed on a Prime computer. There are significant differences between Prime computers and other computers in the way they handle certain array functions and the transfer of data back and forth between subroutines. As a result, there may be some difficulty in converting from one computer to another. To the best of our knowledge, the program in the form transmitted to DOT&PF with the final copy of this report works correctly on the University of Alaska Engineering VAX 11/730.

GEODYN is the most extensive of the programs. It has over 3,500 lines of Fortran code programming, 19 subroutines, one function and one block of data with 12 subblocks.

In addition, the programs require a plotter. The size and orientation of the plots are programmer controlled. The program uses standard CALCOMP commands, so it will work with any CALCOMP-compatible plotting equipment.

2.5 Software Requirements

The programs are written in Fortran and use standard CALCOMP plotter calling routines.

3. ACCURACY OF *GEODYN* CALCULATIONS

3.1 Comparison with Theoretical Calculations

3.1.1 Neumann Solution

The operating instructions (Appendices F, G and H) supplied by RMA include an example of the comparison between the Neumann solution and the GEODYN solution for a one-dimensional nonsteady state problem with freezing. *The* reported results are excellent. We have run similar problems with similar results. We have not included our work in this report as it is redundant to the RMA report.

3.1.2 Modified Berggren Solution

We have compared the results of the GEODYN model with the modified Berggren approach using the soil profile presented in the RMA comparison with the Neumann approach discussed above. The Lambda factor accounts for the sensible heat which in essence reduces the amount of heat available for freeze and thaw. The Neumann solution predicted 1.57 feet, the GEODYN solution predicted 1.52 feet and the modified Beggren solution predicted 1.30 feet. The agreement between *the* modified Beggren solution and the other two was not good.

Loose much of its power and versatility for little increase in usability. Comparing the program calculations with field data from DOT & PF files was not done because none of the instrumented field sites had sufficiently well developed data to make a comparison meaningful. The effort to be expended on the surface energy balance calculations was shifted from one of program development to one of providing simplified data for input. Part of the agreement with RMA included their adding a surface energy balance model to the program. Program run time determination became a mute point once it was decided that the program was more of a research tool than a production calculation tool. It was not meaningful to define the run time in general terms without a standard cross section and standard temperature regime. Run time calculations are not specifically included in the report but it is sufficient to say that they are not excessive for a sophisticated finite element model.

3.2 Comparison with field test data

The proposal was written with the understanding that the DOT&PF had several instrumented test sites that had enough temperature data, climatological data, and subsurface data to make good test cases for the program. Unfortunately, a detailed look at the existing data (Zarling and Braley, **1986**) reveals that there are no good sites for checking the program. Each site is either missing some **key** data or has some anomaly that dominates the thermal behavior at the site, so it would not provide a good check for the program.

3.3 Sensitivity

This program, as any numerical method, carries with it some trade-offs between accuracy and practicality of operation. The solution should be more accurate using smaller elements and smaller time steps, but there is a practical limit of computer size and computer time which limits the problem solution. Making the size of the elements larger or the time steps smaller takes more computer time. In addition, there are other mathematical considerations such as the way in which the model handles the unfrozen water content, and the effects of the shape of the elements. The parameters that have been found to be the most significant to the calculations on road embankments in Alaska are outlined below.

3.3.1 Element Size

There is a loss in accuracy as the elements become larger in the zones of most rapid temperature fluctuations. It appears that elements should have a thickness of less than about one half of the distance from the rapidly varying temperature to the closest point on the element. That is, an element that is ten feet below the ground surface should not be more than five feet thick. There is a practical minimum thickness of about six inches.

3.3.2 Time Step Size

Ideally, the time step should be as small as possible. An increase in time step size decreases accuracy and may increase run time by increasing the number of iterations required to reach stability. The time required for program operation is somewhat less than directly proportional to the time step size. There is not much sacrifice in accuracy, if the problem converges. Therefore, fairly large time steps appear to work well. We have found that time steps on the order of 10 days are reasonable for most practical problems in road design. Time steps up to 30 days have been used with sufficient accuracy under certain conditions.

3.3.3 Latent Heat Algorithm

Latent heat is gained or lost over a temperature range, The temperature range is defined by two equations which are derived to represent the unfrozen water content as a function of time, Sands and gravels with freshwater in the pores should freeze completely within a few hundredths of a degree, so it would seem reasonable to consider all freezing to occur at 32 degrees F. However, the algorithm for calculating the temperature as a function of energy level may become unstable when freezing is considered to take place over a small temperature range.

Our experience has shown that, if stability is reached, the accuracy is reasonable when freezing is considered to take place over a small temperature range. However stability is not always reached. Even if stability is reached, it takes many iterations and the run time becomes exceedingly large. For instance, one problem took 15 seconds of CPU time with a freezing temperature range of one degree F and 25 minutes when freezing took place with a 0.01 degree temperature range. The answers were the same for the first few time steps, but the run with the small temperature range eventually became unstable,

Our experience has been that there is not a significant loss in accuracy if freezing is considered to take place over at least a one degree temperature range, as long as the temperatures on each side of the freezing isotherm are several degrees above or below the freezing temperature. There is some loss in accuracy when a major portion of the problem is within a few degrees of freezing, Our experience has been that freezing should be considered to take place over at least 0.5 degree F in order to get a reasonably accurate solution in a reasonable length of run time,

4. SURFACE ENERGY BALANCE

Energy is transferred to or from the ground surface by several mechanisms: *solar* or short wave radiation, $Q_{s.w.}$; long wave or infrared radiation, $Q_{l.w}$; convection, Q_{conv}; conduction in/out of the ground, Q_{cond}; and phase change, Q_l. The phase change term includes evaporation, condensation and sublimation. In addition, energy is transferred by rain, snow and snowmelt. Over the long term, the magnitude of energy transfers by *snow* and rain are usually assumed small in comparison to the other terms, so the surface energy balance can be expressed as

$$Q_{s.w.} - Q_{l.w.} - Q_{conv} - Q_l = Q_{cond} \qquad (1)$$

A schematic of the surface energy exchange is depicted in Figure 1. *As* will be shown, most of the terms in the surface energy balance depend upon surface temperature. The next sections of this report will discuss each of the terms in detail.

Solar Radiation

Solar radiation incident on a surface is the sum of direct (beam) and diffuse (scattered direct radiation *due* to clouds and dust) radiation. NOAA in 1978 rehabilitated historical solar radiation data from throughout the United States. Using a regression analysis and historical weather data, Cinquemani et al. (1978) calculated solar radiation data for 17 Alaskan locations. The solar and weather data are available on computer magnetic tapes. The result of this work was also published by NOAA as SOLMET data. The Alaskan SOLMET data have been included in Appendix A of this report.

The solar radiation data presented are the monthly average daily radiation (beam plus diffuse) incident on a horizontal surface. However, many surfaces of engineering interest are tilted at an azimuth angle. Therefore, a multiplying factor, R, needs to be applied to the horizontal value in order to calculate the solar radiation incident on the tilted surface at the specified azimuth angle. An algorithm published by Klein and Theilacker (1981) was used to calculate R for the 17 Alaskan SOLMET sites. Values of R are given in Appendix B. R is the ratio of the

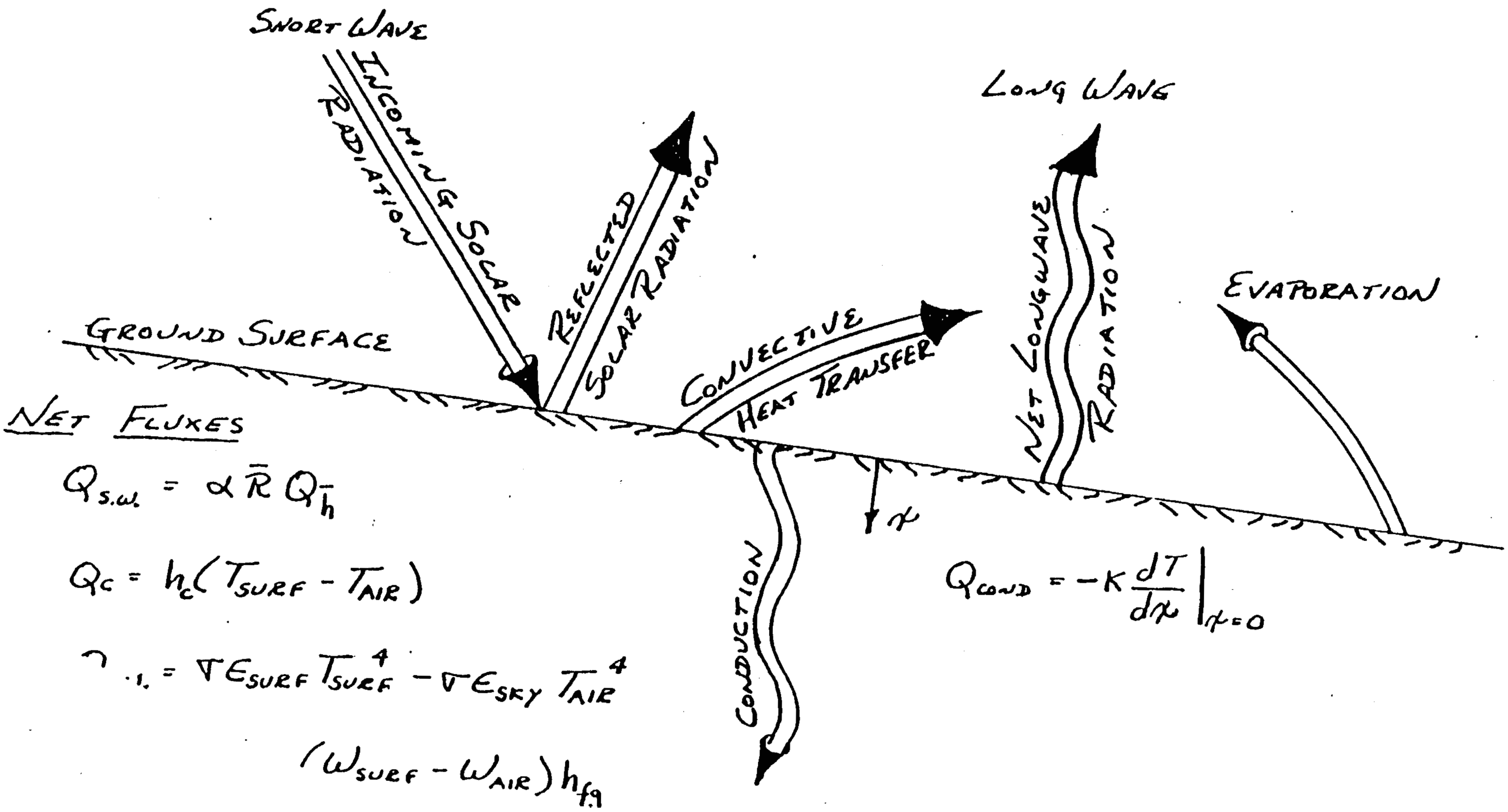

Figure No. 1 Components of surface energy balance daily total radiation on the tilted surface to daily total radiation on the horizontal surface.

The calculation methodology for R splits the total radiation incident on a horizontal surface into the direct and diffuse components. Then the direct radiation incident on the tilted surface is calculated based on the geometric relationship between the sun and the surface. The diffuse component incident on the tilted surface is based on the view factor between the surface and the sky. Next the reflected radiation from the ground surface is calculated to arrive at the total hourly radiation on the tilted surface. The resulting equations are then integrated with respect to time in order to arrive at the total radiation on the tilted surface.

TABLE 2. Solar albedo and long-wave absorptance of materials. (Kreith and Kreider, 1978).

Surface	Solar albedo	Long-wave emittance
Fresh snow	.87	.82
Ice with sparse snow	.69	.96
Snow, ice granules	.67	.89
Rough concrete	.40	.97
Concrete	.40	.88
Grass, green	.33	.98
Grass, dry	.33	.9
Frozen soil	--	.93
Ground, dry plowed	.23	.9
Pine forest	.14	.9
Dry sand	.18	.9
Asphalt pavement	.07	--
Bare moist ground	.10	.95
Wet sand	.09	.95
Water	.06	.95

Solar radiation absorbed on a surface of given tilt and azimuth angle is equal to the solar radiation incident on a horizontal surface multiplied by the surface short-wave absorptivity (1/surface albedo) and R or

$$Q_{s.w.} = aRQ_h \tag{2}$$

Surface albedos are given in Table I for several types of surfaces.

Long-wave Radiation

Infrared or long-wave radiation exchange between the ground surface and the sky is usually treated in an approximate manner due to the difficulty in finding reliable data on sky emissivity or *sky* temperature. This situation is further complicated by the need for dew point temperature, cloud cover and cloud height or temperature data required to even use existing correlations.

An effective sky temperature, T_s, is defined as being the temperature of a black body emitting the **same** radiant flux, Q_{sky}, as the **sky** or

$$Q_{sky} = \sigma T^4_{sky} \tag{3}$$

where σ is the Stefan-Boltzmann constant. The net radiation exchange between the ground surface and **sky** can be written as

$$Q_{l.w.} = \sigma \varepsilon_s (T^4_{surf} - T^4_{sky}) \tag{4}$$

where ε_s is the long-wave surface emissivity. A total apparent sky emissivity, ε, which relates sky temperature to air temperature, is defined as

$$\varepsilon = \frac{Q_{sky}}{\sigma T^4_{air}} = \frac{T^4_{sky}}{T^4_{air}} \tag{5}$$

or

$$T_{sky} = \varepsilon^{1/4} T_{air} \qquad (6)$$

Martin and Berdahl (1984) presented the following methodology for calculating the apparent *sky* emissivity. **The** monthly average clear sky emissivity as a function of dewpoint temperature (°C) is

$$\varepsilon_o = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right) + 0.75\left(\frac{T_{dp}}{100}\right)^2 \qquad (7)$$

This equation can be adjusted for elevation of the site by

$$\Delta\varepsilon_E = 0.00012\ (P-1000) \qquad (8)$$

where P is the local barometric pressure at the site in millibars. A diurnal correction is also available for predicting hourly emissivities as

$$\Delta\varepsilon_H = 0.013\cos\left(\frac{2\pi t}{24}\right) \qquad (9)$$

where t is the hour of the day measured from solar noon.

The presence of clouds increases the emissivity and effective sky temperature. The emissivity of a **sky** with clouds can be expressed by the relationship

$$\varepsilon = \varepsilon_o + (1-\varepsilon_o)\ C \qquad (10)$$

where

$C = n\varepsilon_c\Gamma$

with

n = fraction of sky covered by clouds

ε_c = cloud emissivity

Γ = factor related to cloud base temperature

The parameter, C, can be interpreted as the "infrared cloud amount." The cloud factor, Γ, can either be estimated based on cloud base temperature as

$$\Gamma = \exp\left(-\Delta T_c / \Delta T_o\right) \tag{11}$$

or on cloud base height as

$$\Gamma = \exp\left(-H/H_o\right) \tag{12}$$

where

$\Delta T_c = T_{air} - T_{cloud}$

$\Delta T_o = 46°C$

H = cloud base height

$H_o = 8.2$ km

The cloud emissivity is also a function of cloud base height, or

$\varepsilon_c = 0.15$	$H > 11$ km
$\varepsilon_c = 0.75 = .056H$	$4 < H < 11$ km

Idso and Jackson (1969) developed an alternative expression relating sky emissivity to air temperature. The reasoning behind their formula is that sky radiation is mainly a function of humidity ratio in the lower atmosphere. Because humidity ratio can be correlated with air temperature, the following equation was generated

$$\varepsilon_o = 1 - 0.216 \times \exp[-7.77\times10^{-4} \times \{5/9 \times (T_{air} - 32)\}^2]$$

This function accounts for the freezing of water vapor in the air at temperatures below 32 degrees F

The net long-wave radiation exchange between the ground surface (horizontal grey surface) and the sky can be linearized. Defining

$$\Delta T_R = T_{air} - T_{surf} \tag{13}$$

and

$$\Delta T_s = T_{air} - T_{sky} \tag{14}$$

and then substituting the above two expressions into Equation 4 yields

$$Q_{l.w.} = \sigma\varepsilon_s [(T_{air}-\Delta T_R)^4 - (T_{air}-\Delta T_s)^4] \tag{15}$$

where

ε_s = ground surface emissivity
σ = Stefan-Boltzmann constant (0.1714×10^{-8} Btu/hr-ft^2-R^4)

If ΔT_R and ΔT_s are assumed small, then the above equation, after expansion and neglecting terms second order or above in ΔT_R and ΔT_s, becomes

$$Q_{l.w.} = 4\sigma\varepsilon_s T_{air}^3 [\Delta T_s - \Delta T_R] \tag{16}$$

Substituting Equations 13, 24 and 6 into the above expression yields

$$Q_{l.w.} = 4\varepsilon_s \sigma T_{air}^4 (1-\varepsilon^{1/4}) + 4\varepsilon_s \sigma T_{air}^3 (T_{sur}-T_{air}) \tag{17}$$

The first term on the right side of equation (17) is proportional to sky temperature depression and can be treated as a negative solar load, The second term is proportional to the radiative surface depression and can be combined with the convective heat transfer component. The radiative heat transfere coefficient is defined as

$$h_r = 4\varepsilon_s \sigma T_{air}^3 \tag{18}$$

so that equation 17 becomes

$$Q_{l.w.} = 4\varepsilon_s \sigma T_{air}^4 (1-\varepsilon^{1/4}) + h_r (T_{sur}-T_{air}) \tag{19}$$

Values for the ground surface emissivity and air temperature are needed to calculate h_r. The sky temperature depression term requires the same input values as h_r, plus cloud cover fraction, cloud cover base height (ceiling) or temperature and dew point temperature. These weather data inputs are sometimes available on NOAA weather data records or data tapes.

Convective Heat Transfer

The determination of the forced convective heat transfer coefficient for a neutrally stable atmosphere is based on the Reynolds and Colburn analogies. These relationships require the thermal properties of the air, plus local wind speed and surface roughness. The Colburn analogy states

$$h_c = (C_f/2)\rho c_p (Pr)^{-2/3} U \tag{20}$$

where

C_f = local drag coefficient
ρ = air density, which is calculated based on ambient air temperature and pressure ($\rho = P/RT_{air}$)
c_p = specific heat of air (0.24 Btu/lb-F°)
Pr = Prandtl number of air (0.71)
U = wind speed

Schlichting (1960) published the results of a study by Paeschke (1937) relating surface roughness to the drag coefficient as follows.

$$C_f/2 = [2.5 \ln (5.25/z_o) + 5]^{-2} \tag{21}$$

This relationship assumes the wind speed is measured at a height of 5.25 feet. z_o is the physical height of vegetation or surface roughness in feet.

For smooth surfaces exposed to the outside winds, McAdams (1954) presents a dimensional relationship for the convective heat transfer coefficient as

$$h_c = 1 + .3U \qquad [\text{Btu/hr-ft}^2\text{-F}°] \tag{22}$$

where U is wind speed in miles per hour.

The heat transported by convection is governed by Newton's Law of Cooling or

$$Q_{conv} = h_c (T_{sur}-T_{air}) \tag{23}$$

A portion of the radiative flux from the previous section can also be included in this term as

$$Q = (h_c+h_r) (T_{sur}-T_{air}) \tag{24}$$

The tern $(h_c + h_r)$ can be interpreted as the surface conductance h.

Latent Heat

Energy transfers can be significant by latent heat changes due to evaporation, condensation and sublimation. However, calculations of evaporation, condensation and sublimation rates are very difficult to make. In some cases it is possible to use the Reynolds analogy between heat and mass transfer to predict a convective mass transfer coefficient, h_m.

$$h_m = h_c/\rho c_p Le^{2/3} \tag{25}$$

Where Le = a/D is the Lewis number and

ρ = density of air

c_p = specific heat of air

a = thermal diffusivity of air

D = mass diffusivity of water in air

For a water-air system, the ratio a/D is equal to about .85 from which the value of the convective mass transfer coefficient can be easily calculated.

The rate of heat transfer by evaporation or condensation is then expressed as

$$Q_l = h_m \rho h_{fg} (W_{sur} - W_{air}) \quad (26)$$

where

h_{fg} = enthalpy of vaporization of water
W_{sur} = surface hunidity ratio
W_{air} = ambient hunidity ratio

Practically speaking, it is very difficult to assess the surface hunidity ratio. It would require a moisture balance at the surface, and the available mechanistic relationships are not vary accurate in predicting moisture movement in the ground. Because of these difficulties, a term has **been** included in the energy balance that must be user specified. Evaporation rates of **25%** to **50%** of the precipitation have been specified in past simulations (Miller, 1975).

Snow Laver

The surface energy balance is significantly affected by the presence of a snow cover. Snow provides an insulating blanket on the ground surface. Its thermal resistance can be approximated **as**

$$R_{snow} = \frac{d}{k}$$

where

d = depth of snow
k = thermal conductivity of snow

The thermal conductivity of snow can be approxirmted as

$$k = 0.41 \text{ (S.G.) } [\text{Btu/hr-ft-°F}]$$

in which S.G. is specific gravity of the snow. The insulating effect of the *snow* cover can be included in the surface conductance, h; i.e.,

$$\frac{1}{h} = \frac{1}{h_r + h_c} + R_{snow}$$

The alternative to this approach is to extend the conduction zone to the surface of the snow layer an compute the surface energy balance based on the snow surface conditions. This is easily done in finite element or finite difference sinulations by specifying the thermal conductivity of the snow layer large and specific heat small during spring, summer and fall when no snow is present. The result of doing this is "fooling" the program that those elements have little thermal resistance and small heat capacity.

The radiative properties of snow affect the radiation terms. Snow has a high albedo and a high emissivity. Therefore, it reflects much of the incoming solar as well as being a good emitter in the infrared range. These characteristics can be easily accounted for in the surface energy balance radiation terms. See Table I for radiation properties of snow.

5. SUMMARY

The license to operate the computer program GEODYN and its associated programs GEOGRD and GEOPLT was obtained from Resource Management Associates, and installed on the University of Alaska-Fairbanks VAX 11/730 computer for verification. The programs form an extremely powerful tool for calculating the temperature distribution within a soil mass as a function of time due to a variety of boundary conditions. The programs are written in a user-friendly manner. However, due to the versatility of the capabilities of the programs, a significant effort is required to use them. It might take a week or more to get meaningful results the first time the program is used. It will probably take several days to get meaningful results after the user becomes familiar with the programs.

The programs are more powerful than most other programs that are readily available. Some of the features are as follows:

1. Surface energy balance calculations across selected boundaries.
2. Variable temperatures at selected nodes.
3. variable thermal fluxes across selected boundaries.
4. Heat transfer due to groundwater flow.
5. Freezing over a temperature range.
6. Restart capabilities so that parameters can be changed during a run.

The programs appear to be sufficienty accurate for engineering purposes on problems associated with road construction in Alaska, as long as the appropriate input parameters are used.

6. IMPLEMENTATION

The programs are ready to use at the present time. We suggest that they be used carefully by users who have the time and knowledge and patience to verify the results. They should not be used casually or for answers that are needed in a hurry. The programs should be used only in those situations that do not lend themselves to simplified solutions. It would not be cost effective to use the programs to calculate the depth of thaw in an area with a uniform boundary and no unusual boundary conditions. The modified Berqgren solution would probably be as accurate and would certainly be less costly. Problems involving complex geometry, complex material properties, or external sources of heat such as thermal syphons do not lend themselves to simplified solutions, and **GEODYN** would be an appropriate tool to use.

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APPENDIX A

Alaskan SOMET Data for 17 Locations

ANCHORAGE ALASKA LATITUDE: 61.1

	TEMP. (DEG F) AVE	TEMP. (DEG F) MIN	TEMP. (DEG F) MAX	HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	13.0	6.0	20.0	N/A	1612	6.1	66.0	14.4	N/A	9.[illegible]
FEB	17.9	10.3	25.5	N/A	1319	6.7	70.0	8.5	N/A	9.9
MAR	23.7	15.7	31.7	N/A	1280	6.7	67.0	5.2	N/A	11.1
APR	35.4	28.2	42.6	N/A	888	7.2	71.0	N/A	N/A	25.0
MAY	46.3	38.3	54.2	N/A	580	8.3	77.0	N/A	N/A	32.0
JUN	54.4	47.0	61.8	N/A	318	8.2	80.0	N/A	N/A	42.5
JUL	58.1	51.1	65.[illegible]	N/A	214	7.1	79.0	N/A	N/A	48.0
AUG	56.2	49.2	63.2	N/A	273	6.6	79.0	N/A	N/A	46.5
SEP	48.2	41.1	55.2	N/A	504	6.3	78.0	N/A	N/A	40.0
OCT	34.6	28.4	40.8	N/A	942	6.5	77.0	0.2	N/A	28.8
NOV	21.7	15.4	27.9	N/A	1299	6.1	74.0	2.1	N/A	15.5
DEC	13.8	7.1	20.4	N/A	1587	5.9	71.0	7.9	N/A	5.6

ANNETTE ALASKA LATITUDE: 55.03

	TEMP. (DEG F) AVE	MIN	MAX	HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	33.5	29.0	38.0	178	976	12.1	79.0	N/A	N/A	27.4
FEB	36.7	31.8	41.5	374	792	12.2	81.0	N/A	N/A	30.8
MAR	38.3	32.8	43.7	716	828	11.0	79.0	N/A	N/A	31.5
APR	42.8	36.7	48.8	1148	666	11.3	79.0	N/A	N/A	35.8
HAY	49.4	42.6	56.2	1471	484	9.4	77.0	N/A	N/A	42.2
JUN	54.6	48. ▮	61.0	1464	319	9.0	80.0	N/A	N/A	47.9
JUL	57.8	51.6	64.0	1437	230	8.1	78.0	N/A	N/A	51.5
AUG	58.3	51.9	64.6	1161	211	8.3	77.0	N/A	N/A	52.6
SEP	53.9	48. ▮	59.8	811	329	9.3	78.0	N/A	N/A	48.8
OCT	46.9	42.1	51.7	422	562	12.0	86.0	N/A	N/A	42.1
NOV	39.9	35.5	44.3	218	752	12.4	84.0	N/A	N/A	34.4
DEC	35.8	31.6	40.1	122	902	12.7	84.0	N/A	N/A	30.5

BARROW ALASKA LATITUDE: 71.3

	TEMP. (DEG F) AVE	TEMP. (DEG F) MIN	TEMP. (DEG F) MAX	HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	-14.7	-21.3	-8.0	0	2471	11.3	0.0	9.6	N/A	-21.2
FEB	-18.6	-24.6	-12.6	74	2341	11.0	52.0	14.8	N/A	-25.8
MAR	-15.2	-21.8	-8.6	490	2485	11.1	47.0	14.2	N/A	-22.0
APR	-0.8	-8.2	6.5	1050	1976	11.4	56.0	17.0	N/A	-6.2
MAY	19.1	14.0	24.2	1138	1423	11.6	83.0	14.7	N/A	16.0
JUN	33.0	28.9	37.1	1526	960	11.4	80.0	N/A	N/A	30.8
JUL	38.7	33.0	44.3	1457	815	11.6	78.0	N/A	N/A	36.2
AUG	37.6	33.1	42.0	855	850	12.3	89.0	N/A	N/A	35.7
SEP	30.3	27.2	33.4	414	1040	13.0	92.0	N/A	N/A	28.2
OCT	15.3	10.4	20.2	126	1540	13.2	86.0	0.8	N/A	11.8
NOV	-0.5	-6.4	5.4	4	1965	12.4	0.0	5.6	N/A	-5.3
DEC	-12.3	-18.1	-6.4	0	2395	11.2	0.0	9.1	N/A	-18.5

BETHEL ALASKA **LATITUDE:** 60.78

	TEMP. (DEG F)			HO BTU/ FT'2	HDD P-DAY	WIND SPEED HPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG P
	AVE	HIN	MAX							
JAN	5.[illegible]	-2.2	12.3	97	1857	14.3	65.0	14.2	N/A	-0.6
FEB	8.[illegible]	0.5	15.8	316	1590	15.1	60.0	14.8	N/A	2.0
MAR	11.4	2.5	20.3	738	1661	14.0	61.0	17.0	N/A	6.1
APR	24.5	16.3	32.7	1200	1215	13.4	69.0	14.7	N/A	19.8
MAY	40.[illegible]	31.7	40.5	1451	772	11.7	76.0	N/A	N/A	33.7
JUN	51.6	43.0	60.2	1516	401	11.6	81.0	N/A	N/A	44.5
JUL	54.7	47.4	61.9	1288	319	11.3	85.0	N/A	N/A	49.0
AUG	52.3	46.0	58.5	920	394	11.0	86.0	N/A	N/A	48.[illegible]
SEP	45.0	38.2	51.8	700	600	11.6	82.0	H/A	N/A	40.8
OCT	30.2	24.3	36.[illegible]	370	1078	12.5	79.0	0.3	N/A	26.2
NOV	17.2	10.8	23.6	135	1434	13.4	74.0	2.0	N/A	12.8
DEC	4.4	-2.5	11.3	49	1880	14.2	65.0	8.7	N/A	-1.4

BETTELS ALASKA LATITUDE: 66.91

	TEMP.(DEG F) AVE	MIN	MAX	HO BTU/ FT^2	HDD P-DAY	HIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	-13.2	-21.1	-5.3	10	2424	5.9	47.0	N/A	N/A	-19.4
PEB	-7.8	-16.5	1.0	172	2037	7.1	58.0	N/A	N/A	-14.7
MAR	1.4	-10.0	12.9	615	1970	7.3	61.0	31.0	12.1	-6.3
APR	20.5	9.2	31.7	1227	1335	7.6	60.0	32.0	13.3	12.0
MAY	41.7	31.7	51.6	1697	722	7.6	62.0	N/A	N/A	28.3
JUN	56.2	45.1	67.2	1855	270	6.9	66.0	N/A	N/A	43.2
JUL	57.9	47.5	68.2	1561	230	6.6	76.0	N/A	N/A	47.0
AUG	51.9	42.9	60.9	1074	407	6.2	80.0	N/A	N/A	44.4
SEP	40.0	31.7	48.2	672	750	6.6	67.0	N/A	N/A	33.2
OCT	20.0	13.3	26.6	252	1395	6.5	76.0	N/A	N/A	14.3
NOV	-1.4	-8.6	5.8	40	1992	6.0	60.0	N/A	N/A	-6.7
DEC	-12.2	-20.0	-4.3	0	2392	6.0	64.0	N/A	N/A	-18.0

BIG DELTA **ALASKA** **LATITUDE:** 64. 82

	TEMP. (DEG		PI	HO BTU/ FT^2	HDD P-DAY	WIND SPEED HPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	-4.9	-12.3	2.5	46	2167	10.8	44.0	N/A	N/A	-11.6
FEB	3.4	-5.6	12.4	247	1724	9.9	70.0	14.0	9. 8	-3. 1
MAR	12.3	1. 1	23.4	711	1634	8.2	61.0	16.0	10. 5	4.1
APR	29.3	19.4	39.3	1243	1067	7.6	79.0	14.0	12. 0	17. 6
HAY	46. 3	36. 3	56.2	1668	580	7.9	74.0	2.0	12. 5	30. 7
JUN	57. [illegible]	47.1	67.1	1780	257	6.5	72.0	N/A	N/A	42. 0
JUL	59.4	50.0	68.8	1612	182	6.0	81.0	N/A	N/A	49. 2
AUG	54.8	45.4	64.1	1227	322	6.6	78.0	N/A	N/A	45. [illegible]
SEP	43.6	35.2	51.9	766	643	7.3	72.0	N/A	N/A	35. 3
OCT	25.2	18.2	32.1	326	1234	8.5	79. 0	N/A	N/A	18. 8
NOV	6.9	-0.3	14.1	93	1742	9.5	68.0	N/A	N/A	1.6
DEC	-4.2	-11.5	3.2	9	2145	9.5	66.0	N/A	N/A	-9. 9

FAIRBANKS ALASKA LATITUDE: 64.82

	TEMP.(DEG PI AVE	MIN	MAX	HO BTU/ PT"2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	-11.9	-21.6	-2.2	30	2383	3.0	60.0	14.3	N/A	-19.1
PEB	-2.5	-14.3	9.3	221	1890	4.1	62.0	21.5	N/A	-11.0
UAR	9.5	-4.3	23.3	674	1720	5.2	60.0	20.5	N/A	-0.9
APR	28.9	1.7.3	40.4	1192	1083	6.6	67.0	15.8	N/A	15.7
MAY	47.3	35.7	58.8	1602	549	7.8	69.0	2.0	N/A	29.6
JUN	58.9	47.2	70.7	1750	210	7.1	74.0	N/A	N/A	43,1
JUL	60.7	49.6	71.8	1541	148	6.6	75.0	N/A	N/A	48.7
AUG	55.4	44.9	65.8	1116	304	6.1	78.0	N/A	N/A	46.0
SEP	44.4	34.4	54.4	709	617	6.2	75.0	0.2	N/A	35.0
OCT	25.2	16.9	33.5	292	1234	5.5	81.0	0.2	N/A	18.0
NOV	2.8	-6.2	11.7	74	1866	3.9	70.0	3.5	N/A	-3.9
DEC	-10.4	-19.3	-1.5	3	2336	3.1	68.0	9.1	N/A	-17,4

GULKANA ALASKA LATITUDE: 62.15

	TEMP. (DEG F) AVE	MIN	MAX	HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	-7.3	-16.4	1.9	73	2241	5.1	47.0	N/A	N/A	-14.1
FEB	3.9	-6.9	14.7	286	1711	5.6	70.0	N/A	N/A	-2.6
MAR	14.5	0.8	28.1	757	1564	6.5	60.0	N/A	N/A	6.1
APR	30.2	18.5	41.8	1303	1044	8.6	68.0	N/A	N/A	18.9
MAY	43.8	32.5	55.1	1612	657	8.8	72.0	N/A	N/A	29.7
JUN	54.2	42.4	66.0	1756	333	8.8	74.0	N/A	N/A	39.4
JUL	56.9	45.6	68.1	1610	254	8.2	72.0	N/A	N/A	45.6
AUG	53.2	42.1	64.3	1250	365	8.0	74.0	N/A	N/A	42.9
SEP	43.6	33.5	53.7	795	643	7.6	68.0	N/A	N/A	34.8
OCT	26.8	17.8	35.7	390	1184	6.3	78.0	N/A	N/A	20.9
NOV	6.1	-1.6	13.8	116	1767	4.8	75.0	N/A	N/A	1.6
DEC	-5.1	-13.1	3.0	28	2172	3.6	67.0	N/A	N/A	-11.3

HOHER **ALASKA** LATITUDE: 59.63

	TEMP. (DEG F)			HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	21.4	14.7	28.0	122	1351	7.8	67.0	N/A	N/A	15.8
FEB	24.8	17.9	31.8	334	1123	7.7	68.0	N/A	N/A	19.2
MAR	27.6	20.2	35.0	759	1159	7.4	69.0	N/A	N/A	21.6
APR	35.0	27.7	42.3	1247	900	7.3	71.0	N/A	N/A	28.5
MAY	42.3	34.2	50.3	1581	704	7.7	78.0	N/A	N/A	35.7
JUN	48.7	40.7	56.7	748	490	7.0	73.0	N/A	N/A	42.1
JUL	52.3	44.5	60.1	1596	394	6.8	75.0	N/A	N/A	46.6
AUG	52.4	44.6	60.1	1187	391	5.7	72.0	N/A	N/A	47.4
SEP	47.0	39.2	54.8	791	540	6.2	73.0	N/A	N/A	42.1
OCT	37.3	30.3	44.4	437	857	6.8	75.0	N/A	N/A	32.1
NOV	28.2	21.8	34.5	175	1103	7.5	72.0	N/A	N/A	23.2
DEC	21.4	15.2	27.6	64	1351	7.1	67.0	N/A	N/A	16.4

JUNEAU ALASKA LATITUDE: 58.37

	TEMP.(DEG F)			HO BTU/ FT^2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	23.5	17.8	29.1	116	1287	8.3	76.0	5.0	N/A	18.2
FEB	28.0	22.1	33.9	282	1036	8.6	81.0	3.8	N/A	22.9
MAR	31.9	25.6	38.2	609	1026	8.6	82.0	3.7	N/A	26.3
APR	38.9	31.3	46.5	1044	783	8.8	82.0	0.8	N/A	32.5
MAY	46.8	38.2	55.4	1290	563	8.4	80.0	N/A	N/A	40.0
JUN	53.2	44.4	62.0	1413	355	7.7	81.0	N/A	N/A	46.3
JUL	55.7	47.7	63.6	1277	288	7.5	83.0	N/A	N/A	49.8
AUG	54.3	46.2	62.3	983	331	7.4	80.0	N/A	N/A	49.5
SEP	49.2	42.3	56.[illegible]	638	473	8.0	85.0	N/A	N/A	45.7
OCT	41.8	36.4	47.2	320	718	9.6	89.0	N/A	N/A	38.5
NOV	32.5	27.6	37.3	149	976	8.5	84.0	0.1	N/A	28.6
DEC	27.3	22.5	32.0	62	1168	9.0	85.0	1.6	N/A	22.7

KING SALMON ALASKA LATITUDE: 58.68

	TEMP. (DEG F)			HO BTU/ PT`2	HDD P-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	13.4	5.7	21.0	146	1600	10.6	66.0	N/A	N/A	6.7
FEB	16.6	8.6	24.6	377	1355	11.1	66.0	N/A	N/A	9.3
MAR	20.4	12.1	28.6	798	1382	11.4	67.0	N/A	N/A	13.2
APR	31.5	23.8	39.[illegible]	1204	1004	11.1	77.0	N/A	N/A	23.9
MAY	42.6	33.8	51.3	1480	695	11.3	81.0	N/A	N/A	33.4
JUN	50.7	41.7	59.7	1539	428	10.8	85.0	N/A	N/A	42.6
JUL	54.5	46.4	62.5	1382	326	10.[illegible]	86.0	N/A	N/A	47.3
AUG	53.8	46.7	60.9	1044	347	10.[illegible]	86.0	N/A	N/A	47.7
SEP	47.3	39.7	54.8	777	531	10.5	83.0	N/A	N/A	41.3
OCT	33.6	26.3	40.8	473	974	10.5	76.0	N/A	N/A	27.7
NOV	22.[illegible]	15.1	29.0	204	1287	10.8	72.0	N/A	N/A	16.8
DEC	11.7	3.8	19.6	91	1652	10.3	68.0	N/A	N/A	5.5

RODIAK ALASKA LATITUDE: 57.75

	TEMP. (DEG F)			HO BTU/ FT^2	HDD F-DAY	WIND SPEED WPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	30.4	26.3	34.5	149	1072	12.6	71.0	2.0	N/A	25.0
FEB	31.4	27.0	35.7	355	941	12.1	72.0	[illegible]	N/A	25.b
MAR	[illegible]	27.2	36.9	781	1020	11.9	73.0	1.4	N/A	25.7
APR	36.9	32.2	41.6	1206	842	11.0	74.0	0.2	N/A	30.2
HAY	43.2	38.5	47.9	1374	677	10.3	83.0	N/A	N/A	37.2
JUN	49.7	44.7	54.6	1528	459	8.6	77.0	N/A	N/A	43.9
JUL	54.1	[illegible]	59.1	1406	338	7.2	80.0	N/A	N/A	49.2
AUG	54.9	49.7	60.1	1163	313	7.6	75.0	N/A	N/A	49.9
SEP	50.0	45.0	54.9	793	450	9.2	75.0	N/A	N/A	44.7
OCT	40.7	35.8	45.6	489	752	10.9	71.0	N/A	N/A	34.3
NOV	34.8	30.5	39.0	206	905	12.2	70.0	0.1	N/A	29.0
DEC	29.9	25.5	34.3	97	1087	10.5	70.0	0.4	N/A	23.0

KOTZEBUE ALASKA LATITUDE: 66.86

	TEMP. (DEG F)			HO BTU/ FT^2	HDD	WIND SPEED	CLOUD COVER	SNOW DEPTH	DENS LB/	DEW PT TEMP
	AVE	MIN	MAX	FT^2	F-DAY	MPH	%	IN.	FT^3	DEG F
JAN	-3.7	-10.6	3.2	8.5	2129	14.7	59.0	N/A	N/A	-10.0
FEB	-4.3	-11.8	3.3	164	1940	12.7	53.0	N/A	N/A	-10.5
MAR	-0.5	-9.1	8.[illegible]	594	2030	12.4	56.0	N/A	N/A	-6.6
APR	13.0	3.7	22.3	1180	1560	12.6	59.0	N/A	N/A	7.7
MAY	30.8	23.7	37.8	1641	1060	10.9	62.0	N/A	N/A	26.2
JUN	43.4	37.3	49.6	1834	644	12.4	68.0	N/A	N/A	39.0
JUL	52.9	47.1	58.7	1526	374	12.9	75.0	N/A	N/A	47.8
AUG	50.7	45.4	55.9	1043	443	13.2	79.0	N/A	N/A	46.0
SEP	41.1	35.7	46.5	648	716	13.2	73.0	N/A	N/A	36.2
OCT	23.6	18.5	28.7	256	1283	13.6	69.0	N/A	N/A	18.8
NOV	7.7	2.0	13.4	33	1719	14.6	67.0	N/A	N/A	2.4
DEC	-3.9	-10.3	2.6	0	2136	12.8	58.0	N/A	N/A	-9.8

MATANUSKA ALASKA LATITUDE: 61.57

	TEMP. (DEG F)			HO BTU/ FT'2	HDD F-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	-8.9	-18.2	0.5	118	1645	9.2	75.0	N/A	N/A	-15.0
FEB	-0.2	-11.2	10.9	339	1285	10.9	71.0	N/A	N/A	-8.0
MAR	8.9	-4.3	22.0	892	1240	12.2	70.0	N/A	N/A	-0.5
APR	26.5	15.3	37.7	1312	858	12.3	70.0	N/A	N/A	17.0
MAY	44.1	33.6	54.5	1606	558	14.7	59.0	N/A	N/A	29.5
JUN	55.7	45.2	66.1	1702	303	12.7	53.0	N/A	N/A	41.5
JUL	58.2	48.7	67.7	1507	232	12.4	56.0	N/A	N/A	46.0
AUG	53.5	44.9	62.1	1157	304	12.6	59.0	N/A	N/A	45.0
SEP	43.8	35.2	52.3	730	518	10.9	62.0	N/A	N/A	35.5
OCT	25.3	18.2	32.4	369	947	12.4	68.0	N/A	N/A	20.2
NOV	5.0	-2.9	12.9	140	1328	12.9	75.0	N/A	N/A	1.0
DEC	-9.2	-17.6	-0.8	55	1627	13.2	79.0	N/A	N/A	-14.0

MCGRATH ALASKA LATITUDE: 62.97

	TEMP. (DEG F)			HO BTU/ FT^2	HDD	WIND SPEED	CLOUD COVER	SNOW DEPTH	DENS LB/	DEW PT TEMP
	AVE	MIN	MAX	FT^2	P-DAY	MPH	%	IN.	FT^3	DEG P
JAN	-10.2	-19.4	-1.[illegible]	58	2291	2.9	62.0	N/A	N/A	-22.0
FEB	-2.5	-14.0	9.[illegible]	258	1825	4.2	61.0	N/A	N/A	-6.0
MAR	8.2	-5.2	21.5	692	1738	5.1	62.0	N/A	N/A	-2.0
APR	26.7	15.9	37.5	1186	1155	6.4	66.0	N/A	N/A	15.2
MAY	44.6	34.3	54.9	1486	648	6.5	73.0	N/A	N/A	30.5
JUN	55.2	45.0	65.5	1585	284	6.2	79.0	N/A	N/A	42.3
JUL	58.2	48.4	68.0	1378	219	6.0	80.0	N/A	N/A	48.0
AUG	54.4	45.1	52.7	1018	356	5.6	82.0	N/A	N/A	46.5
SEP	44.0	35.2	63.8	695	635	5.7	79.0	N/A	N/A	35.8
OCT	25.0	18.0	31.8	316	1231	5.2	82.0	N/A	N/A	18.8
NOV	5.5	-2.5	13.4	100	1800	3.6	73.0	N/A	N/A	-2.0
DEC	-9.4	-17.8	-0.8	20	2300	3.0	66.0	N/A	N/A	-13.0

NOME ALASKA LATITUDE: 64.5

	TEMP. (DEG F)			HO BTU/ FT^2	HDD P-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	6.0	-1.6	13.5	30	1828	11.7	63.0	14.7	N/A	-0.7
FEB	5.2	-3.3	13.7	224	1674	11.0	54.0	22.9	N/A	-2.4
MAR	7.4	-1.9	16.6	630	1785	10.4	58.0	26.0	N/A	0.2
APR	18.9	10.8	27.0	1184	1382	10.6	62.0	34.5	N/A	12.0
MAY	34.8	28.1	41.4	1571	936	10.2	66.0	17.4	N/A	26.5
JUN	45.5	38.8	52.2	1751	585	10.0	69.0	N/A	N/A	37.2
JUL	50.1	44.4	55.8	1412	463	10.0	77.0	N/A	N/A	42.6
AUG	49.2	43.7	54.6	992	490	10.5	81.0	N/A	N/A	42.4
SEP	42.1	35.9	48.2	673	688	11.1	75.0	N/A	N/A	34.3
OCT	28.5	22.6	34.4	306	1132	11.0	69.0	N/A	N/A	21.4
NOV	15.6	9.1	22.1	65	1481	12.0	71.0	1.7	N/A	8.9
DEC	4.4	-3.0	11.7	3	1880	10.3	60.0	8.[illegible]	N/A	-2.8

SUMMIT ALASKA LATITUDE: 63.33

	TEMP. (DEG F) AVE	MIN	MAX	HO BTU/ FT^2	HDD F-DAY	HIND SPEED MPH	CLOUD COVER %	*SNOW DEPTH IN.	*DENS LB/ FT^3	DEW PT TEMP DEG F
JAN	[illegible].6	-4.8	7.9	56	1965	15.[illegible]	52.0	N/A	N/A	-5.6
FEB	6.6	-0.4	13.5	251	1634	11.9	70.0	28.0	13.2	1.0
MAR	11.2	3.0	19.4	697	1668	11.1	62,0	32.0	13.1	5.0
APR	23.5	14.[illegible]	32.9	1238	1245	7.6	72,0	32.5	14.8	16.9
MAY	37.4	2'9.[illegible]	45.7	1631	857	7.7	75.0	32.0	17.2	28.9
JUN	49.0	39.9	58.0	1637	481	8.3	82.0	N/A	N/A	40.0
JUL	52.0	43.8	60.2	1409	403	7.8	82.0	N/A	N/A	44.8
AUG	48.7	41.4	56.0	1042	508	7.4	83.0	N/A	N/A	42.[illegible]
SEP	39.8	32.6	47.[illegible]	703	752	7.5	74.0	N/A	N/A	33.1
OCT	24.0	17,5	30.4	344	1270	8.0	76.0	N/A	N/A	19.4
NOV	9.7	3.7	15.7	107	1659	11.3	71.0	N/A	N/A	4.9
DEC	2.9	-3.4	9.2	17	1924	12.7	65.0	N/A	N/A	-2.2

* DATA TAKEN FROM PAXON STATION

YUKATAT ALASKA LATITUDE: 59.52

	TEMP. (DEG F)			HO BTU/ FT^2	HDD P-DAY	WIND SPEED MPH	CLOUD COVER %	SNOW DEPTH IN.	DENS LB/ FT^3	DEW PT TEMP DEG F
	AVE	MIN	MAX							
JAN	24.2	17.1	31.2	100	1265	7.6	76.0	N/A	N/A	19.1
FEB	28.0	20.9	35.0	265	1036	7.8	79.0	N/A	N/A	23.5
MAR	30.3	22.6	37.9	623	1076	7.3	79.0	N/A	N/A	25.8
APR	30.3	22.6	37.9	1049	868	7.3	79.0	N/A	N/A	25.7
HAY	36.▮	28.5	43.6	1266	673	7.8	04.0	N/A	N/A	31.7
JUN	43.3	35.7	50.8	1343	459	7.3	86.0	N/A	N/A	39.3
JUL	49.7	43.0	56.4	1206	360	6.8	86.0	N/A	N/A	46.5
AUG	53.4	47.4	59.3	941	375	6.5	83.0	N/A	N/A	50.5
SEP	48.4	41.4	55.4	634	499	7.1	85.0	N/A	N/A	45.8
OCT	40.7	34.▮	47.3	344	752	8.3	86.0	N/A	N/A	37.6
NOV	32.2	26.2	38.2	135	985	7.8	82.0	N/A	N/A	28.6
DEC	26.7	20.7	32.7	51	1186	8.1	81.0	N/A	N/A	22.4

APPENDIX B

Calculated "R" Values
for
the 17 Alaskan SOMET Sites

ANNETTE

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.20	1.39	1.57	1.75	2.06	2.43
FEB	1.12	1.23	1.34	1.44	1.62	1.81
MAR	1.07	1.13	1.20	1.25	1.34	1.42
APR	1.04	1.07	1.10	1.13	1.15	7.15
MAY	1.03	1.04	1.05	1.05	1.05	1.00
JUN	1.02	1.03	1.03	1.03	1.01	0.94
JUL	1.02	1.03	1.04	1.04	1.02	0.97
AUG	1.03	1.05	1.07	1.09	1.10	1.07
SEP	1.05	1.10	1.14	1.18	1.24	1.28
OCT	1.09	1.17	1.25	1.33	1.46	1.58
NOV	1.17	1.33	1.49	1.64	1.90	2.21
DEC	1.21	1.41	1.61	1.79	2.12	2.52

AZIMUTH ANGLE=45

TILT ANGLE

5	10	15	20	30	45
1.14	1.27	1.40	1.52	1.73	1.96
1.08	1.16	1.24	1.30	1.42	1.53
1.04	1.09	1.13	1.17	1.23	1.27
1.03	1.05	1.07	1.09	1.10	1.09
1.02	1.03	1.04	1.04	1.03	0.99
1.02	1.02	1.02	1.02	1.00	0.94
1.02	1.02	1.03	1.03	1.01	0.96
1.02	1.04	1.05	1.06	1.06	1.03
1.03	1.07	1.10	1.12	1.16	1.17
1.06	1.12	1.17	1.22	1.30	1.37
1.12	1.23	1.34	1.44	1.62	1.81
1.15	1.29	1.43	1.55	1.77	2.03

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.01	1.01	1.02	1.02	1.04	1.04
FEB	0.99	0.99	0.99	0.99	0.99	0.97
MAR	0.99	0.99	0.98	0.98	0.96	0.93
APR	1.00	0.99	0.99	0.98	0.96	0.91
MAY	1.00	1.00	0.99	0.98	0.96	0.90
JUN	1.01	1.00	1.00	0.98	0.96	0.90
JUL	1.01	1.00	0.99	0.98	0.96	0.90
AUG	1.00	0.99	0.99	0.98	0.95	0.90
SEP	0.99	0.99	0.98	0.97	0.96	0.92
OCT	0.99	0.99	0.99	0.98	0.97	0.94
NOV	1.00	1.00	1.01	1.01	1.02	1.02
DEC	1.01	1.01	1.02	1.03	1.04	1.04

AZIMUTH ANGLE=135

TILT ANGLE

5	10	15	20	30	45
0.87	0.75	0.66	0.59	0.52	0.50
0.91	0.82	0.74	0.68	0.59	0.52
0.94	0.88	0.82	0.76	0.67	0.57
0.96	0.93	0.89	0.84	0.76	0.65
0.99	0.97	0.94	0.91	0.84	0.73
1.00	0.99	0.96	0.94	0.88	0.77
1.00	0.98	0.95	0.93	0.86	0.75
0.98	0.95	0.91	0.88	0.80	0.70
0.95	0.90	0.85	0.80	0.72	0.62
0.92	0.86	0.79	0.73	0.64	0.56
0.88	0.77	0.69	0.62	0.51	0.51
0.87	0.75	0.66	0.60	0.58	0.55

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.81	0.63	0.54	0.54	0.52	0.50
FEB	0.87	0.74	0.62	0.51	0.48	0.45
MAR	0.91	0.83	0.74	0.65	0.46	0.41
APR	0.95	0.90	0.85	0.79	0.66	0.45
MAY	0.98	0.95	0.92	0.88	0.79	0.63
JUN	1.00	0.98	0.95	0.93	0.86	0.72
JUL	0.99	0.97	0.94	0.91	0.83	0.68
AUG	0.97	0.93	0.89	0.84	0.73	0.55
SEP	0.93	0.87	0.80	0.72	0.57	0.43
OCT	0.89	0.79	0.69	0.59	0.50	0.48
NOV	0.83	0.67	0.54	0.53	0.51	0.49
DEC	0.81	0.64	0.60	0.60	0.58	0.55

BARROW

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	0.00	0.00	0.00	0.00	0.00	0.00
FEB	1.64	2.25	2.85	3.42	4.51	5.88
MAR	1.20	1.40	1.60	1.78	2.12	2.51
APR	1.08	1.16	1.23	1.29	1.39	1.48
MAY	1.00	1.02	1.04	1.05	1.07	1.06
JUN	0.99	1.02	1.03	1.05	1.07	1.06
JUL	1.00	1.02	1.04	1.06	1.08	1.07
AUG	1.05	1.09	1.13	1.16	1.20	1.22
SEP	1.09	1.18	1.26	1.34	1.47	1.61
OCT	1.31	1.62	1.91	2.19	2.71	3.35
NOV	0.00	0.00	0.00	0.00	0.00	0.00
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE=45

TILT ANGLE

	5	10	15	20	30	45
JAN	0.00	0.00	0.00	0.00	0.00	0.00
FEB	1.45	1.88	2.30	2.71	3.46	4.40
MAR	[illegible]14	1.29	1.43	1.57	1.81	2.09
APR	1.06	1.12	1.17	1.23	1.31	1.39
MAY	0.99	1.00	1.02	1.03	1.04	1.02
JUN	0.99	1.00	1.01	1.02	1.04	1.02
JUL	0.99	1.00	1.02	1.03	1.04	1.03
AUG	1.04	1.07	1.10	1.12	1.16	1.77
SEP	1.06	1.13	1.19	1.24	1.34	1.43
OCT	1.22	1.43	1.64	1.84	2.20	2.63
NOV	0.00	0.00	0.00	0.00	0.00	0.00
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	0.00	0.00	0.00	0.00	0.00	0.00
FEB	1.04	1.10	1.17	1.25	1.42	1.62
MAR	1.00	1.01	1.04	1.08	1.15	1.24
APR	1.01	1.01	1.02	1.03	1.06	1.09
MAY	0.97	0.97	0.96	0.95	0.94	0.91
JUN	0.97	0.97	0.96	0.96	0.95	0.93
JUL	0.97	0.97	0.96	0.96	0.95	0.93
AUG	1.01	1.01	1.01	1.01	1.02	1.01
SEP	0.99	1.00	1.00	1.01	1.02	1.03
OCT	1.01	1.03	1.07	1.11	1.19	1.28
NOV	0.00	0.00	0.00	0.00	0.00	0.00
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE=135

TILT ANGLE

	5	10	15	20	30	45
JAN	0.00	0.00	0.00	0.00	0.00	0.00
FEB	0.64	0.46	0.45	0.45	0.44	0.42
MAR	0.84	0.72	0.62	0.56	0.52	0.50
APR	0.95	0.89	0.83	0.77	0.71	0.68
MAY	0.96	0.93	0.91	0.88	0.81	0.76
JUN	0.96	0.94	0.92	0.89	0.82	0.78
JUL	0.96	0.94	0.91	0.89	0.82	0.77
AUG	0.98	0.95	0.91	0.86	0.80	0.76
SEP	0.92	0.85	0.79	0.74	0.69	0.65
OCT	0.80	0.65	0.56	0.51	0.54	0.51
NOV	0.00	0.00	0.00	0.00	0.00	0.00
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.00	0.00	0.00	0.00	0.00	0.00
FEB	0.49	0.46	0.45	0.45	0.44	0.42
MAR	0.78	0.56	0.35	0.31	0.31	0.30
APR	0.93	0.84	0.75	0.66	0.48	0.43
MAY	0.95	0.92	0.89	0.85	0.77	0.67
JUN	0.95	0.93	0.90	0.87	0.79	0.69
JUL	0.95	0.93	0.90	0.87	0.79	0.68
AUG	0.97	0.92	0.87	0.82	0.69	0.61
SEP	0.89	0.79	0.68	0.57	0.52	0.50
OCT	0.70	0.52	0.52	0.51	0.50	0.48
NOV	0.00	0.00	0.00	0.00	0.00	0.00
DEC	0.00	0.00	0.00	0.00	0.00	0.00

BETHEL
VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0
TILT ANGLE

	5	10	15	20	30	45
JAN	1.41	1.80	2.18	2.55	3.23	4.07
FEB	1.20	1.40	1.59	1.77	2.10	2.48
MAR	1.10	1.21	1.31	1.40	1.55	1.71
APR	1.05	1.10	1.14	1.18	1.23	1.26
MAY	1.03	1.05	1.07	1.08	1.08	1.05
JUN	1.03	1.03	1.04	1.04	1.03	0.98
JUL	1.03	1.04	1.05	1.05	1.04	1.00
AUG	1.03	1.06	1.08	1.10	1.11	1.10
SEP	1.06	1.13	1.18	1.24	1.32	1.39
OCT	1.14	1.28	1.42	1.54	1.76	2.01
NOV	1.32	1.63	1.93	2.21	2.73	3.38
DEC	1.46	1.88	2.30	2.70	3.45	4.39

AZIMUTH ANGLE=45
TILT ANGLE

	5	10	15	20	30	45
JAN	1.30	1.57	1.83	2.09	2.55	3.12
FEB	1.14	1.28	1.41	1.54	1.76	2.01
MAR	1.07	1.14	1.21	1.28	1.39	1.49
APR	1.04	1.07	1.10	1.13	1.17	1.19
MAY	1.03	1.04	1.05	1.06	1.06	1.03
JUN	1.02	1.03	1.03	1.03	1.02	0.97
JUL	1.02	1.03	1.04	1.04	1.03	0.99
AUG	1.03	1.04	1.06	1.07	1.08	1.06
SEP	1.04	1.09	1.13	1.16	1.22	1.26
OCT	1.10	1.20	1.29	1.38	1.53	1.68
NOV	1.23	1.44	1.65	1.85	2.20	2.63
DEC	1.33	1.63	1.92	2.20	2.71	3.35

AZIMUTH ANGLE=90
TILT ANGLE

	5	10	15	20	30	45
JAN	1.02	1.04	1.07	1.11	1.18	1.26
FEB	1.00	1.01	1.02	1.03	1.06	1.10
MAR	0.99	0.99	1.00	1.00	1.01	1.00
APR	1.00	1.00	0.99	0.99	0.98	0.95
XAY	1.01	1.01	1.00	0.99	0.97	0.93
JUN	1.01	1.01	1.00	0.99	0.97	0.92
JUL	1.01	1.01	1.00	0.99	0.97	0.92
AUG	1.00	1.00	0.99	0.98	0.96	0.92
SEP	0.99	0.99	0.99	0.98	0.97	0.95
OCT	0.99	1.00	1.00	1.01	1.02	1.03
NOV	1.01	1.03	1.05	1.08	1.13	1.19
DEC	1.03	1.05	1.08	1.12	1.19	1.26

AZIMUTH ANGLE=135
TILT ANGLE

	5	10	15	20	30	45
JAN	0.76	0.58	0.50	0.49	0.48	0.46
FEB	0.85	0.73	0.63	0.55	0.40	0.44
MAR	0.91	0.83	0.75	0.69	0.59	0.52
APR	0.96	0.91	0.86	0.81	0.72	0.64
MAY	0.99	0.97	0.94	0.90	0.83	0.73
JUN	1.00	0.99	0.97	0.94	0.87	0.77
JUL	1.00	0.98	0.96	0.93	0.84	0.76
AUG	0.98	0.95	0.92	0.88	0.80	0.71
SEP	0.94	0.88	0.83	0.78	0.69	0.61
OCT	0.89	0.79	0.70	0.64	0.55	0.51
NOV	0.80	0.64	0.54	0.48	0.47	0.45
DEC	0.75	0.61	0.61	0.60	0.59	0.55

AZIMUTH ANGLE=180
TILT ANGLE

	5	10	15	20	30	45
JAN	0.65	0.50	0.50	0.49	0.48	0.46
FEB	0.79	0.59	0.43	0.41	0.40	0.38
MAR	0.87	0.75	0.63	0.50	0.35	0.33
APR	0.94	0.88	0.81	0.74	0.58	0.40
MAY	0.98	0.95	0.92	0.87	0.78	0.61
JUN	1.00	0.98	0.96	0.93	0.85	0.72
JUL	1.00	0.97	0.94	0.91	0.83	0.69
AUG	0.97	0.93	0.89	0.84	0.73	0.56
SEP	0.92	0.84	0.76	0.67	0.49	0.43
OCT	0.84	0.69	0.55	0.45	0.44	0.42
NOV	0.71	0.49	0.49	0.48	0.47	0.45

BETTLES

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0
TILT ANGLE

	5	10	15	20	30	45
JAN	2.24	3.42	4.58	5.72	7.85	10.6
FEB	1.36	1.70	2.03	2.35	2.94	3.67
MAR	1.15	1.30	1.45	1.58	1.82	2.09
APR	1.07	1.14	1.20	1.25	1.34	1.40
MAY	1.04	1.07	1.09	1.10	1.12	1.11
JUN	0.98	1.00	1.01	1.01	1.02	0.98
JUL	1.02	1.04	1.05	1.06	1.07	1.04
AUG	1.05	1.09	1.13	1.15	1.19	1.21
SEP	1.09	1.19	1.28	1.36	1.50	1.63
OCT	1.24	1.47	1.69	1.90	2.29	2.75
NOV	1.93	2.81	3.68	4.53	6.11	8.15
DEC	1.39	1.38	1.37	1.35	1.31	1.22

AZIMUTH ANGLE=45
TILT ANGLE

	5	10	15	20	30	45
JAN	1.88	2.72	3.54	4.33	5.83	7.75
FEB	1.25	1.49	1.73	1.95	2.35	2.85
MAR	7.10	1.21	1.32	1.42	1.59	1.78
APR	1.05	1.10	1.15	1.19	1.26	1.32
MAY	1.03	1.05	1.07	1.08	1.10	1.09
JUN	0.98	0.99	0.99	1.00	0.99	0.96
JUL	1.02	1.03	1.04	1.04	1.05	1.02
AUG	1.04	1.07	1.09	1.12	1.15	1.16
SEP	1.07	1.13	1.20	1.26	1.36	1.46
OCT	1.17	1.33	1.49	1.63	1.90	2.21
NOV	1.66	2.29	2.90	3.49	4.59	6.00
DEC	1.39	1.38	1.37	1.35	1.37	1.22

AZIMUTH ANGLE=90
TILT ANGLE

	5	10	15	20	30	45
JAN	1.08	1.16	1.25	1.35	1.53	1.75
FEB	1.01	1.04	1.07	1.12	1.20	1.30
MAR	0.99	1.00	1.02	1.03	1.07	1.11
APR	1.00	1.00	1.01	1.01	1.02	1.03
MAY	1.01	1.01	1.01	1.01	1.00	0.99
JUN	0.97	0.96	0.95	0.95	0.93	0.89
JUL	1.01	1.00	1.00	0.99	0.98	0.95
AUG	1.01	1.01	1.00	1.00	1.00	0.98
SEP	0.99	1.00	1.00	1.01	1.02	1.03
OCT	1.00	1.02	1.04	1.06	1.12	1.18
NOV	1.06	1.13	1.21	1.31	1.49	1.72
DEC	1.39	1.38	1.37	1.35	1.31	1.22

AZIMUTH ANGLE=135
TILT ANGLE

	5	10	15	20	30	45
JAN	0.67	0.66	0.66	0.65	0.64	0.60
FEB	0.77	0.60	0.50	0.41	0.40	0.42
MAR	0.88	0.77	0.68	0.61	0.54	0.50
APR	0.95	0.89	0.83	0.78	0.70	0.64
MAY	0.99	0.97	0.94	0.90	0.76	0.75
JUN	0.96	0.95	0.93	0.91	0.85	0.77
JUL	1.00	0.98	0.96	0.93	0.86	0.79
AUG	0.98	0.94	0.90	0.85	0.78	0.71
SEP	0.92	0.84	0.77	0.72	0.64	0.59
OCT	0.83	0.70	0.60	0.54	0.42	0.47
NOV	0.54	0.47	0.47	0.47	0.46	0.43
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE=180
TILT ANGLE

	5	10	15	20	30	45
JAN	0.67	0.66	0.66	0.65	0.64	0.60
FEB	0.66	0.42	0.41	0.41	0.40	0.39
MAR	0.83	0.66	0.49	0.33	0.32	0.31
APR	0.93	0.85	0.76	0.67	0.49	0.38
MAY	0.99	0.95	0.92	0.87	0.77	0.61
JUN	0.96	0.95	0.93	0.90	0.84	0.71
JUL	0.99	0.97	0.94	0.91	0.84	0.69
AUG	0.96	0.91	0.86	0.80	0.67	0.53
SEP	0.89	0.78	0.66	0.54	0.40	0.38
OCT	0.76	0.53	0.43	0.42	0.42	0.40
NOV	0.47	0.47	0.47	0.47	0.46	0.43
DEC	0.00	0.00	0.00	0.00	0.00	0.00

BIG DELTA
VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0
TILT ANGLE

	5	10	15	20	30	45
JAN	1.68	2.32	2.95	3.56	4.71	6.16
FEB	1.27	1.53	1.79	2.03	2.47	3.01
MAR	1.13	1.26	1.38	1.50	1.70	1.91
APR	1.06	1.12	1.17	1.22	1.29	1.34
MAY	1.04	1.06	1.08	1.10	1.11	1.09
JUN	1.02	1.03	1.04	1.04	1.04	1.00
JUL	1.03	1.05	1.06	1.07	1.07	1.03
AUG	1.05	1.09	1.12	1.15	1.18	1.19
SEP	1.08	1.17	1.25	1.32	1.44	1.55
OCT	1.19	1.38	1.56	1.73	2.03	2.39
NOV	1.55	2.08	2.59	3.09	4.02	5.19
DEC	1.35	1.67	1.97	2.26	2.81	3.49

AZIMUTH ANGLE=45
TILT ANGLE

5	IO	15	20	30	45
I.49	I.94	2.38	2.81	3.60	4.60
I.19	1.38	1.55	1.72	2.03	2.38
1.09	1.18	I.27	I.35	I.50	1.65
1.05	1.09	1.13	1.16	I.22	1.26
1.03	1.05	1.06	I.07	I.09	I.07
1.02	1.03	I.03	I.03	1.03	0.99
1.03	1.04	1.04	1.05	I.05	I.02
I.04	I.06	1.09	I.11	1.14	I.15
1.06	I.12	I.18	I.23	I.32	I.39
1.13	1.26	1.39	1.51	1.72	1.95
1.40	I.77	2.13	2.47	3.11	3.91
1.26	1.48	1.69	1.89	2.27	2.73

AZIMUTH ANGLE=90
TILT ANGLE

	5	IO	15	20	30	45
JAN	1.04	1.09	1.14	1.21	1.33	1.48
FEB	1.01	1.02	1.04	1.07	1.13	1.19
MAR	0.99	1.00	1.01	1.02	1.04	1.06
APR	1.00	1.00	1.00	1.00	1.00	0.99
MAY	1.01	1.01	1.00	1.00	0.99	0.96
JUN	1.01	1.00	1.00	0.99	0.97	0.94
JUL	1.01	1.01	1.00	1.00	0.98	0.95
AUG	1.01	1.00	1.00	1.00	0.99	0.97
SEP	0.99	0.99	1.00	1.00	1.00	1.00
OCT	1.00	1.01	1.02	1.04	1.07	1.10
NOV	1.03	1.07	1.12	1.17	1.29	1.42
DEC	1.04	1.05	1.07	1.08	1.10	1.11

AZIMUTH ANGLE=135
TILT ANGLE

5	IO	15	20	30	45
0.64	0.53	0.52	0.52	0.51	0.48
0.82	0.66	0.56	0.48	0.39	0.42
0.89	0.80	0.71	0.64	0.55	0.50
0.95	0.90	0.85	0.79	0.70	0.63
0.99	0.97	0.93	0.90	0.80	0.73
1.00	0.99	0.97	0.94	0.87	0.78
1.00	0.98	0.96	0.93	0.85	0.76
0.97	0.93	0.89	0.85	0.77	0.69
0.92	0.86	0.79	0.73	0.64	0.58
0.86	0.74	0.64	0.58	0.43	0.47
0.68	0.44	0.43	0.43	0.42	0.40
0.89	0.88	0.88	0.87	0.84	0.79

AZIMUTH ANGLE=180
TILT ANGLE

	5	IO	15	20	30	45
JAN	0.53	0.53	0.52	0.52	0.51	0.48
FEB	0.73	0.49	0.40	0.40	0.39	0.37
MAR	0.85	0.70	0.55	0.40	0.31	0.30
APR	0.93	0.86	0.78	0.70	0.53	0.38
MAY	0.99	0.95	0.91	0.87	0.77	0.59
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	1.00	0.97	0.94	0.91	0.82	0.67
AUG	0.96	0.91	0.85	0.79	0.66	0.49
SEP	0.90	0.79	0.69	0.58	0.39	0.36
OCT	0.80	0.61	0.44	0.41	0.41	0.39
NOV	0.54	0.43	0.43	0.43	0.42	0.40
DEC	0.89	0.88	0.88	0.87	0.84	0.79

FAIRBANKS
VALUBS FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.69	2.35	2.99	3.61	4.77	6.26
FEB	1.29	1.56	1.83	2.09	2.56	3.14
MAR	1.13	1.27	1.39	1.51	1.72	1.95
APR	1.06	1.12	1.18	1.22	1.29	1.34.
MAY	1.04	1.06	1.08	1.10	1.11	1.09
JUN	1.02	1.03	1.04	1.04	1.04	1.00
JUL	1.03	1.05	1.06	1.06	1.07	1.03
AUG	1.05	1.09	1.12	1.14	1.18	1.19
SEP	1.08	1.17	1.25	1.32	1.44	1.55
OCT	1.19	1.39	1.57	1.74	2.06	2.43
NOV	1.61	2.19	2.76	3.31	4.33	5.63
DEC	1.14	1.14	1.13	1.11	1.08	1.00

AZIXUTH ANGLE-45

TILT ANGLE

5	10	15	20	30	45
1.50	1.96	2.41	2.84	3.65	4.67
1.20	1.40	1.59	1.76	2.09	2.47
1.09	1.19	1.28	1.37	1.52	1.67
1.05	1.09	1.13	1.17	1.22	1.26
1.03	1.05	1.06	1.08	1.09	1.07
1.02	1.02	1.03	1.03	1.02	0.99
1.03	1.04	1.04	1.05	1.05	1.02
1.04	1.06	1.09	1.11	1.14	1.14
1.06	1.12	1.18	1.23	1.32	1.39
1.14	1.27	1.40	1.52	1.74	1.98
1.44	1.84	2.24	2.63	3.34	4.22
1.14	1.14	1.13	1.11	1.08	1.00

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.05	1.09	1.15	1.21	1.32	1.46
FEB	1.01	1.02	1.05	1.08	1.14	1.21
MAR	0.99	1.00	1.01	1.02	1.05	1.07
APR	1.00	1.00	1.00	1.00	1.00	1.00
MAY	1.01	1.01	1.01	1.00	0.99	0.97
JUN	1.01	1.00	0.99	0.99	0.97	0.94
JUL	1.01	1.01	1.00	1.00	0.98	0.95
AUG	1.01	1.00	1.00	1.00	0.99	0.97
SEP	0.99	0.99	1.00	1.00	1.00	1.00
OCT	1.00	1.01	1.02	1.04	1.07	1.11
NOV	1.04	1.08	1.13	1.20	1.32	1.47
DEC	1.14	1.14	1.13	1.11	1.08	1.00

AZIMUTH ANGLE=135

TILT ANGLE

5	10	15	20	30	45
0.66	0.61	0.60	0.60	0.58	0.55
0.81	0.65	0.55	0.46	0.40	0.43
0.89	0.79	0.70	0.64	0.55	0.50
0.95	0.90	0.85	0.79	0.71	0.64
0.99	0.97	0.94	0.90	0.80	0.74
1.00	0.99	0.97	0.94	0.88	0.79
1.00	0.98	0.96	0.93	0.85	0.77
0.98	0.94	0.90	0.85	0.77	0.70
0.93	0.86	0.79	0.73	0.65	0.59
0.86	0.74	0.64	0.58	0.43	0.48
0.66	0.46	0.45	0.45	0.44	0.42
1.32	1.59	1.86	2.12	2.60	1.00

AZIHUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.61	0.61	0.60	0.60	0.58	0.55
FEB	0.72	0.47	0.41	0.41	0.40	0.38
MAR	0.84	0.69	0.54	0.39	0.32	0.31
APR	0.93	0.86	0.78	0.70	0.53	0.39
MAY	0.99	0.95	0.91	0.87	0.77	0.60
JUN	1.00	0.98	0.96	0.93	0.86	0.73
JUL	1.00	0.97	0.94	0.91	0.83	0.68
AUG	0.96	0.91	0.86	0.80	0.67	0.51
SEP	0.90	0.80	0.69	0.58	0.41	0.38
OCT	0.79	0.60	0.44	0.43	0.43	0.41
NOV	0.52	0.46	0.45	0.45	0.44	0.42
DEC	1.43	1.83	2.21	2.58	3.27	4.16

GULKANA

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.49	1.96	2.41	2.84	3.66	4.68
FEB	1.23	1.45	1.66	1.87	2.23	2.68
MAR	1.12	1.23	1.34	[illegible].45	1.62	1.81
APR	1.06	1.11	1.16	1.20	1.27	1.31
MAY	1.04	1,06	1.08	1.09	1.10	1.07
JUN	1.03	1.04	1.04	1.04	1.04	0.99
JUL	1.03	1.05	1.06	1.06	1.06	1.02
AUG	1.05	1.08	1.11	1.14	1.17	1.17
SEP	1.08	1.15	1.23	1.29	1.39	1.49
OCT	1.17	1.34	1.51	1.66	1.94	2.26
NOV	1.40	1.77	2.13	2.49	3.14	3.95
DEC	1.48	1.93	2.36	2.78	3.56	4.56

AZIMUTH ANGLE=45

TILT ANGLE

	5	10	15	20	30	45
JAN	1.35	1.68	1.99	2.30	2.86	3.55
FEB	1.16	1,32	1.47	1.61	1.86	2.15
MAR	1.08	1.16	[illegible]24	1.32	1.44	1.57
APR	1.04	1.08	1.12	1.15	1.20	1.23
MAY	1.03	1.05	1.06	1.07	1.08	1.05
JUN	1.02	1.03	1.03	1.03	1.03	0.99
JUL	1.03	1.04	1.04	1.05	1.05	1.01
AUG	1.03	1.06	1.08	1.10	1.13	1.12
SEP	1.05	1.11	1.16	1.21	1.28	1.34
OCT	1.12	1.24	1.36	1.46	1.65	1.86
NOV	1.28	1.55	1.80	2.04	2.49	3.03
DEC	1.35	1.66	1.96	2.26	2.80	3.47

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.03	1.06	1.10	1.14	1.23	1.33
FEB	1.00	1.01	1.03	1.05	1.09	1.13
MAR	0.99	0.99	1.00	1.01	1.02	1.03
APR	1.00	1.00	1.00	0.99	0.99	0.98
MAY	1.01	1.01	1.00	1.00	0.98	0.95
JUN	1.01	1.01	1.00	0.99	0.97	0.93
JUL	1.01	1.01	1.00	0.99	0.98	0.94
AUG	1.00	1.00	1.00	0.99	0.98	0.95
SEP	0.99	0.99	0.99	0.99	0.99	0.98
OCT	1.00	1.00	1.01	1.03	1.05	1.08
NOV	1.02	1.04	1.07	1.11	1.18	1.27
DEC	1.04	1.06	1.09	1.13	1.19	1.26

AZIMUTH ANGLE=135

TILT ANGLE

	5	10	15	20	30	45
JAN	0.72	0.52	0.51	0.51	0.50	0.47
FEB	0.84	0.70	0.60	0.53	0.40	0.44
MAR	0.90	0.81	0.73	0.66	0.57	0.50
APR	0.95	0.90	0.85	0.80	0.71	0.62
MAY	0.99	0.97	0.93	0.90	0.82	0.73
JUN	1.00	0.99	0.97	0.94	0.87	0.77
JUL	1.00	0.98	0.95	0.92	0.80	0.75
AUG	0.97	0.94	0.90	0.85	0.77	0.68
SEP	0.93	0.87	0.80	0.74	0.65	0.58
OCT	0.87	0.75	0.66	0.59	0.48	0.47
NOV	0.76	0.58	0.47	0.46	0.45	0.43
DEC	0.76	0.70	0.69	0.68	0.67	0.63

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.60	0.52	0.51	0.51	0.50	0.47
FEB	0.77	0.55	0.41	0.40	0.40	0.38
MAR	0.86	0.73	0.59	0.45	0.32	0.31
APR	0.93	0.86	0.79	0.71	0.54	0.37
MAY	0.98	0.95	0.91	0.87	0.77	0.59
JUN	1.00	0.98	0.96	0.93	0.85	0.71
JUL	0.99	0.97	0.94	0.90	0.82	0.66
AUG	0.96	0.91	0.86	0.80	0.67	0.48
SEP	0.90	0.81	0.71	0.61	0.41	0.37
OCT	0.81	0.63	0.47	0.39	0.39	0.37
NOV	0.65	0.47	0.47	0.46	0.45	0.43
DEC	0.70	0.70	0.69	0.68	0.67	0.63

HOMER

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.37	1.72	2.06	2.39	3.00	3.75
FEB	1.18	1.36	1.53	1.69	1.98	2.32
MAR	1.10	1.19	1.29	1.37	1.51	1.65
APR	1.05	1.10	1.14	1.17	1.22	1.24
MAY	1.03	1.05	1.07	1.08	1.08	1.05
JUN	1.03	1.03	1.04	1.04	1.03	0.98
JUL	1.03	1.04	1.05	1.06	1.05	1.00
AUG	1.04	1.07	1.09	1.11	1.14	1.13
SEP	1.06	1.13	1.19	1.24	1.33	1.40
OCT	1.14	1.29	1.42	1.55	1.77	2.02
NOV	1.31	1.61	1.90	2.18	2.69	3.32
DEC	1.39	1.75	2.11	2.45	3.08	3.87

AZIMUTH ANGLE=45

TILT ANGLE

5	10	15	20	30	45
1.27	1.51	1.75	1.98	2.39	2.89
1.13	1.25	1.37	1.48	1.68	1.90
1.07	1.14	1.20	1.26	1.36	1.45
1.04	1.07	1.10	1.13	1.16	1.18
1.03	1.04	1.05	1.06	1.06	1.03
1.02	1.03	1.03	1.03	1.02	0.97
1.02	1.03	1.04	1.04	1.04	1.00
1.03	1.05	1.07	1.08	1.10	1.09
1.04	1.09	1.13	1.17	1.23	1.27
1.10	1.20	1.29	1.38	1.53	1.69
1.22	1.43	1.64	1.83	2.18	2.59
1.28	1.54	1.78	2.02	2.45	2.98

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.02	1.04	1.06	1.09	1.15	1.22
FEB	1.00	1.00	1.01	1.02	1.05	1.07
MAR	0.99	0.99	0.99	0.99	1.00	0.99
APR	1.00	1.00	0.99	0.99	0.98	0.95
MAY	1.01	1.00	1.00	0.99	0.97	0.93
JUN	1.01	1.01	1.00	0.99	0.97	0.92
JUL	1.01	1.01	1.00	0.99	0.97	0.92
AUG	1.00	1.00	0.99	0.99	0.97	0.93
SEP	0.99	0.99	0.99	0.98	0.98	0.95
OCT	0.99	1.00	1.00	1.01	1.02	1.03
NOV	1.01	1.03	1.05	1.07	1.12	1.18
DEC	1.03	1.04	1.07	1.10	1.15	1.21

AZIMUTH ANGLE=135

TILT ANGLE

5	10	15	20	30	45
0.78	0.60	0.48	0.47	0.46	0.44
0.87	0.75	0.65	0.58	0.45	0.46
0.91	0.84	0.76	0.70	0.60	0.52
0.96	0.91	0.86	0.82	0.73	0.63
0.99	0.97	0.93	0.90	0.82	0.72
1.00	0.99	0.96	0.94	0.87	0.76
1.00	0.98	0.95	0.92	0.84	0.75
0.97	0.94	0.90	0.86	0.78	0.69
0.94	0.88	0.82	0.77	0.68	0.59
0.89	0.79	0.70	0.63	0.54	0.48
0.80	0.64	0.52	0.43	0.42	0.41
0.78	0.63	0.59	0.59	0.57	0.54

AZIMUTH ANGLE-180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.67	0.48	0.47'	0.47	0.46	0.44
FEB	0.81	0.63	0.47	0.42	0.41	0.39
MAR	0.88	0.77	0.65	0.53	0.35	0.34
APR	0.94	0.88	0.81	0.74	0.59	0.39
MAY	0.98	0.95	0.91	0.87	0.77	0.60
JUN	1.00	0.98	0.95	0.92	0.85	0.70
JUL	0.99	0.97	0.94	0.90	0.82	0.66
AUG	0.96	0.92	0.87	0.82	0.70	0.50
SEP	0.92	0.83	0.75	0.66	0.48	0.40
OCT	0.84	0.69	0.54	0.41	0.40	0.38
NOV	0.71	0.47	0.44	0.43	0.42	0.40
DEC	0.69	0.60	0.59	0.59	0.57	0.54

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VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE-0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.26	1.50	1.74	1.97	2.38	2.88
FEB	1.13	1.26	1.38	1.50	1.70	1.93
MAR	1.07	1.15	1.22	1.28	1.38	1.48
APR	1.04	1.08	1.11	1.14	1.18	1.18
MAY	1.03	1.04	1.06	1.06	1.06	1.02
JUN	1.02	1.03	1.03	1.03	1.02	0.96
JUL	1.03	1.04	1.04	1.04	1.03	0.98
AUG	1.03	1.06	1.08	1.09	1.10	1.08
SEP	1.05	1.10	1.14	1.18	1.24	1.28
OCT	1.09	1.18	1.27	1.34	1.48	1.62
NOV	1.21	1.40	1.59	1.77	2.10	2.49
DEC	1.23	1.44	1.64	1.84	2.19	2.62

AZIMUTH ANGLE=45

TILT ANGLE

5	10	15	20	30	45
1.19	1.36	1.52	1.67	1.95	2.28
1.09	1.18	1.27	1.34	1.48	1.62
1.05	1.10	1.15	1.19	1.26	1.31
1.03	1.06	1.08	1.10	1.12	1.12
1.02	1.03	1.04	1.05	1.04	1.00
1.02	1.03	1.03	1.02	1.01	0.96
1.02	1.03	1.03	1.03	1.02	0.97
1.02	1.04	1.05	1.06	1.07	1.04
1.03	1.07	1.10	1.12	1.16	1.17
1.06	1.12	1.18	1.23	1.32	1.40
1.15	1.29	1.42	1.54	1.76	2.01
1.17	1.31	1.45	1.59	1.82	2.10

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.01	1.02	1.03	1.05	1.08	1.10
FEB	1.00	1.00	1.00	1.00	1.00	0.99
MAR	0.99	0.99	0.99	0.98	0.97	0.95
APR	1.00	0.99	0.99	0.98	0.96	0.92
MAY	1.01	1.00	1.00	0.99	0.96	0.91
JUN	1.01	1.01	1.00	0.99	0.96	0.91
JUL	1.01	1.01	1.00	0.99	0.96	0.91
AUG	1.00	1.00	0.99	0.98	0.96	0.91
SEP	0.99	0.99	0.98	0.97	0.96	0.92
OCT	0.99	0.99	0.99	0.98	0.98	0.95
NOV	1.01	1.01	1.02	1.03	1.05	1.06
DEC	1.02	1.02	1.03	1.04	1.05	1.05

AZIMUTH ANGLE=135

TILT ANGLE

5	10	15	20	30	45
0.84	0.70	0.62	0.57	0.55	0.52
0.90	0.81	0.73	0.67	0.57	0.54
0.93	0.87	0.81	0.75	0.66	0.58
0.96	0.92	0.88	0.84	0.75	0.66
0.99	0.97	0.94	0.91	0.84	0.74
1.00	0.99	0.97	0.94	0.88	0.77
1.00	0.98	0.96	0.93	0.86	0.76
0.98	0.95	0.92	0.88	0.81	0.71
0.95	0.90	0.86	0.81	0.73	0.64
0.92	0.85	0.79	0.73	0.65	0.59
0.87	0.75	0.66	0.59	0.55	0.53
0.87	0.76	0.71	0.70	0.68	0.64

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.77	0.58	0.57	0.57	0.55	0.52
FEB	0.86	0.72	0.59	0.53	0.51	0.49
MAR	0.90	0.81	0.72	0.62	0.45	0.43
APR	0.95	0.90	0.84	0.78	0.64	0.45
MAY	0.99	0.96	0.92	0.88	0.80	0.64
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	0.99	0.97	0.94	0.91	0.83	0.69
AUG	0.97	0.93	0.89	0.84	0.74	0.56
SEP	0.93	0.87	0.80	0.73	0.58	0.49
OCT	0.89	0.79	0.69	0.59	0.56	0.53
NOV	0.80	0.63	0.57	0.56	0.55	0.52
DEC	0.81	0.71	0.71	0.70	0.68	0.64

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VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.35	1.68	2.00	2.31	2.87	3.57
FEB	1.18	1.35	1.52	1.68	1.96	2.29
MAR	1.09	1.19	1.28	1.36	1.50	1.63
APR	1.05	1.09	1.13	1.16	1.20	1.22
HAY	1.03	1.05	1.06	1.07	1.07	1.03
JUN	1.02	1.03	1.04	1.04	1.02	0.97
JUL	1.03	1.04	1.05	1.05	1.04	0.99
AUG	1.03	1.06	1.08	1.10	1.11	1.09
SEP	1.06	1.12	1.18	1.22	1.30	I.36
OCT	1.14	1.28	1.41	1.53	I.75	1.99
NOV	1.30	1.58	1.85	2.11	2.59	3.18
DEC	1.41	1.79	2.17	2.53	3.20	4.03

AZIMUTH ANGLE-45

TILT ANGLE

5	10	15	20	30	45
I.25	1.48	1.70	1.91	2.30	2.76
1.12	1.25	I.36	1.47	I.66	1.87
I.06	7.13	I.19	1.25	1.35	1.43
1.03	1.06	I.09	I.12	1.15	I.15
1.02	1.04	1.05	1.05	I.05	1.02
1.02	1.03	1.03	1.03	1.01	0.96
1.02	1.03	I.03	1.04	1.03	0.98
I.02	I.04	I.06	1.07	1.08	1.06
1.04	1.08	I.12	I.16	1.21	1.24
1.10	1.19	1.28	1.37	1.51	1.67
1.21	1.41	I.60	I.78	2.10	2.49
I.29	1.56	1.82	2.07	2.53	3.09

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.02	1.03	1.05	1.08	1.14	1.20
PEB	1.00	1.00	1.01	1.02	1.04	1.06
HAR	0.99	0.99	0.99	0.99	0.99	0.98
APR	1.00	0.99	0.99	0.98	0.97	0.94
MAY	1.01	1.00	1.00	0.99	0.97	0.92
JUN	1.01	1.01	1.00	0.99	0.96	0.91
JUL	1.01	1.01	1.00	0.99	0.96	0.91
AUG	1.00	1.00	0.99	0.98	0.96	0.91
SEP	0.99	0.99	0.99	0.98	0.97	0.94
OCT	0.99	1.00	1.00	1.01	1.02	1.02
NOV	1.01	1.02	1.04	1.06	1.11	1.16
DEC	1.02	1.04	1.07	1.10	1.16	1.23

AZIMUTH ANGLE=135

TILT ANGLE

5	IO	15	20	30	45
0.79	0.61	0.50	0.45	0.44	0.42
0.87	0.75	0.65	0.58	0.46	0.44
0.92	0.84	0.77	0.70	0.60	0.52
0.96	0.92	0.87	0.82	0.73	0.64
0.99	0.97	0.94	0.90	0.83	0.73
1.00	0.99	0.97	0.94	0.87	0.77
1.00	0.98	0.95	0.93	0.86	0.76
0.98	0.95	0.91	0.88	0.80	0.70
0.94	0.89	0.83	0.78	0.69	0.60
0.89	0.79	0.70	0.63	0.54	0.48
0.81	0.65	0.53	0.44	0.41	0.40
0.76	0.58	0.51	0.51	0.49	0.47

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.69	0.46	0.45	0.45	0.44	0.42
FEB	0.81	0.63	0.47	0.39	0.39	0.37
MAR	0.88	0.77	0.66	0.54	0.34	0.33
APR	0.94	0.88	0.82	0.75	0.61	0.41
HAY	0.98	0.95	0.92	0.88	0.78	0.61
JUN	1.00	0.98	0.95	0.92	0.85	0.71
JUL	0.99	0.97	0.94	0.91	0.83	0.68
AUG	0.97	0.93	0.88	0.83	0.72	0.54
SEP	0.92	0.84	0.76	0.68	0.50	0.41
OCT	0.84	0.69	0.55	0.42	0.39	0.37
NOV	0.72	0.48	0.42	0.41	0.41	0.39
DEC	0.66	0.51	0.51	0.51	0.49	0.47

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VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.29	1.56	1.83	2.08	2.55	3.12
PEB	1.15	1.30	1.45	1.58	1.82	2.09
MAR	1.09	1.17	1.26	1.33	1.45	1.57
APR	1.05	1.09	1.12	1.15	1.19	1.20
MAY	1.03	1.04	1.06	1.06	1.06	1.02
JUN	1.02	1.03	1.03	1.03	1.02	0.96
JUL	1.03	1.04	1.04	1.05	1.04	0.98
AUG	1.03	1.06	7.08	1.10	1.12	1.10
SEP	1.06	1.12	1.17	1.22	1.29	1.34
OCT	1.13	1.26	1.38	1.50	1.70	1.92
NOV	1.25	1.50	1.73	1.96	2.37	2.86
DEC	1.33	1.65	1.95	2.24	2.78	3.45

AZIMUTH ANGLE=45

TILT ANGLE					
5	10	15	20	30	45
1.21	1.40	1.58	1.76	2.07	2.44
1.11	1.21	1.31	1.40	1.56	1.73
1.06	1.12	1.18	1.23	1.31	1.39
1.03	1.06	1.09	1.11	1.14	1.14
1.02	1.03	1.04	1.05	1.04	1.00
1.02	1.03	1.03	1.02	1.01	0.96
1.02	1.03	1.03	1.03	1.02	0.98
1.03	1.04	1.06	1.07	1.08	1.06
1.04	1.08	1.12	1.15	1.20	1.22
1.09	1.18	1.27	1.34	1.48	1.62
1.18	1.35	1.51	1.67	1.94	2.26
1.24	1.46	1.67	1.87	2.24	2.68

AZIMUTH ANGLE=90

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.01	1.02	1.04	1.06	1.10	1.14
FEB	1.00	1.00	1.00	1.01	1.02	1.02
MAR	0.99	0.99	0.99	0.99	0.99	0.97
APR	1.00	0.99	0.99	0.98	0.97	0.93
MAY	1.01	1.00	1.00	0.99	0.96	0.91
JUN	1.01	1.01	1.00	0.99	0.96	0.91
JUL	1.01	1.00	1.00	0.99	0.96	0.91
AUG	1.00	1.00	0.99	0.98	0.96	0.92
SEP	0.99	0.99	0.98	0.98	0.97	0.93
OCT	0.99	0.99	1.00	1.00	1.01	1.01
NOV	1.01	1.02	1.03	1.05	1.08	1.11
DEC	1.02	1.03	1.05	1.07	1.12	1.16

AZIHUTH ANGLE=135

TILT ANGLE					
5	10	15	20	30	45
0.82	0.67	0.56	0.49	0.48	0.46
0.88	0.78	0.69	0.62	0.52	0.48
0.92	0.85	0.78	0.72	0.62	0.54
0.96	0.92	0.87	0.83	0.74	0.64
0.99	0.97	0.94	0.91	0.83	0.73
1.00	0.99	0.96	0.94	0.87	0.77
1.00	0.98	0.95	0.93	0.86	0.75
0.98	0.94	0.91	0.87	0.79	0.69
0.94	0.89	0.84	0.79	0.70	0.60
0.90	0.80	0.72	0.65	0.55	0.49
0.83	0.69	0.58	0.51	0.44	0.43
0.80	0.64	0.55	0.54	0.53	0.50

AZIMUTH ANGLE=180

	TILT ANGLE					
	5	10	15	20	30	45
JAN	0.74	0.52	0.49	0.49	0.48	0.45
FEB	0.84	0.68	0.53	0.44	0.43	0.41
MAR	0.89	0.79	0.68	0.57	0.36	0.35
APR	0.95	0.89	0.83	0.76	0.62	0.41
MAY	0.98	0.95	0.92	0.88	0.79	0.63
JUN	1.00	0.98	0.95	0.92	0.85	0.71
JUL	0.99	0.97	0.94	0.91	0.83	0.68
AUG	0.97	0.92	0.88	0.83	0.71	0.52
SEP	0.92	0.85	0.77	0.69	0.52	0.41
OCT	0.85	0.71	0.57	0.44	0.39	0.38
NOV	0.76	0.54	0.45	0.45	0.44	0.42
DEC	0.71	0.55	0.55	0.54	0.53	0.50

KOTZEBUE

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.90	2.75	3.59	4.40	5.93	7.90
FEB	1.34	1.67	1.98	2.29	2.85	3.54
MAR	1.15	1.29	1.43	1.56	1.80	2.06
APR	1.07	1.14	1.19	1.25	1.33	1.39
MAY	1.04	1.06	1.09	1.10	1.12	1.11
JUN	0.99	1.00	1.01	1.02	1.02	0.99
JUL	1.02	1.04	1.05	1.06	1.07	1.04
AUG	1.05	1.09	1.12	1.15	1.19	1.20
SEP	1.09	1.18	1.27	1.35	1.48	1.61
OCT	1.24	1.47	1.69	1.91	2.29	2.76
NOV	1.74	2.45	3.14	3.81	5.07	6.67
DEC	1.39	1.38	1.37	1.35	1.31	1.22

AZIMUTH ANGLE=45

TILT ANGLE

	5	10	15	20	30	45
JAN	1.65	2.25	2.84	3.41	4.48	5.84
FEB	1.24	1.47	1.69	1.90	2.29	2.75
MAR	1.10	1.21	1.31	1.40	1.57	1.75
APR	1.05	1.10	1.15	1.19	1.25	1.31
MAY	1.03	1.05	1.07	1.08	1.10	1.09
JUN	0.98	0.99	1.00	1.00	1.00	0.97
JUL	1.02	1.03	1.04	1.04	1.05	1.02
AUG	1.04	1.07	1.09	1.11	1.15	1.15
SEP	1.06	1.13	1.19	1.25	1.35	1.44
OCT	1.17	1.33	1.49	1.64	1.91	2.22
NOV	1.53	2.03	2.51	2.98	3.86	4.97
DEC	1.39	1.38	1.37	1.35	1.31	1.22

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.06	1.12	1.18	1.25	1.37	1.51
FEB	1.01	1.04	1.07	1.11	1.18	1.28
MAR	0.99	1.00	1.01	1.03	1.06	1.10
APR	1.00	1.00	1.01	1.01	1.02	1.03
MAY	1.01	1.01	1.01	1.00	1.00	0.98
JUN	0.97	0.97	0.96	0.95	0.94	0.90
JUL	1.01	1.00	1.00	0.99	0.98	0.95
AUG	1.01	1.01	1.00	1.00	1.00	0.98
SEP	0.99	1.00	1.00	1.01	1.02	1.02
OCT	1.00	1.02	1.04	1.06	1.12	1.18
NOV	1.05	1.10	1.17	1.24	1.38	1.54
DEC	1.39	1.38	1.37	1.35	1.31	1.22

AZIMUTH ANGLE=135

TILT ANGLE

	5	10	15	20	30	45
JAN	0.76	0.76	0.75	0.74	0.72	0.68
FEB	0.78	0.62	0.52	0.43	0.43	0.43
MAR	0.88	0.78	0.69	0.62	0.54	0.51
APR	0.95	0.89	0.84	0.78	0.70	0.64
MAY	0.99	0.97	0.94	0.90	0.77	0.75
JUN	0.97	0.96	0.94	0.92	0.86	0.78
JUL	1.00	0.98	0.96	0.93	0.86	0.79
AUG	0.98	0.94	0.90	0.85	0.78	0.71
SEP	0.92	0.85	0.78	0.72	0.65	0.59
OCT	0.83	0.69	0.60	0.54	0.41	0.47
NOV	0.63	0.57	0.57	0.57	0.55	0.52
DEC	0.00	0.00	0.00	0.00	0.00	0.00

AZIMUTH ANGLE-180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.76	0.76	0.75	0.74	0.72	0.68
FEB	0.68	0.44	0.44	0.43	0.43	0.41
MAR	0.83	0.67	0.50	0.35	0.33	0.32
APR	0.93	0.85	0.77	0.68	0.50	0.39
MAY	0.99	0.95	0.92	0.87	0.78	0.62
JUN	0.97	0.95	0.93	0.91	0.85	0.72
JUL	0.99	0.97	0.94	0.91	0.84	0.69
AUG	0.96	0.91	0.86	0.80	0.67	0.53
SEP	0.89	0.78	0.67	0.56	0.41	0.39
OCT	0.76	0.53	0.42	0.42	0.41	0.39
NOV	0.58	0.57	0.57	0.57	0.55	0.52
DEC	0.00	0.00	0.00	0.00	0.00	0.00

MATANUSKA
VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.59	2.16	2.72	3.25	4.25	5.51
FEB	1.24	1.47	1.69	1.90	2.29	2.75
MAR	1.12	1.25	1.37	1.48	1.67	1.87
APR	1.06	1.11	1.16	1.20	1.26	1.29
MAY	1.04	1.06	1.07	1.09	1.09	1.06
JUN	1.03	1.04	1.04	1.04	1.03	0.99
JUL	1.03	1.04	1.05	1.06	1.06	1.01
AUG	1.04	1.07	1.10	1.12	1.15	1.15
SEP	1.07	1.14	1.20	1.26	1.35	1.43
OCT	1.15	1.31	1.45	1.59	1.84	2.12
NOV	1.40	1.78	2.15	2.50	3.16	3.97
DEC	1.72	2.41	3.09	3.74	4.97	6.53

AZIMUTH ANGLE=45

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.42	1.82	2.21	2.58	3.27	4.13
FEB	1.17	1.33	1.49	1.63	1.90	2.20
MAR	1.09	1.18	1.26	1.34	1.48	1.62
APR	1.04	1.08	1.12	1.15	1.19	1.22
MAY	1.03	1.04	1.06	1.07	1.07	1.05
JUN	1.02	1.03	1.03	1.03	1.02	0.98
JUL	1.03	1.03	1.04	1.04	1.04	1.00
AUG	1.03	1.06	1.08	1.09	1.11	1.10
SEP	1.05	1.10	1.14	1.18	1.25	1.30
OCT	1.11	1.22	1.32	1.41	1.58	1.76
NOV	1.28	1.55	1.81	2.05	2.50	3.05
DEC	1.52	2.00	2.48	2.93	3.78	4.86

AZIMUTH ANGLE=90

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.03	1.07	1.12	1.18	1.30	1.44
FEB	1.00	1.01	1.03	1.05	1.09	1.15
MAR	0.99	7.00	1.00	1.01	1.03	1.05
APR	1.00	1.00	1.00	0.99	0.99	0.97
MAY	1.01	1.01	1.00	0.99	0.98	0.94
JUN	1.01	1.01	1.00	0.99	0.97	0.93
JUL	1.01	1.01	1.00	0.99	0.97	0.93
AUG	1.00	1.00	1.00	0.99	0.97	0.94
SEP	0.99	0.99	0.99	0.99	0.98	0.96
OCT	7.00	1.00	1.01	1.02	1.03	1.05
NOV	1.02	1.04	1.07	1.11	1.18	1.27
DEC	1.04	1.09	1.15	1.21	1.34	1.50

AZIMUTH ANGLE=135

	TILT ANGLE					
	5	10	15	20	30	45
	0.65	0.42	0.36	0.35	0.35	0.34
	0.83	0.69	0.58	0.50	0.35	0.40
	0.89	0.80	0.71	0.64	0.54	0.47
	0.95	0.90	0.85	0.80	0.71	0.62
	0.99	0.97	0.93	0.90	0.82	0.73
	1.00	0.99	0.97	0.94	0.87	0.77
	1.00	0.98	0.95	0.92	0.82	0.76
	0.97	0.94	0.90	0.86	0.78	0.69
	0.94	0.88	0.82	0.76	0.67	0.60
	0.88	0.78	0.69	0.62	0.52	0.49
	0.76	0.57	0.45	0.42	0.41	0.40
	0.61	0.47	0.46	0.46	0.45	0.43

AZIMUTH ANGLE=180

	TILT ANGLE					
	5	10	15	20	30	45
JAN	0.50	0.36	0.36	0.35	0.35	0.34
FEB	0.76	0.53	0.36	0.35	0.35	0.34
MAR	0.85	0.71	0.56	0.41	0.26	0.25
APR	0.94	0.87	0.79	0.72	0.55	0.37
MAY	0.98	0.95	0.91	0.87	0.77	0.59
JUN	1.00	0.98	0.96	0.93	0.85	0.71
JUL	0.99	0.97	0.94	0.90	0.82	0.67
AUG	0.96	0.92	0.86	0.81	0.69	0.50
SEP	0.91	0.83	0.74	0.64	0.45	0.41
OCT	0.83	0.67	0.51	0.43	0.42	0.40
NOV	0.64	0.43	0.43	0.42	0.41	0.40
DEC	0.48	0.47	0.46	0.46	0.45	0.43

MCGRATH

VALUBS FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.54	2.05	2.54	3.02	3.92	5.05
FEB	1.24	1.47	1.69	1.90	2.29	2.76
MAR	1.12	1.23	1.35	1.45	1.63	1.82
APR	1.06	1.11	1.16	1.20	1.26	1.30
MAY	1.04	1.06	1.07	1.09	1.10	1.07
JUN	1.02	1.03	1.04	1.04	1.04	0.99
JUL	1.03	1.04	1.05	1.06	1.06	1.02
AUG	1.04	1.07	1.10	1.12	1.15	1.14
SEP	1.07	1.15	1.21	1.28	1.37	1.46
OCT	1.16	1.32	1.47	1.62	1.87	2.17
NOV	1.43	1.85	2.25	2.64	3.35	4.25
DEC	1.50	1.96	2.41	2.85	3.67	4.70

AZIMUTH ANGLE=45

TILT ANGLE					
5	10	15	20	30	45
1.39	1.74	2.09	2.42	3.04	3.81
1.17	1.33	1.49	1.63	1.90	2.20
1.08	1.16	1.24	1.32	1.44	1.57
1.04	1.08	1.12	1.15	1.20	1.22
1.03	1.05	1.06	1.07	1.07	1.05
1.02	1.03	1.03	1.03	1.02	0.98
1.03	1.03	1.04	1.04	1.04	1.00
1.03	1.05	1.07	1.09	1.11	1.10
1.05	1.10	1.15	1.19	1.26	1.32
1.11	1.22	1.33	1.43	1.61	1.80
1.31	1.60	1.88	2.15	2.64	3.25
1.36	1.69	2.00	2.31	2.87	3.58

AZIMUTH ANGLE=90

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.03	1.07	1.11	1.16	1.25	1.36
FEB	1.00	1.01	1.03	1.05	1.10	1.14
MAR	0.99	0.99	1.00	1.01	1.02	1.03
APR	1.00	1.00	1.00	1.00	0.99	0.97
MAY	1.01	1.01	1.00	1.00	0.98	0.95
JUN	1.01	1.01	1.00	0.99	0.97	0.93
JUL	1.01	1.01	1.00	0.99	0.97	0.93
AUG	1.00	1.00	1.00	0.99	0.97	0.94
SEP	0.99	0.99	0.99	0.99	0.99	0.97
OCT	1.00	1.00	1.01	1.02	1.04	1.06
NOV	1.02	1.05	1.08	1.13	1.21	1.30
DEC	1.04	1.06	1.10	1.13	1.19	1.25

AZIMUTH ANGLE=135

TILT ANGLE					
5	10	15	20	30	45
0.70	0.54	0.54	0.53	0.52	0.49
0.84	0.70	0.59	0.53	0.41	0.44
0.go	0.81	0.73	0.66	0.57	0.51
0.95	0.91	0.85	0.80	0.72	0.63
0.99	0.97	0.94	0.90	0.82	0.73
1.00	0.99	0.97	0.94	0.88	0.78
1.00	0.98	0.96	0.93	0.80	0.77
0.98	0.94	0.91	0.87	0.79	0.70
0.93	0.87	0.81	0.76	0.67	0.60
0.88	0.77	0.68	0.62	0.50	0.50
0.74	0.56	0.48	0.47	0.46	0.44
0.77	0.75	0.74	0.73	0.71	0.67

AZIMUTH ANGLE=180

	TILT ANGLE					
	5	10	15	20	30	45
JAN	0.59	0.54	0.54	0.53	0.52	0.49
FEB	0.76	0.54	0.42	0.42	0.41	0.39
MAR	0.86	0.73	0.59	0.45	0.34	0.33
APR	0.94	0.87	0.79	0.72	0.55	0.40
MAY	0.99	0.95	0.92	0.87	0.77	0.60
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	1.00	0.97	0.94	0.91	0.83	0.68
AUG	0.97	0.92	0.87	0.82	0.70	0.53
SEP	0.91	0.82	0.73	0.63	0.44	0.41
OCT	0.82	0.66	0.50	0.46	0.45	0.43
NOV	0.63	0.48	0.48	0.47	0.46	0.44
DEC	0.75	0.75	0.74	0.73	0.71	0.67

NOME

VALUBS FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.56	2.08	2.59	3.08	4.00	5.17
FEB	1.27	1.54	1.79	2.04	2.49	3.03
MAR	1.12	1.25	1.37	1.48	1.67	1.88
APR	1.06	1.12	1.17	1.22	1.29	1.33
MAY	1.04	1.06	1.08	1.10	1.11	1.09
JUN	1.02	1.03	1.04	1.04	1.04	1.00
JUL	1.03	1.04	1.05	1.06	1.06	1.03
AUG	1.04	1.08	1.11	1.13	1.16	1.16
SEP	1.08	1.16	1.23	1.30	1.41	1.51
OCT	1.19	1.38	1.56	1.74	2.05	2.41
NOV	1.48	1.94	2.38	2.81	3.61	4.61
DEC	1.15	1.14	1.14	1.12	1.09	1.01

AZIMUTH ANGLE=45

TILT ANGLE					
5	10	15	20	30	45
1.40	1.77	2.12	2.47	3.11	3.91
1.19	1.38	1.56	1.73	2.04	2.40
1.09	1.18	1.26	1.34	1.48	1.62
1.05	1.09	1.13	1.16	1.22	1.26
1.03	1.05	1.06	1.07	1.08	1.07
1.02	1.02	1.03	1.03	1.03	0.99
1.02	1.03	1.04	1.05	1.04	1.01
1.03	1.06	1.08	1.10	1.12	1.11
1.05	1.11	1.17	1.21	1.29	1.36
1.13	1.27	1.40	1.52	1.73	1.97
1.35	1.67	1.98	2.27	2.82	3.51
1.15	1.14	1.14	1.12	1.09	1.01

AZIMUTH ANGLE=90

	TILT ANGLE					
	5	10	15	20	30	45
JAN	1.04	1.07	1.11	1.16	1.25	1.34
PEB	1.01	1.02	1.04	1.07	1.13	1.19
MAR	0.99	1.00	1.00	1.01	1.03	1.05
APR	1.00	1.00	1.00	1.00	1.00	0.99
MAY	1.01	1.01	1.00	1.00	0.99	0.96
JUN	1.01	1.00	1.00	0.99	0.97	0.94
JUL	1.01	1.01	1.00	0.99	0.98	0.94
AUG	1.01	1.00	1.00	0.99	0.98	0.95
SEP	0.99	0.99	0.99	0.99	1.00	0.99
OCT	1.00	1.01	1.02	1.04	1.07	1.11
NOV	1.03	1.06	1.10	1.14	1.23	1.34
DEC	1.15	1.14	1.14	1.12	1.09	1.01

AZIMUTH ANGLE=135

TILT ANGLE					
5	10	15	20	30	45
0.72	0.66	0.65	0.65	0.63	0.59
0.82	0.66	0.56	0.48	0.41	0.43
0.90	0.80	0.72	0.65	0.57	0.52
0.95	0.90	0.85	0.79	0.71	0.64
0.99	0.97	0.94	0.90	0.80	0.74
1.00	0.99	0.97	0.94	0.88	0.79
1.00	0.98	0.96	0.93	0.86	0.77
0.98	0.94	0.90	0.86	0.79	0.71
0.93	0.86	0.80	0.74	0.66	0.60
0.86	0.74	0.64	0.58	0.42	0.48
0.73	0.55	0.54	0.54	0.52	0.50
1.30	1.57	1.82	2.07	2.53	1.01

AZIMUTH ANGLE=180

	TILT ANGLE					
	5	10	15	20	30	45
JAN	0.66	0.66	0.65	0.65	0.63	0.59
FEB	0.73	0.49	0.42	0.42	0.41	0.39
MAR	0.85	0.71	0.57	0.42	0.35	0.34
APR	0.93	0.86	0.78	0.70	0.53	0.39
MAY	0.99	0.95	0.91	0.87	0.77	0.60
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	1.00	0.97	0.94	0.91	0.83	0.68
AUG	0.97	0.92	0.87	0.81	0.69	0.54
SEP	0.90	0.81	0.71	0.61	0.43	0.41
OCT	0.80	0.60	0.44	0.43	0.42	0.40
NOV	0.61	0.55	0.54	0.54	0.52	0.50
DEC	1.42	1.79	2.15	2.51	3.17	4.02

SUMMIT

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE=0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.60	2.18	2.73	3.27	4.28	5.57
FEB	1.25	1.49	1.72	1.94	2.34	2.82
MAR	1.12	1.24	1.36	1.46	1.65	1.85
APR	1.06	1.12	1.17	1.21	1.28	1.32
MAY	1.04	1.06	1.08	1.09	1.11	1.08
JUN	1.02	1.03	1.04	1.04	1.04	0.99
JUL	1.03	1.04	1.05	1.06	1.06	1.02
AUG	1.04	1.08	1.10	1.13	1.15	1.15
SEP	1.08	1.15	1.22	1.29	1.39	1.48
OCT	1.18	1.36	1.53	1.69	1.99	2.33
NOV	1.51	1.99	2.46	2.91	3.76	4.82
DEC	1.53	2.02	2.50	2.96	3.82	4.92

AZIMUTH ANGLE=45

TILT ANGLE

	5	10	15	20	30	45
JAN	1.43	1.83	2.23	2.60	3.30	4.18
FEB	1.17	1.34	1.50	1.65	1.93	2.25
MAR	1.08	1.17	1.25	1.33	1.46	1.60
APR	1.04	1.09	1.12	1.16	1.21	1.24
MAY	1.03	1.05	1.06	1.07	1.08	1.06
JUN	1.02	1.03	1.03	1.03	1.02	0.98
JUL	1.03	1.03	1.04	1.05	1.04	1.01
AUG	1.03	1.06	1.08	1.09	1.11	1.11
SEP	1.05	1.11	1.16	1.20	1.28	1.34
OCT	1.13	1.25	1.37	1.49	1.69	1.91
NOV	1.36	1.70	2.03	2.34	2.93	3.64
DEC	1.38	1.73	2.06	2.38	2.98	3.74

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	7.04	1.07	1.13	1.18	1.29	1.42
FEB	1.00	1.02	1.03	1.06	1.10	1.16
MAR	0.99	7.00	1.00	1.01	1.03	1.04
APR	1.00	1.00	1.00	1.00	1.00	0.98
MAY	1.01	1.01	1.00	1.00	0.99	0.96
JUN	1.01	1.01	1.00	9.99	0.97	0.93
JUL	1.01	1.01	1.00	0.99	0.97	0.94
AUG	1.00	1.00	1.00	0.99	0.98	0.95
SEP	0.99	0.99	0.99	0.99	0.99	0.98
OCT	1.00	1.00	1.02	1.03	1.06	1.09
NOV	1.03	1.06	1.10	1.15	1.26	1.38
DEC	1.04	1.07	1.10	1.14	1.20	1.27

AZIMUTH ANGLE=135

TILT ANGLE

	5	10	15	20	30	45
JAN	0.67	0.52	0.51	0.51	0.50	0.47
FEB	0.83	0.69	0.58	0.52	0.41	0.44
MAR	0.90	0.81	0.72	0.66	0.57	0.51
APR	0.95	0.90	0.85	0.80	0.71	0.63
MAY	0.99	0.97	0.93	0.90	0.81	0.73
JUN	1.00	0.99	0.97	0.94	0.88	0.78
JUL	1.00	0.98	0.96	0.93	0.86	0.77
AUG	0.98	0.94	0.90	0.86	0.78	0.70
SEP	0.93	0.87	0.81	0.75	0.66	0.59
OCT	0.86	0.75	0.65	0.58	0.46	0.47
NOV	0.70	0.50	0.42	0.42	0.41	0.39
DEC	0.77	0.76	0.75	0.75	0.73	0.68

AZIMUTH ANGLE-180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.55	0.52	0.51	0.51	0.50	0.47
FEB	0.75	0.53	0.42	0.42	0.41	0.39
MAR	0.86	0.72	0.58	0.43	0.33	0.32
APR	0.93	0.86	0.79	0.71	0.54	0.38
MAY	0.98	0.95	0.91	0.87	0.77	0.59
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	1.00	0.97	0.94	0.91	0.83	0.68
AUG	0.96	0.92	0.87	0.81	0.69	0.53
SEP	0.91	0.81	0.72	0.62	0.43	0.40
OCT	0.81	0.62	0.45	0.41	0.40	0.39
NOV	0.57	0.43	0.42	0.42	0.41	0.39
DEC	0.76	0.76	0.75	0.75	0.73	0.68

YUKATAT

VALUES FOR R (R=INCLINED RADIATION/HORIZONTAL RADIATION)

AZIMUTH ANGLE-0

TILT ANGLE

	5	10	15	20	30	45
JAN	1.30	1.58	1.85	2.11	2.59	3.19
FEB	1.14	1.29	1.42	1.55	1.78	2.03
MAR	1.08	1.17	1.24	1.31	1.43	1.55
APR	1.05	1.09	1.12	1.15	1.19	1.20
MAY	1.03	1.05	1.06	1.07	1.07	1.03
JUN	1.02	1.03	1.04	1.04	1.02	0.97
JUL	1.03	1.04	1.04	1.05	1.04	0.99
AUG	1.03	1.06	1.08	1.09	1.11	1.09
SEP	1.05	1.11	1.15	1.20	1.26	1.31
OCT	1.11	1.23	1.33	1.43	1.61	1.80
NOV	1.24	1.47	1.69	1.90	2.29	2.75
DEC	1.28	1.53	1.78	2.01	2.45	2.98

AZIMUTH ANGLE-45

TILT ANGLE

	5	10	15	20	30	45
JAN	1.21	1.41	1.60	1.78	2.11	2.50
FEB	1.10	1.20	1.29	1.38	1.53	1.69
MAR	1.05	1.11	1.17	1.22	1.30	1.36
APR	1.03	1.06	1.09	1.11	1.14	1.14
MAY	1.02	1.04	1.04	1.05	1.05	1.01
JUN	1.02	1.03	1.03	1.03	1.01	0.96
JUL	1.02	1.03	1.03	1.03	1.02	0.98
AUG	1.02	1.04	1.05	1.06	1.07	1.05
SEP	1.03	1.07	1.10	1.13	1.17	1.19
OCT	1.08	1.16	1.23	1.30	1.41	1.53
NOV	1.17	1.33	1.48	1.63	1.89	2.19
DEC	1.20	1.38	1.55	1.71	2.01	2.36

AZIMUTH ANGLE=90

TILT ANGLE

	5	10	15	20	30	45
JAN	1.02	1.03	1.05	1.07	1.10	1.14
FEB	1.00	1.00	1.00	1.01	1.02.	1.01
MAR	0.99	0.99	0.99	0.99	0.98	0.96
APR	1.00	0.99	0.99	0.98	0.97	0.93
MAY	1.01	1.00	1.00	0.99	0.96	0.92
JUN	1.01	1.01	1.00	0.99	0.96	0.91
JUL	1.01	1.01	1.00	0.99	0.96	0.91
AUG	1.00	1.00	0.99	0.98	0.96	0.91
SEP	0.99	0.99	0.98	0.98	0.96	0.92
OCT	0.99	0.99	0.99	1.00	1.00	0.98
NOV	1.01	1.02	1.03	1.04	1.07	1.10
DEC	1.02	1.03	1.04	1.06	1.08	1.10

AZIMUTH ANGLE=135

TILT ANGLE

	5	10	15	20	30	45
JAN	0.82	0.67	0.58	0.56	0.55	0.52
FEB	0.89	0.79	0.71	0.65	0.54	0.53
MAR	0.92	0.86	0.79	0.73	0.64	0.56
APR	0.96	0.92	0.88	0.83	0.75	0.65
MAY	0.99	0.97	0.94	0.91	0.84	0.74
JUN	1.00	0.99	0.97	0.94	0.88	0.78
JUL	1.00	0.98	0.96	0.93	0.86	0.77
AUG	0.98	0.95	0.92	0.88	0.81	0.71
SEP	0.95	0.90	0.85	0.80	0.72	0.63
OCT	0.91	0.82	0.75	0.69	0.61	0.55
NOV	0.85	0.72	0.63	0.55	0.54	0.51
DEC	0.85	0.73	0.70	0.70	0.68	0.64

AZIMUTH ANGLE=180

TILT ANGLE

	5	10	15	20	30	45
JAN	0.74	0.57	0.57	0.56	0.55	0.52
FEB	0.85	0.70	0.56	0.52	0.51	0.48
MAR	0.90	0.80	0.69	0.59	0.43	0.41
APR	0.95	0.89	0.83	0.77	0.63	0.45
MAY	0.99	0.96	0.92	0.88	0.79	0.63
JUN	1.00	0.98	0.96	0.93	0.86	0.72
JUL	0.99	0.97	0.94	0.91	0.84	0.70
AUG	0.97	0.93	0.89	0.84	0.74	0.56
SEP	0.93	0.86	0.79	0.71	0.56	0.48
OCT	0.87	0.74	0.62	0.52	0.50	0.47
NOV	0.78	0.59	0.55	0.55	0.54	0.51
DEC	0.78	0.71	0.70	0.70	0.68	0.64

APPENDIX C

GEOGRD

Input Instructions

GEOGRD

INPUT INSTRUCTIONS

INPUT TYPE SEQ	NAME	DESCRIPTION
A. Run Title - One line required.		
1	TITLE	Up to 80 characters to appear on the printed and plotted output.
B. Run Controls - One line required.		
1	IPRT	* 1 if node and element input data are to be echo printed. * 2 if both input data and complete network specifications are to be printed. * 0 otherwise
2	IPPN	*1 if node numbers are to be plotted. * 0 otherwise.
3	IPEN	*1 if element numbers are to be plotted. * 2 if material types are to be plotted. * 3 if both element numbers and material types are to be plotted. (option does not always work). * 0 otherwise.
4	IPO	* 0 if no plot is to be drawn. * 1 if only network is to be plotted. * 2 if only boundary is to be plotted. * 3 if both network and boundary are to be drawn. The boundary will identically overlap the extremities of the network if plotter does not advance the paper.
5	IPP	* 1 if a subsection of the network is to be drawn. This will require input type D. * 0 otherwise.
6	IRFN	* 1 if this run is to refine an existing network by subdivision of existing elements. This will require input type H as shown on Figure 4-2 in the operating instructions manual. * 0 otherwise.

INPUT TYPE SEQ	NAME	DESCRIPTION
7	IGIN	* 0 if new grid is to be generated. Fortran logical unit number of existing GEOGRD output file "LUNIT.DAT" to be modified.
8	LUNIT	Fortran logical unit number on which the file "LUNIT.DAT" will be written with the results of the GEOGRD run. This file will be used as input to GEOGRD and/or GEODYN.
9	IGEN	* 1 if a grid is to be generated from its quadrilateral corner points. This will require input type I. * 0 otherwise.
10	NXZL	Number of Line segments in the network on which the program is to internally calculate exact nodal coordinates to assure a straight line. A non zero value will require input type G.
11	IRO	* 1 if GEORGD is to internally rearrange the element order for more efficient GEODYN calculations. The printed output numbering will be unchanged. This option will require input type J. * 0 otherwise.

C. Plotting Scale Factors - One line required.

1	HORIZ	* 0 if XSCALE (C.3) and YSCALE (C.4) are used. * Otherwise the maximum horizontal size of plot. -in. If HORIZ and VERT are not zero the plot size will be adjusted so that a natural horizontal to vertical scale will be maintained and the entire plot will fit on the paper with one axis filled. The HP7475 plotter assumes the long dimension of the paper is horizontal.
2	VERT	* 0 if XSCALE (C.3) and YSCALE **(C.4)** are used. * Otherwise input the maximum vertical size of the plot - in.
3	XSCALE	* 0 if HORIZ (C.1) and VERT (C.2) are used. * Otherwise the horizontal scale factor, ie. (inches on the plot)/ (units in the mesh). The HP7475 plotter assumes the long dimension of the paper is horizontal.

INPUT TYPE SEQ	NAME	DESCRIPTION
4	YSCALE	* 0 if HORIZ (C.1) and VERT (C.2) are used. * Otherwise the vertical scale factor, ie. (inches on the plot)/ (units in the mesh).
5	AR	The clockwise angle in degrees from the horizontal axis on the plot to the **X-axis** in the mesh. Zero and -90 are typically used.
6	XFACT	Scale factor for the X-coordinates. All X-coordinate values will be multiplied by XFACT. (Default = 1.0).
7	YFACT	Scale factor for the Y-coordinates. All Y-coordinate values will be multiplied by YFACT. (Default = 1.0).

D. <u>Subsection Plot Control</u> - One line required if IPP (B.5) =1. Omit if **IPP** (B.5) = 0.

1	NXPMIN	Node number of node with minimum X-coordinate in the partial network to be plotted. (Default = network minimum).
1	NXPMAX	Node number of node with maximum X-coordinate in the partial network to be plotted. (Default = network maximum).
1	NYPMIN	Node number of node with minimum Y-coordinate in the partial network to be plotted. (Default = network minimum).
1	NYPMAX	Node number of node with maximum Y-coordinate in the partial network to be plotted. (Default = network maximum).

E. <u>Element Definition</u> - One line required for each element to be generated individually. Must include a 9999/ line even if no elements are input.

1	J	Element number.
2	IMAT(J)	Soil Zone number to be used in GEODYN.

INPUT TYPE SEQ	NAME	DESCRIPTION
3	NOP(J,K)	Enter **3** or 6 node numbers for triangular elements and 4 or **8** node numbers for quadralateral elements. If only the corner nodes are specified, GEOGRD will insert the midside nodes midway between the corners. **Start** at any corner and proceed counterclockwise.

>>>>> Signal end of list of elements by an additional line containing only 9999/.

F. Node Definition - One line required for each node to be input individually. Must include a 9999/ line even if no nodes are input.

1	J	Node number
2	CORD(J,1)	X-coordinate. - ft. (m).
3	CORD(J,2)	Y-coordinate. - ft. (m).
4	WD(J)	Network width at node J. - ft. (m). (Default = 1.0).

>>>>> Signal end of list of nodes by an additional line containing only 9999/.

G. Line Segment Coordinate Generation - **NXZL** (B.lO) lines required. Omit if **NXZL** = 0.

1	NA	Node number at one end of line segment. Must be a corner node of an element.
2	NB	Node number at other end of line segment. Must be a corner node of an element.
3-16	NIP	Up to **14** corner node numbers that are to lie on the line. The X-cordinate is assumed to be correct and the **Y-**cordinate will be adjusted so that the point lies on the line.

INPUT TYPE

SEQ	NAME	DESCRIPTION

H. Element Refinement - One line required for each area if IRFN (B.6) = 1. Omit if IRFN = 0.

1-4	NEW	Four node numbers (include a trailing 0 for triangular elements) that are to become the new comer nodes of the refined element. The nodes may be comer or midside nodes of an existing element (See Figure 4-2 of the GEOGRD Operating Instructions Manual).

>>>>> Signal end of list of refined elements by an additional line containing only 9999/.

I. Automatic Grid Generation - One line required for each area to be subdivided. Omit if IGEN (B.9) = 0.

1	IBLK	Numeric designator of the block being defined. The number is arbitrary.
2	NXI	Number of subdivisions (elements) to be made in the X direction. (Limit 1 to 25).
3	NYI	Number of subdivisions (elements) to be made in the **Y** direction. (Limit 1 to 25).
4	ITP	Material type number to be assigned to all of the elements generated within this area.
5	ISHP	* 0 if quadrilateral elements are to be generated. * 1 if triangular elements are to be generated.
6	TC(1)	X-coordinate of the upper left corner of area to be subdivided. - ft (m).
7	TC(2)	Y-coordinate of the upper left corner. - ft (m).
8	TC(3)	X-coordinate of the lower left corner. - ft (m).
9	TC(4)	Y-coordinate of the lower left corner. - ft (m).
10	TC(1)	X-coordinate of the lower right corner. - ft (m).
11	TC(2)	Y-coordinate of the lower right corner. - ft (m).

INPUT SEQ	TYPE NAME	DESCRIPTION
12	TC(3)	X-coordinate of the upper right corner. - ft (m),
13	TC(4)	Y-coordinate of the upper right corner. - ft (m).
14	ELC(1)	Width of upper left corner of area being subdivided. - ft (m). (Default = 1.0).
15	ELC(2)	Width of lower left corner. - ft (m). (Default = 1.0).
16	ELC(3)	Width of lower right corner. - ft (m). (Default = 1.0).
17	ELC(4)	Width of upper right corner. - ft (m). (Default = 1.0).

>>>>> Signal end of list of nodes by an additional line containing only 9999/.

J. Element Renumbering - One line required for each list of starter nodes that are to be tried if IRO (B.11) = 1. Only the one producing the most efficient operation will be retained for future use. The renumbering will not effect the numbers printed in the output or used in input specifications. Omit if IRO = 0.

1-50	NLIST	Up to 50 node numbers from which the program will reorder the internal sequence of elements to obtain the most efficient GEODYN program operation. **As** a general rule, at least two starting locations should be tried, one at each end of the grid. **A** single node number is enough to create a renumbered sequence. The list may include corner nodes and/or midside nodes and the results are sometimes slightly different even though the nodes all lie along a line.

>>>>> Signal end of list of trial starting locations by an additional line containing only blanks.

APPENDIX D

GEODYN
Input Instructions

GEODYN

INPUT INSTRUCTIONS

INPUT TYPE

SEO	NAME	DESCRIPTION
O. Units Control - One line required.		
1	MORE	* 1 if Metric units are to be used. * **2** if English units are to be used.
A. Run Title - One line required.		
1	TITLE	Up to 80 characters to appear on the printed output.
B. Run Controls - One line required.		
1	NCD	* 0 If all elements to be used are included in file LUNIT.DAT from GEOGRD, a restart file LI.DAT from a previous GEOGRD run, or input type K of this data set. * Number of elements to be defined individually.
2	NPX	* 0 If all nodes to be used are included in file LUNIT.DAT from GEOGRD, a restart file LI.DAT from a previous GEOGRD run, or input type **K** of this data set. * Number of nodes to be defined individually.
3	NMAT	Number of material zones. Each unique combination of characteristics constitutes a different zone. This must conform to the constraints placed in GEOGRD if a geogrd input file is used. (Limit **1** to 20).
4	IS1	Control for initial temperature conditions. * 0 if all initial temperatures are to be input in a restart file LI.DAT from a previous GEODYN run. * >0 The number of nodes at which the initial temperature is to be explicitely input. The temperatures of all nodes will be set initially to the temperature of the first node specified, ie., if the entire field is to have the same initial temperature, only one node need be specified. Each additional value modifies the first value. Midside nodes must be included. The nodes and initial temperaturese are specified on input type M.

INPUT DATA TYPE

SEO	NAME	DESCRIPTION
		* -1 or **-2** The initial nodal temperatures will be set according to the equation given below: $T = T1 + (T2 - T1)e-kl$ Where: $T1$ = temperature at $1 = 0$. $T2$ = temperature at l = infinity. k =constant. 1 = **X** if **IS1** = -1 and Y if IS1 = -2. T1, T2, and k are input in input type N. Note that, if IS1 < 0, the initial temperature distribution is dependant upon the initial coordinate system used and the location of the network in that coordinate system.
5	IPRT	* 1 if nodal coordinates, nodal connections, and element areas are to be printed. * 0 otherwise.
6	NSPN	Number of nodes to be used in a summary of temperatures at each time step to be output at the end of the printout. The node numbers will be included in input type **H.** (Limit 0 to 12).
7	ISOC	* 1 if the program is to calculate and print the location of the freezing isotherm. * 0 otherwise.
8	LUNIT	FORTRAN logical unit number for the input file LUNIT.DAT that was generated by GEOGRD.
9	LI	FORTRAN logical unit number for the restart file LI.DAT that was generated by a previous run of GEODYN. The file was named IT.DAT during creation and must be renamed.
10	IT	FORTRAN logical unit number for the output restart file IT.DAT to be used by a future GEODYN run. It must be renamed LI.DAT before it is used.
11	**IS5**	FORTRAN logical unit number for the complete time history output file IS5.DAT from this simulation. The file can be used for post processing such as input to program GEOPLT. **It** must be renamed LUG.DAT before it is used in GEOPLT.

INPUT DATA TYPE

SEQ	NAME	DESCRIPTION
12	ISINO	Number of surface boundary nodes at which an annual sinusodial temperature variation is to be imposed. These nodes will be the last **ISINO** node numbers assigned for boundary condition specifications and are listed in input type T. Midside nodes must be included. (Note: **ISINO** and NSFl (B.13) can not both be non-zero). (Limit 0 to Total number of surface nodes).
13	NSFl	Number of element sides (faces) which define the network interface to receive full energy balance calculations. **If** NSFl > 0, data types P1 through P5 and **W** 1 and W2 will be reqired. (Note: NSFl and ISINO(B.12) can not both be non-zero). (Limit 0 to 100).
14	NSF2	Number of element sides (faces) which define the network interface to receive a specified thermal flux. The thermal flux is specified in input type R. **It** is assumed that the thermal flux is 0 on all surface element faces unless otherwise specified.
15	**NBCG**	Number of profiles of annual surface boundary temperatures. The profiles are specified by input type **S.**
16	IRO	* 1 if GEODYN is to internally reorder the elements for more efficient computation. The printed output numbering system will be unchanged. The reordering will be specified by input type L. Reording may have already been done in GEOGRD. * 0 otherwise.

C. Numeric Solution Controls - One line required.

SEQ	NAME	DESCRIPTION
1	MAXI	Maximum number of Newtonian iterations for a given time step for a given level of numeric integration. Usually start with 10. (Limit 1 to 25).

C. (Cont.)

SEQ	NAME	DESCRIPTION
2	MINGP	Minimum level of numeric integration. Usually start with 1. (Limit 1 to 5 and MINGP <= MAXGP).
3	MAXGP	Maximum level of numeric integration. Usually start with **2.** (Limit 1 to 5 and MINGP **<= MAXGP).**

INPUT DATA TYPE

SEQ	NAME	DESCRIPTION
4	NURF	The iteration number at which the program will apply an under relaxation factor of 0.5 for the Newtonian iteration. Normally this is set to 0 and if convergence problems develop the value is changed to **8.**
5	MAXSUB	The program will automatically half the time specified step if a stable solution cannot be reached. MAXSUB is the maximum number of times this will be allowed before the program stops on error. Usually start with 4.
6	CONVC	The temperature convergence criteria. - °F (°C). The program will stop on error if this limit is exceeded by a factor of 10 on the last iteration. Normally start with 0.01 °F (°C).
7	ALPHA	The Alpha factor used in the time iteration scheme shown in equation 1.6 of the operating instructions for GEODYN. Usually start with 1.5 and modify if convergence problems develop. (Limit 1.0 to **2.0).**

D. Scale Factors - One line required.

SEQ	NAME	DESCRIPTION
1	**XSCALE**	**X-** direction (or R-direction) inputs for nodal locations will be multiplied by this factor to change input values to field values of feet (meters). For example, if the input value was 2.5 because it was 2.5 inches (centimeters) from the origin of the paper on which it was drawn but it should be 5.0 feet (5 meters) in the field, XSCALE would be **2.0,** because the input number was a unitless 2.5 and the program will use the units of feet (meters).
2	YSCALE	Y-direction (or Z-direction) inputs for nodal locations will be multiplied by this factor to change scaled input values to field values of feet (meters).

D. (Cont.)

SEQ	NAME	DESCRIPTION
3	WSCALE	Thickness inputs for nodal locations will be multiplied by this factor to change scaled input values to field values of feet (meters).
4	USCALE	x- direction (R-direction) inputs for groundwater velocity will be multiplied by this factor to change scaled input values to field values of feet/hour (meters/hour).

INPUT DATA TYPE SEQ	NAME	DESCRIPTION
5	**VSCALE**	Y- direction (2-direction) inputs for groundwater velocity will be multiplied by this factor to change scaled input values to field values of feet/hour (meters/hour).

E. Time Step Controls - One line required.

SEQ	NAME	DESCRIPTION
1	NTIME	Number of time steps in this simulation.
2	NTSEG	Number of calculation time steps between printouts. If NTSEG = 1, printouts will occur at every calculated time step.
3	NVTS	Number of different time steps to be read in input type F. (Limit at least 1).
4	TSTART	Starting time in days after January 1 for this run. This value will be overridden if a restart file is used.

F. Time Step Length - NVTS (E.3) lines required.

SEQ	NAME	DESCRIPTION
1	N	Number of time step.
2	DELTX	* 0 if a steady state solution is desired. If DELTX = 0, MAXI (C.1) should be 1. * >0 Time step size in days.

G. Sinusoidal Temperature Boundary Condition - Omit if ISINO (B.12) = 0. The equation used is as follows:

$$T = TMEAN + AMP*Sin(\frac{Day + PHASE}{365} * 90)$$

SEQ	NAME	DESCRIPTION
1	TMEAN	Base temperature for the sinusoidal temperature relationship. There will be 182.5 days of higher and 182.5 days of lower temperature in the year. This is node temperature and not air temperature. - °F, (°C).
2	AMP1	Maximum amplitude of sinusoidal temperature in summer, ie., the absolute value of the difference between TMEAN and the maximum summertime temperature. - °F, (°C).
3	AMP2	Maximum amplitude of sinusoidal temperature in winter, ie., the absolute value of the difference between TMEAN and the minimum summertime temperature. - °F, (°C).

INPUT DATA TYPE

SEO	NAME	DESCRIPTION
4	PHASE	PHASE relates to the time between the coldest day and January 1. Input the negative of the number of days after January 1 that the temperature equals **TMEAN** on rising temperature. A value on the order of -120 is frequently appropriate.

H. Time History Summary Nodes - Omit if NSPN (B.6) = 0.

1-12	ISPN	Node Numbers for which complete time history summaries will be printed out at the end of the computer run. (Limit 1 to 12).

I. Zone Material Properties - NMAT (B.3) lines required.

1	J	Material Zone Number. Corresponds to element zone definitions in file LUNIT.DAT from GEOGRD, the restart file LI.DAT from a previous GEODYN run, or IMATL (K.10) from this data set.
2	ORT(J,1)	Frozen thermal conductivity in the **X** or R-direction. - BTU/ft-hr-°F (W/m-°C).
3	ORT(J,2)	Frozen thermal conductivity in the Y or 2-direction. - BTU/ft-hr-°F (W/m-°C).
4	ORT(J,3)	Unfrozen thermal conductivity in the **X** or R-direction. - BTU/ft-hr-°F (W/m-°C).
5	ORT(J,4)	Unfrozen thermal conductivity in the Y or Z-direction. - BTU/ft-hr-°F (W/m-°C).

I. (Cont.)

6	ORT(J,5)	Frozen volumetric heat capacity. - BTU/ft^3-°F (kJ/m^3-°C).
7	ORT(J,6)	Unfrozen volumetric heat capacity. - BTU/ft^3-°F (kJ/m^3-°C).
8	HEATL(J)	Heat of fusion. - BTU/ft^3, (mJ/m^3).

9 ALPE(J) Alpha in the soil moisture - temperature function for this material. The relationship shown in figure land is given as **Eq.** 1.3 and is shown pictorily on Fig. B-6 in the operating instruction for GEODYN". Examples of Alpha values are given in Figure **2.**

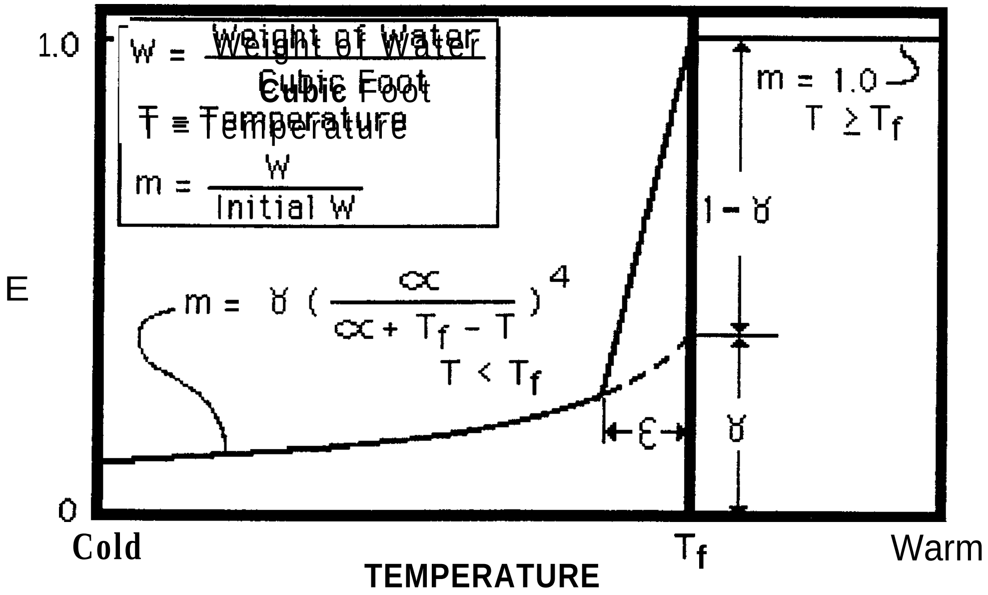

Figure 1 Relationship between moisture content and temperature.

10 GAME(J) Fraction of moisture not frozen isothermally **.**

11 EPSE(J) Absolute value of the temperature range over which isothermally released latent heat takes place. (Limit > 0, but calculational efficiency drops drastically if EPSE(J) is less than about 0.5 oF. - oF (oC).

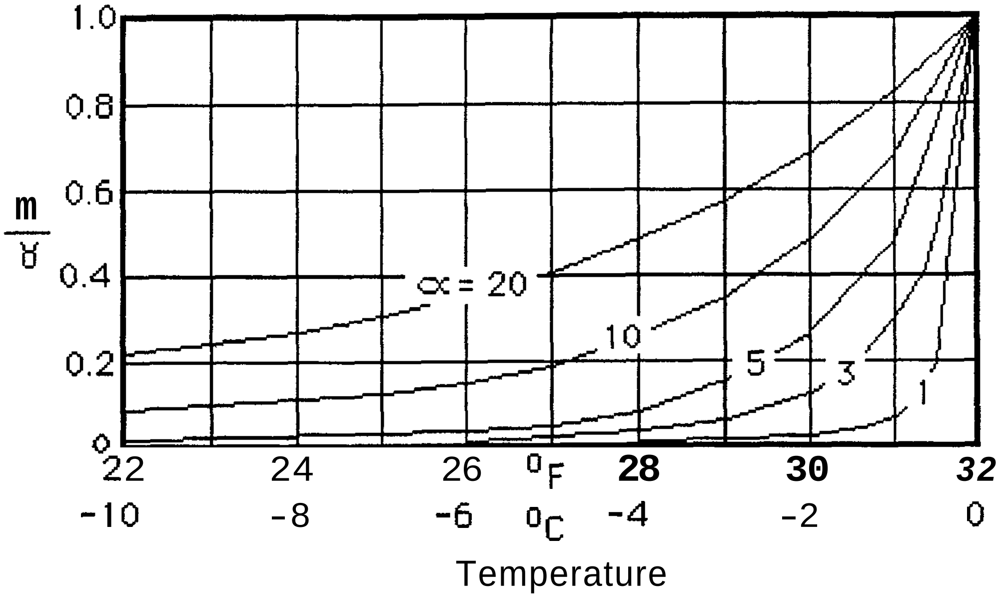

Figure **2.** Example values of Alpha

J. Node Definitions - NPX (B.2) lines required. Omit if NPX = 0.

SEQ	NAME	DESCRIPTION
1	J	Node number.
2	CORD(J,1)	X or R-coordinate location. - ft (m).
3	CORD(J,2)	Y or Z-coordinate location. - ft (m).
4	WD(J)	Width of network at this node. (default = 1). - ft (m).

K. Element Defininition - NCD (B.1) lines required. Omit if NCD = 0.

SEQ	NAME	DESCRIPTION
1	J	Element number.
2-9	NOP(J,K)	Eight node numbers, starting at a comer and going counterclockwise around the element. For triangular elements the last two node numbers must be 0.
10	IMAT(J)	Material number used in input type **I** to be used with this element. **If** 0 is used it will null the element and, in effect, remove it from the mesh without regenerating the mesh.

INPUT DATA TYPE
SEQ **NAME** DESCRIPTION

L. Element Renumbering - One line required for each list of starter nodes that are to be tried if IRO (B.16) = 1. Only the data set producing the most efficient operation will be retained for future use. The renumbering will not effect the numbers printed in the output or used in input specifications. Omit if IRO = 0.

1-50	NLIST	Up to 50 node numbers from which the program will reorder the internal sequence of elements to obtain the most efficient GEODYN program operation. As a general rule, at least two starting locations should be tried, one at each end of the mesh. **A** single node number is enough to create a renumbered sequence. The list may include corner nodes and/or midside nodes and the results are sometimes slightly different even though the nodes all lie along a line.

>>>>> Signal end of list of nodes by an additional line containing only **9999/.**

M. Initial Temperature Specification at Individual Nodes - IS1 **(B.4)** lines required. Omit if IS1 <= 0.

1	J	Node number at which the initial temperature is to be explicitly input.
2	TNEW(J,)	Initial temperature of node J.

N. Initial Temperature Relationship Specified bv Equation - One line required. Omit if IS1 (B.4) <= 0. See input type B.4 for a complete description of the input parameters.

1	T2	Initial temperature on axis. **-** °F (°C).
2	T1	Initial temperature at inifinity. **-** °F, (°C).
3	K	The exponential decay factor to transition from **T2** to Tl.

P & O & W Surface Energy Balance

Note: Data types Pland P2 are used to initially define the parameters for a full surface energy balance across particular element faces with arbitrary time intervals. Data types Q1 through ***Q3*** are used to define the parameters for a full surface energy balance if regular time intervals are used. Data type ***Q*** is used if NSFl (B.13) is not 0. Data type P may be used if **NSF = O** but may be omitted by including a **9999/** line.

P. P1&P2 Surface Energy Balance with Arbitrary Time Intervals -

May only be used if **NSFl** (B.13) = 0. To omit if **NSF** = 0, include only a 9999/ line.

Note: Data types P1 and P2 are taken in pairs to define element faces for a complete surface energy balance. The node numbers numbers defined by data type P1 are used with the data defined by data type P2. A 9999/ line must follow the last pair of lines. Data types W1 and W2 are used to update the data in data types P1 and P2 at arbitrary time intervals. The control for data types W1 and W2 is **NSF** (T.3).

P1. Nodes for Surface Energy Balance. - Omit if data types P1 & P2 are not desired.

SEQ	NAME	DESCRIPTION
1 - 100	NSM(I)	List of midside node numbers of the element sides to be treated with a full surface energy balance according to the input defined by input type P2.

P2. Initial Surface Flux Parameters - Omit if data types P1 & P2 are not desired.

SEQ	NAME	DESCRIPTION
1	QSWJ	Short wave solar radiation on surface with no cloud cover. BTU/$_{ft^2}$ hr, ($^W/_{m^2}$).
2	TAIRJ	**Air** temperature. ^oF, (^oC).
3	WSPDJ	Wind Speed. $^{mi}/_{hr}$, ($^{km}/_{hr}$).
4	CLDCVJ	Fractional cloud cover. (Limit 0 to 1.0).
5	EVPRTJ	Evapotranspirtation flux. BTU/$_{ft^2}$ hr, ($^W/_{m^2}$).
6	SDEPJ	Snow depth. ft, (m).
7	SDENJ	Relative density of snow. (Limit 0.1 to 0.9)
8	ALXJ	Short wave radiation albedo. Use the albedo of snow if there is snow on the ground. (Limit 0 to 1).

P2. (Cont.)

SEQ	NAME	DESCRIPTION
9	EMXJ	Long wave radiation emissivity. Use the emissivity of snow if there is snow on the ground. (Limit 0 to 1).

INPUT DATA TYPE

SEO	NAME	DESCRIPTION
10	RUFJ	Surface roughness. Use the roughness of snow if there is snow on the ground. ft, (m).

>>>>>> End data set with a line containing only 9999/.

O. OI through 0 3 Surface Energy Balance with monthly property variations - omit all three data types if NSFl (B.13) = 0.

0 1 Meterological Conditions - Twelve cards required, one for each month.

1	N	Month. (Limit 1 to 12).
2	DOM(N)	Day of year corresponding to this month. (Limit 1 to 365).
3	QSW(N)	**Short** wave solar radiation for this month. - $\mathrm{BTU}/\mathrm{ft}^2\,\mathrm{hr}$ (W/m^2).
4	TAIR(N)	Air temperature this month. - ^{o}F (^{o}C).
5	WSPD(N)	Wind speed for this month. - mi/hr (km/hr).
6	CLDCV(N)	Fractional cloud cover for this month. (Limit 0 to 1.0).
7	EVPRT(N)	**Evapotranspiration** flux for this month. - $\mathrm{BTU}/\mathrm{ft}^2\,\mathrm{hr}$ (W/m^2).
8	SDEP(N)	Snow depth for this month. - ft (m).
9	SDEN(N)	Relative density of snow for this month. (Limit 0.1 to 0.9)

02. Meteorological Data Multipliers

1	CVF(1)	Multiplier applied to QSW (Q1.3).
2	CVF(2)	Multiplier applied to TAIR (Q1.4).
3	CVF(3)	Multiplier applied to WSPD (Q1.5).

02. (Cont.)

4	CVF(4)	Multiplier applied to CLDCVR (Q1.6).
5	CVF(5)	Multiplier applied to EVPRT (Q1.7).
6	CVF(6)	Multiplier applied to SDEP (Q1.8).

INPUT DATA TYPE

SEQ	NAME	DESCRIPTION
7	CVF(7)	Multiplier applied to **SDEN** (Q1.9).

03. Surface Energy Balance Parameters - NSFl (B.13) lines required.

SEQ	NAME	DESCRIPTION
1	NLIST1(J,2)	Midside node number of an element face which is to be included in a surface energy balance calculation.
2	ALGND(J)	Short wave radiation albeto for this face when snow free. (Limit 0 to 1.0).
3	ALSNO(J)	Short wave radiation albeto for this face when snow covered. (Limit 0 to 1.0).
4	VFACT(J)	Short wave view factor. (Limit 0 to 1.0).
5	EMGND(J)	Long wave radiation emissivity for this face when snow free. (Limit 0 to 1.0).
6	EMSNO(J)	Long wave radiation emissivity for this face when snow covered. (Limit 0 to 1.0).
7	RBARE(J)	Surface roughness for this face when snow free. - ft (m).
8	RSNOW(J)	Surface roughness for this face when snow covered. - ft (m).
9	EFACT(J)	Ratio of the monthly evapotranspiration flux to the evapotranspiration flux assigned to this element face. (Limit 0 to 1.0).
10	TFACT(J)	Ratio of the monthly snow depth to the snow depth assigned to this element face. (Limit 0 to 1.0).
11	DFACT(J)	Ratio of the monthly snow density to the snow density assigned to this element face. (Limit 0 to 1.0).

R. Constant Heat Flux - NSF2 (B.14) lines required. Omit if NSF2 = 0.

SEQ	NAME	DESCRIPTION
1	NLIST2(N.2)	The midside node number of an element face across which a flux is to be specified.
2	FLUXC(N)	The constant flux to be applied across the element face. A positive value is an input and a negative value is a withdrawl. - $\mathrm{BTU}/\mathrm{ft}^2\text{-hr}$ (W/m^2).

S. Time Dependant Boundary Condition - One line required if NBCG (B.15) >= 0. Omit if NBCG = 0.

SEQ	NAME	DESCRIPTION
1	JJ	The time series order number. This number will be IG (B.3) used for reference purposes when the boundary conditions are specified on data type U.
2	N	Number of day temperature pairs used to define the annual temperature schedule. (Limit 2 to 20).
3-22	TBC,VBC	N **(S.2)** pairs of Julian day (TBC) and the associated temperature (VBC). The temperature at intermediate days will be linearly interpreted detween the two adjacent pairs. (Limit on TBC, 0 to 365).

Note: The set of T, U, **V** and W input types may be repeated for as many time steps as desired. After the last set of inputs has been exhausted, the program will use the last set of values read for the remainder of the run. The temperature boundary conditions and/or convective velocities may be time dependant. If, for example, one wished to change only 10 of the 25 originally specified velocities and leave the temperatures alone, the proper specification would be **NXX** = 0 and NVEL = 10.

T. Boundarv Condition Control - One line required.

SEQ	NAME	DESCRIPTION
1	NXX	Number of nodes to which the time dependant boundary conditions specified by data type *S* are to be applied, plus **ISINO** (B.12) which is the number of nodes to which the sinusodial temperature boundary conditions specified by input type U are to be applied. (Limit 0 to total number of nodes).
2	NVEL	Number of nodes at which a groundwater velocity is to be specified by input type **V.**

T. (Cont.)

SEQ	NAME	DESCRIPTION
3	**NSF**	Number of sets of surface heat flux updates (input type **W**1 & W2 pairs) to be used in the next time step.

U. Temperature Boundary Conditions - NXX **(T.**1) lines required.

SEQ	NAME	DESCRIPTION
1	J	Node number where the boundary condition is to be applied.

2	TNEW	Node temperature if a constant temperature is to be applied to this node. If TNEW is to be used, IG (U.3) must be 0. If an annual temperature profile defined by data type *S* is to be applied to this node, then IG will be greater than 0 and the value of TNEW will be overridden so any value may be used for TNEW. °F (°C).
3	IG	* 0 if a constant value of TNEW is to be used for this node. * IG > 0 will result in the temperature being taken from the **IG** annual temperature profile specified by input type *S*.

V. Flow Velocitv Boundarv Conditions - NEVL (T.2) lines required. Omit **if** NEVL = 0.

1	N	Node number where flow velocities are to be defined.
2	UX	The Darcy flow velocity to be assigned to the node in the X-direction. This value will be multiplied by USCALE (D.4). to convert this unitless number to the correct units of feet/hour (meters/hour).
2	*u Y*	The Darcy flow velocity to be assigned to the node in the **Y** direction. This value will be multiplied by VSCALE (D.5). to convert this unitless number to the correct units of feet/hour (meter/hour).

W1. Surface heat flux nodes to be updated. - Omit if NSF (T.3) = 0.

1-	**NSM(I)**	List of node numbers to have updated surface energy balance parameters. The node numbers must be in the list **of** nodes originally specified by data type P1 but not all of those nodes must be upgraded. The parameters specified remain in effect until they are changed by a **W** 1 & W2 combination.

W2. Surface Flux Parameters for Element Sides Specified In Input Type W1 - Omit if NSF (T.3) = 0.

1	**QSWJK**	Short wave solar radiation on surface with no cloud cover. - $\mathrm{BTU}/\mathrm{ft}^2\,\mathrm{hr}$ (W/m^2).
2	TAIRJK	Air temperature. - °F (°C).
3	WSPDJK	Wind Speed. - mi/hr (km/hr).

INPUT DATA TYPE		
SEQ	NAME	DESCRIPTION
4	CLDCVJK	Fractional cloud cover. (Limit 0 to 1.0).
5	EVPRTJK	Evapotranspirtation flux. - $\mathrm{BTU}/\mathrm{ft}^2\,\mathrm{hr}$ (W/m^2).
6	SDEPJK	Snow depth. - ft (m).
7	SDENJK	Relative density of snow. (Limit 0.1 to 0.9)
8	ALXJK	Short wave radiation albedo. Use albedo of snow if there is snow on the ground. (Limit 0 to 1.0).
9	EMXJK	Long wave radiation emissivity. Use emissivity of snow if there is snow on the ground. (Limit 0 to 1.0).
10	RUFJK	Surface roughness. Use roughness of snow if there is snow on the ground. - ft (m).

APPENDIX E

GEOPLT

Input Instructions

GEOPLT

INPUT INSTRUCTIONS

INPUT TYPE SEQ	NAME	DESCRIPTION
A Title		
1	TITLE	**Up** to 80 characters to be used in file OUT.DAT. Does not appear on plots.
B Run Controls		
1	LUG	FORTRAN logical unit number containing the output file LUG.DAT from GEODYN. This file is named IS5.DAT when it is output from GEODYN. (Default = 1).
2	LUV	Number of plots to be made. (Limit 1 to 100).
3	IBPP	* 1 if the outer boundary of the network and/or a series of connected straight line segments forming element sides is to be plotted. * 0 otherwise.
4	NX	Number of grid lines in the X-direction to be used in developing the contour plot. (Limit 10 to 65). (Default = 35).
5	NY	Number of grid lines in the Y-direction to be used in developing the contour plot. (Limit 10 to 65). (Default = 35).
6	XSCALE	Scale factor applied to the X-coordinate values before plotting, ie. (size on plot in inches)/(units in the mesh).
7	YSCALE	Scale factor applied to the Y-coordinate values before plotting, ie. (size on plot in inches)/(units in the mesh).
8	NXPMIN	Node number which has the minimum X-coordnate to be used in the plot. (Default = network minimum).
9	NPXMAX	Node number which has the maximum X-coordnate to be used in the plot. (Default = network minimum).

INPUT TYPE SEQ	NAME	DESCRIPTION
10	NPYMIN	Node number which has the minimum Y-coordinate to be used in the plot. (Default = network minimum).
11	NYPMAX	Node number which has the maximum Y-coordinate to be used in the plot. (Default = network minimum).

C File Record Numbers

1-100	List	List of file record numbers (ie., time step numbers) to be plotted from the GEODYN file LUG.DAT. LUV **(B.2)** numbers must be included. The numbers may be in any order.

Note: Input types D through G are repeated for each plot. There must be LUV (B.2) sets of these input types.

D Plot Outline Control - Omit if IBPP **(B.3)** = 0.

1	NPTS	* 0 if only the boundary of the network is to be plotted along with the temperature contours. * IF NPTS < 0, the series of lines defined by connecting the **NPTS** points given in input type **E** will be plotted along with the temperature contours. (Limit -400 to -1). * **If** NPTS > 0, the network boundary and the series of lines defined by connecting the **NPTS** points given in input type **E** will be plotted along with the contours. (Limit 1 to 400).

E Specified Line Definition - Omit if NPTS (D.l) or IBPP **(B.3)** = 0).

1-400	NPB	List of NPTS (D.l) node numbers following element sides which define a series of connected lines to be plotted along with the temperature contours.

F Plot Title

1	LITL	Up to 80 characters to be included on the plot.

G Contour Specifications

1	**NUMV**	The number of contours to be attempted on this plot. (Limit 1 to 20).
2-21		The contour values to be plotted. - °F (°C)

APPENDIX F

GEOGRD

Operating Instructions

OPERATING INSTRUCTIONS FOR THE COMPUTER PROGRAM GEOGRD

A Program for Generation of Finite Element Grids

by

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TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

The purpose of the computer program GEOGRO is to generate two-dimensional finite element grids for use by other computer programs such as GEODYN. As such, GEOGRD is not a simulation program, but rather a data preprocesssor in RMA's modeling system.

The specific capabilities of GEOGRD are the following:

- To read, edit and print all geometric data required for the GEODYN computer program. Input for this process may come either from cards or a file written by a previously executed application of GEOGRD.
- To refine, update, modify and change a network which has been generated by a previous run of GEOGRD.
- To generate quadrilateral or triangular grids from the specification of outside corners.
- To produce a graphical plot of the entire user-defined network as it is perceived by the finite element program.
- To produce a graphical plot of outside limits of the network which Can be used as a check on network construction.
- To write a data file which can be used as input to GEOOYN.

CHAPTER 2

PROGRAM ORGANIZATION AND DESCRIPTION

The GEOGRD program consists of one master routine and several subroutines, as shown in Figure 2-1. Pen plots are produced through calls to standard Calcomp library routines. GEOGRD plots curved sided elements according to the same mathematical functions as are used by the finite element shape functions. Brief descriptions of each of the program's routines are provided below (in alphabetical order after the main routine).

MAIN ROUTINE

The main routine is used as a starting point for the program and to issue calls to various program subroutines. Program execution is initiated in the main routine after which the specified input data is read either from cards or an input file. As a general rule all input data will be echo printed out imnediately after input.

The first item of input is the run control information. This information sets various internal switches to direct the program's logical activity. Following that, the program reads a set of plot and coordinate scale factors and an optional set of limits on the extent of the network to be plotted. Next, the user-defined element definitions and coordinate locations are input, with subroutine FILL called to fill in any missing node numbers. If requested, subroutine REFINE is then called and will undertake the refinement of the currently defined network according to user specifications. At this point the program will output to the line printer the current status of the network (i.e., element definitions and nodal locations) and then (optionally) call the network generation subroutine, GNET. Upon return from GNET, the program will apply the user-defined scale factors and write a file for subsequent use by GEODYN. At this point the user may request a call to subroutine PRTNET which will output a final sumnary of the network generation exactly as it has been written to the output file.

Subsequent to writing the output file the program will either halt or continue to the plotting function. If plotting is requested, the network will be drawn element side by element side via calls to subroutine FIT. In this process the element numbers, node numbers and material zone numbers may or may not be plotted as the user desires. Following the plotting of the full network, the outer boundary of the network may be plotted separately by a call to BNDIT; if the network

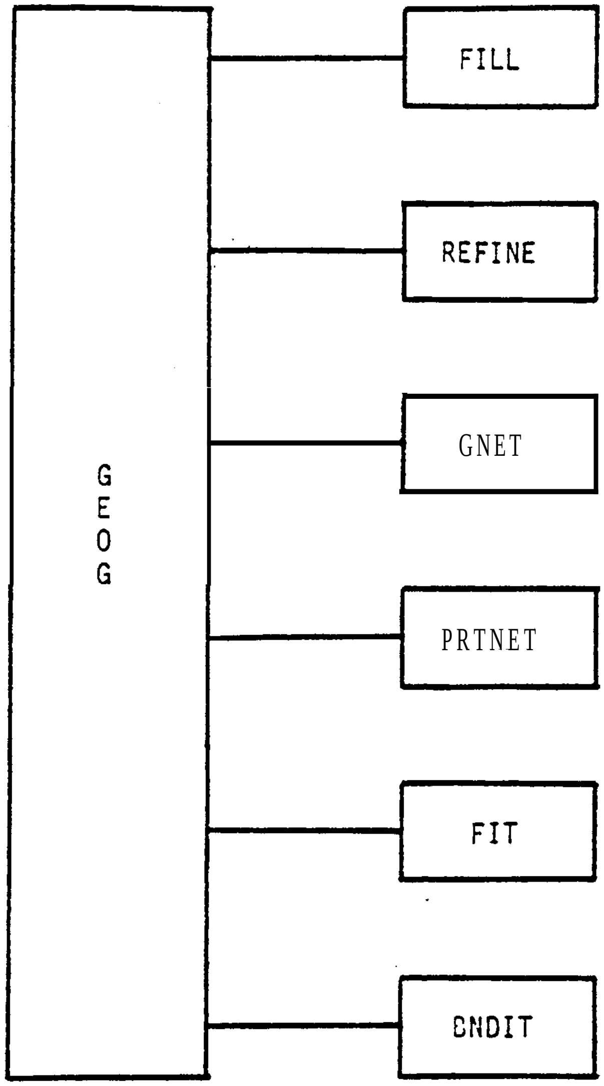


FIGURE 2-1

PROGRAM ORGANIZATION
GEOGRD **PROGRAM**

has been refined this is a useful check to make sure no "holes" have been left in the network. Following the plotting, the program terminates.

Subroutine BNDIT

If the user so requests, subroutine BNDIT will plot the outside boundary of the network. This option is used mainly as a check to see that no internal regions have been omitted from the network in the generation or refinement process.

Subroutine BNDIT is called from the main program and makes no additional calls except to standard Calcomp plotting routines.

Subroutine FILL

If the user elects to hand number the network (or a port on thereof) he will be required to define either six noded triangu ar elements or eight noded quadrilateral elements. In either case, node numbers are needed at the corners of these elements as well as at midside locations between the corners. To facilitate data entry, if the user defines only the corner nodes of an element (either 3 or 4 values), FILL will assign midside node numbers as required. The option for the user to assign only corner node numbers can be used in any combination with fully defined elements, and in no way alters numbers assigned by the user.

In order to find out what midside node numbers have been assigned by FILL, the user must inspect the printed and/or plotted program output. Subroutine FILL is called from and returns to the main program and makes no further subroutine calls.

Subroutine FIT

When a plot of the network is requested, the main routine generates a list of the nodes which define each element side and then plots each side via calls to FIT. The x and y coordinates of the three nodes on an element side are passed to FIT. This enables FIT to pass a finite element shape function tnrough the points and to plot, in a piecewise linear fashion, the exact shape of both straight and curved element sides.

Subroutine GNET

As a program option, the user may generate four-sided network regions automatically by using subroutine GNET. This routine, which will generate either triangular or quadrilateral elements, begins by reading and outputing to the printer the specifications for the area to be generated. Such a network generation can be either of a stand alone type or can be an addition to an existing network. In either case, GNET will assign element numbers, zone types, nodal numbers and nodal coordinates according to user specifications, and all assignments will be compatible with network definition existing at the The order in which node numbers are assigned by GNET can be influenced by the user's order of specification of the corners of the area to be generated.

Subroutine GNET is called from the main routine and returns control after completing all generation activities. It makes no further calls, but the user should invoke PRTNET and the plotting options if GNET has been used.

Subroutine PRTNET

Subroutine PRTNET outputs to the line printer the exact network specifications after all generation and data input is complete. This routine is called by a user option. It is a very good idea to use this routine to produce a hard copy of the final network once generation is complete to ensure that errors in the network do not exist. Subroutine PRTNET is called from the main routine and makes no further calls.

Subroutine REFINE

As a program option, the user may subdivide existing triangular' or quadrilateral elements into new elements according to a set of input specifications. This option is quite useful if the need arises to add additional detail into selected portions of an existing network.

To provide this option, subroutine REFINE reads and prints the existing node numbers of what are to be the new corner node numbers of a subdivided element. If an input node number does not exist, an error message is printed and program execution is stopped. Assuming proper specifications, REFINE defines a new element from the old, and adds additional midside node numbers as required. The material zone type of the original element is assigned to the new element created.

This process is repeated until all refinement is complete. All the elements in the network are then renumbered to eliminate voids, and the new element numbers and nodal connections output to the printer, Subroutine REFINE is called from the main routine and makes no further calls. If subroutine REFINE is called, the user should plot both the new network and the network boundary to check for errors in network construction.

CHAPTER 3

EXAMPLE PROBLEM

To demonstrate the operation of GEOGRD, a test problem has been constructed as an example. Various views of the test network are shown in Figures 3-1, 3-2 and 3-3 and presents a two-dimensional representation of a pipeline in a soil mass. The major subdivisions in Figure 3-1 are zones of different material properties while Figure 3-2 shows an enlarged view of the network in the region near the pipe. Figure 3-3 provides another plot of the entire network, but in this case the 12 zones which were defined by GEOGRD's network generation option are shown by heavy outlines.

Proper network layout is a fundamental aspect of finite element modeling and one which becomes considerably easier with experience. The reader is referred to the example problem for a graphical interpretation of the proper procedure for network layout. The first step in the layout procedure is to get a diagram or map of the system and sketch out the problem's overall boundaries. This should be done with the prototype's major chracteristics in mind so as not to be overly concerned with local details. As a general rule, the extremeties of the system should be set at locations where boundary conditions can be reasonably specified. The general rule is to provide extra detail in those areas where large thermal gradients are expected, such as near load points or shape changes in system geometry; when in doubt, provide extra detail.

Once the network's overall limits have been set it is usually advisable to construct a series of lines more or less parallel to the long axis of the problem. The position and frequency of these lines should reflect the areas of special importance in the problem. Once such lines have been located, transverse lines can be drawn, again recognizing the requirements and details of the problem. After the basic network has been established, the triangular and/or quadrilateral structure can be filled in with special attention to corners and other areas where gradients are expected to be large. Node and element definitions can be made either manually or via GEOGRD's grid generation option.

To accommodate irregular boundaries, and to eliminate sharp corners, GEOGRD will accept any combination of triangular or quadrilateral elements with curved sides. Each side of each element is defined in terms of the coordinates of the three nodal points which lie along the element side. In all cases there exists a nodal point at each end of an element side with an internal, or midside node, at an arbitrary location between the end points. For straight element sides

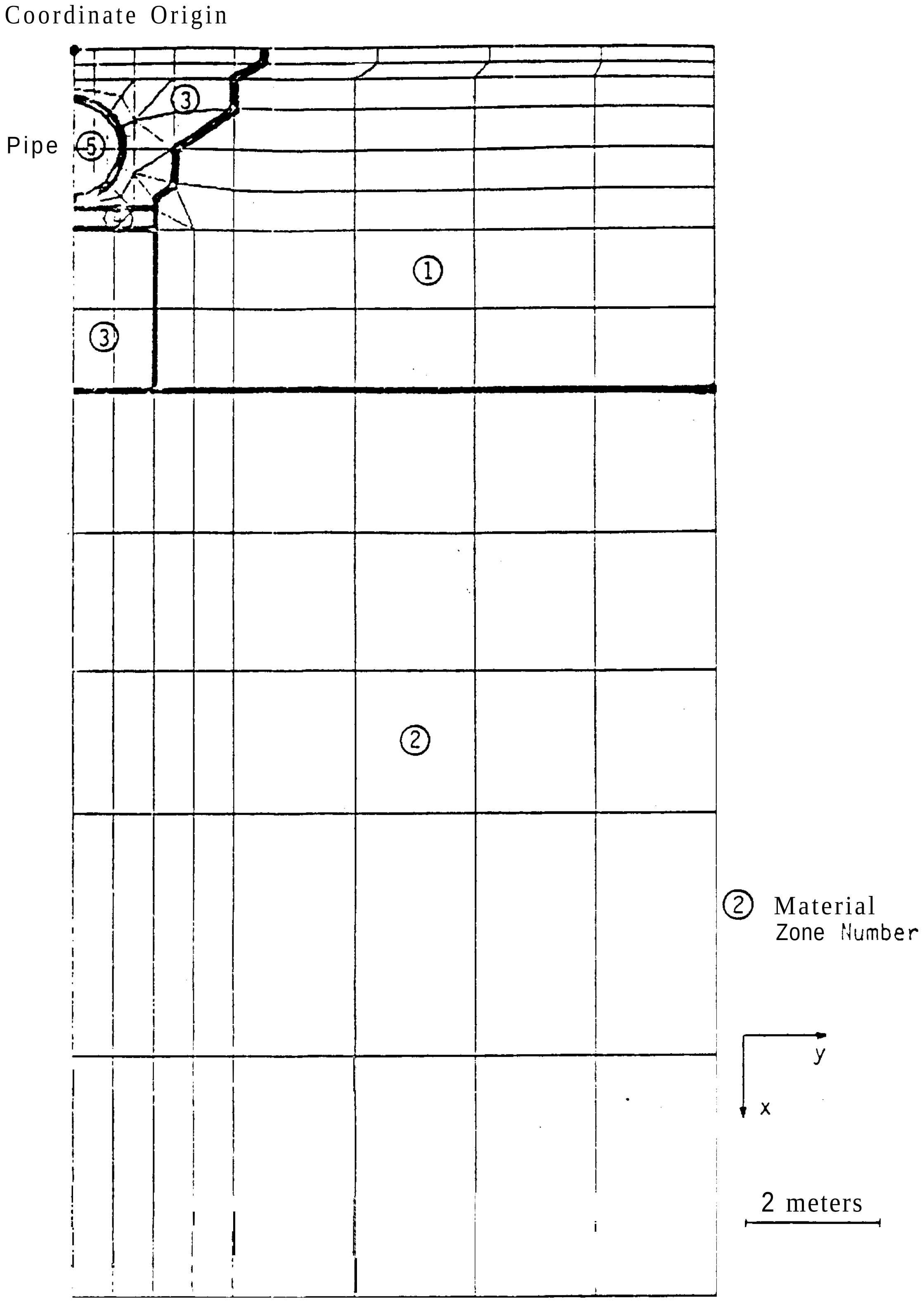


FIGURE 3-1

EXAMPLE PROBLEM NETWORK SHOWING MATERIAL ZONES

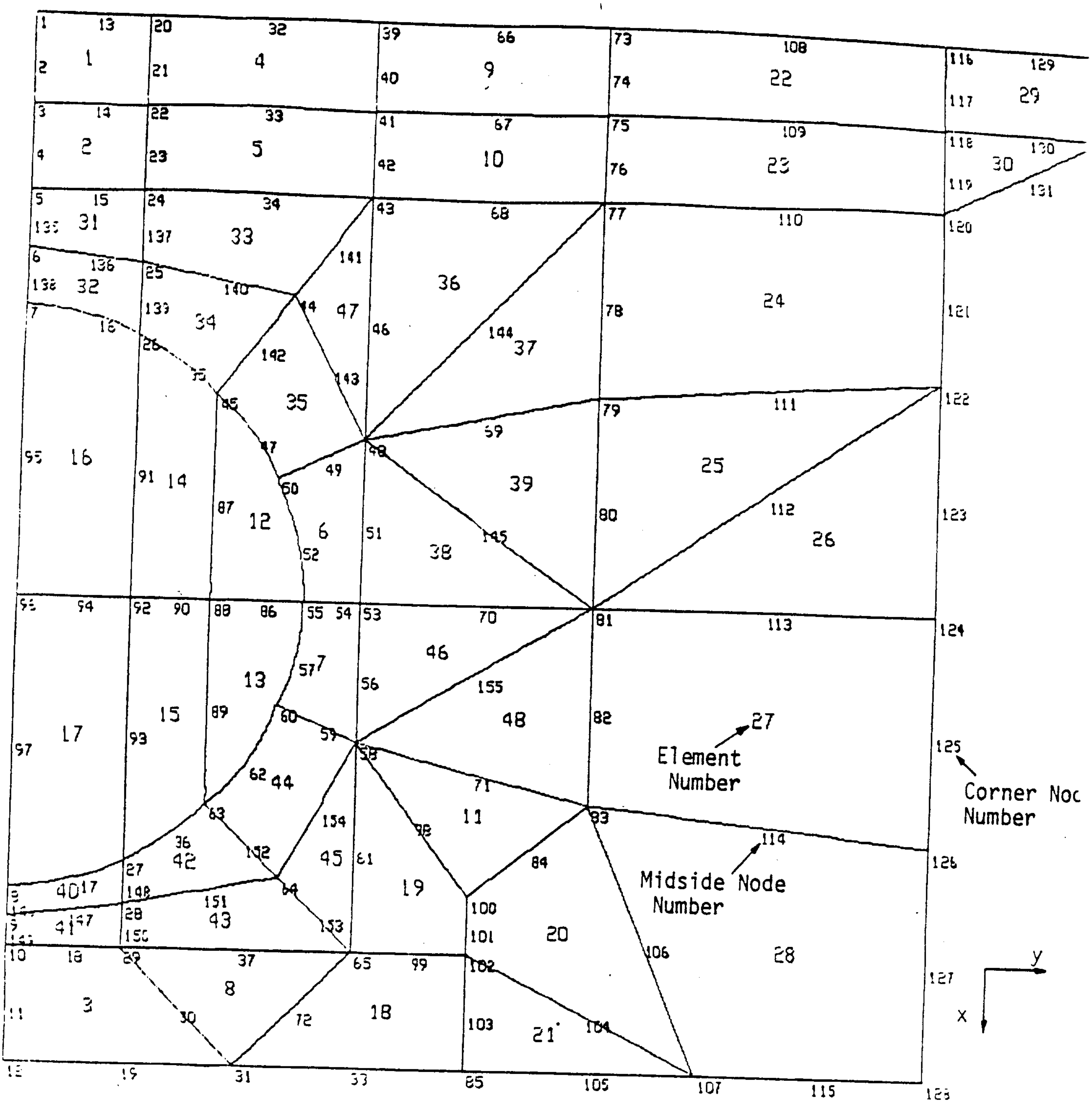


FIGURE 3-2

DETAIL OF EXAMPLE NETWORK IN REGION NEAR
THE PIPE AS PRODUCED BY GEOGRD'S
PARTIAL PLOT OPTION (IPP)

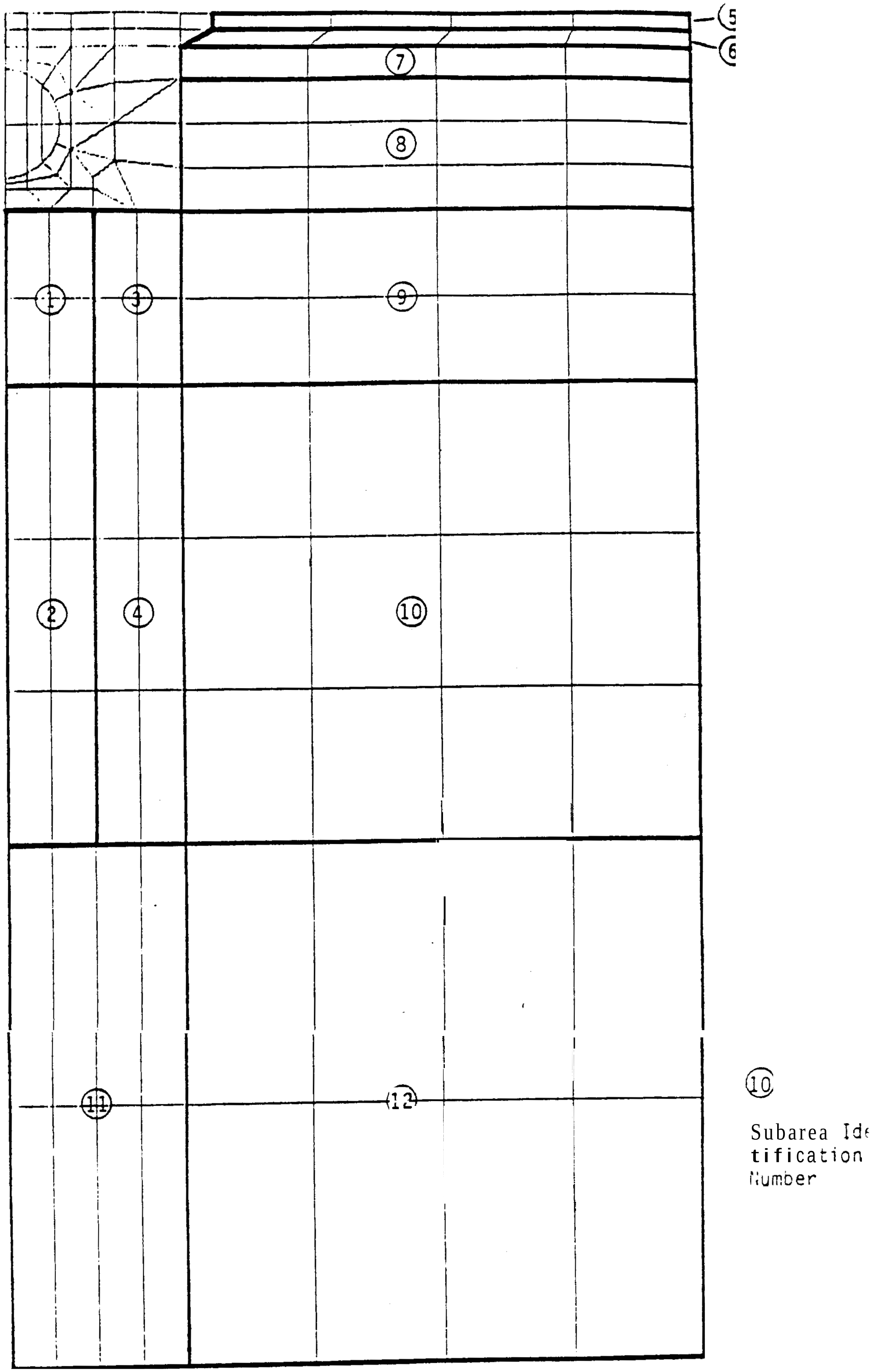


FIGURE 3-3

SUBAREAS DEFINED BY GEOGRD'S
GRID GENERATION OPTION (IGEN)

the position of the midside node is internally calculated from the position of the end nodes, and lies exactly midway between the ends. On input, the user need only input the coordinates of the corner nodes for straight element sides.

If the user wishes to define an element side as being other than straight, he simply inputs to the program the coordinates of the three nodes along the desired curve. The program will then pass a smooth curve through the three points which define the element side. The shape of the curve is approximately quadratic and will pass exactly through the end and midside nodes.

The only practical way for a user to determine and examine the exact shape of a curved sided element is to plot the internally generated shapes. The user is urged to make a plot of any and all networks which will be used with the finite element programs.

The test network shown in Figures 3-1 and 3-3 was run from the card input reproduced as Figure 3-4. As can be seen, curved sided elements were desired around the outside of the pipe. The input coordinates are all specified in inches and will be later modified by scale factors in the simulation program.

The printed output from the example problem is reproduced as Figure 3-5 (the plotted output is shown in Figures 3-1, 3-2 and 3-3). All the output is self documented and straightfoward and is produced in the same order as data is input to the program.

In reviewing this output, the reader should be aware of the fact that this network was developed by a combination of specific node and element definitions using a network generator, This procedure allows development of large and complicated networks at a very rapid pace.

```
1:   NETWORK FOR GEOGRD DOCUMENTATION
2:      2,    0,    0,    1,    0,    1,    a.   61,    I.    0.    1
3:    0.0,  0.0,  0.2,  0.2,  0.0,  0.0,  0.0
4:      1.    3,    1,    2.    3.   14,   22,   21,   20,   13
5:      2.    3,    3,    4,    5,   15,   24,   23,   22.   14
6:      3,    3,    5,    6,    7,   16,   26,  21).   24,   15
7:      4,    3,    e.    9,   10,   18,   29,   28,   27.   17
8:      5,    4,   10,   11,   12,   19,   31,   30,   29,   18
9:      6,    3,   20,   21,   22,   33,   41,   40.   39,   32
10:     7,    3,   22,   23,   24,   34,   43,   42,   41.   33
11:     8.    3,   24,   25,   26,   35,   45,   44.   43.   34
12:     9,    3,   43,   44,   45,   47,   50,   49,   48,   46
13:    10,    3,   48,   49,   50,   52,   55,   54,   53,   51
14:    11,    3,   53,   54,   55,   57,   60,   59,   58.   56
15:    12,    3,   58,   59,   60,   62,   63,   b4,   65,   61
16.    13,    3,   65,   64,   63,   36,   27,   28,   29,   37
17:    14,    4,   29,   30,   31,   72,   65,   37,   0.    0
18:    15,    3,   39,   40,   41,   67,   75,   74,   73.   6b
19:    16,    3,   41,   42,   43.   68,   77,   76,   75.   67
20:    17.    3,   43.   46,   48,   69,   79,   78.   77.   68
21:    18.    3,   48,   51,   53,   70,   81,   80,   79.   69
22:    19,    3,   53,   56,   58,   71.   83,   82,   81,   70
23:    20,    3,   58,   98,  100,   84,   83,   71,   0.    0
24:    21,    5,   45,   87,   88,   86,   55,   52,   50.   47
23:    22,    5,   88,   89,   63,   62,   60,   57,   55,   86
26:    23,    5,   26,   91,   92,   90,   88,   87.   45,   33
27:    24,    5,   92,   93,   27,   36,   63,   a9,   88,   90
28:    25.    5,    7.   95,   96,   94,   92,   91,   26,   16
29:    26,    5,   96,   97,    8,   17,   27,   93,   92,   94
30:    27,    4,   65,   72,   31,   38,   85,  103,  102,   99
31:    28,    3,   58,   61,   65,   99,  102,  101.  100,   98
32:    29,    1,  100,  101,  102,  104,  107,  106,   83.   84
33:    30,    1,   85,  105,  107,  104,  102,  103,   0,    0
34:    31,    3,   73,   74,   75,  109,  118,  117,  116,  108
35:    32,    3,   75,   76,   77,  110,  120,  119,  118,  109
36:    33,    3,   77.   78,   79,  111,  122,  121,  120,  110
37:    34,    3,   79.   80,   81,  112,  122,  111,   0.    0
38:    35.    1,   81,  113,  124,  123,  122,  112,   0.    0
39:    36,    1,   81,   82,   83,  114,  126,  125,  124.  113
40:    37.    1,   83,  106,  107,  115,  128,  127,  126,  114
41:    38,    3,  116,  117,  118,  130,  134,  133,  132.  129
42:    39,    3,  118,  119,  120,  131,  134,  130,   0.    0
43:  9999/
44:     1,  0.00,  0.00,  1.00
45:     3,  0.73.  0.00,  I.00
46:     5,  1.50,  0.00,  1.00
47:     7,  2.50,  0.00,  1.00
48:     8,  7.50,  0.00,  I.00
49:    10,  8.00,  0.00,  1.00
50:    12,  9.00,  0.00.  1.00
51:    16,  2.60,  0.60,  1.00
52:    17,  7 40,  0.60,  1.00
53:    20,  0.00,  1.00,  1.00
54:    22,  0.75,  1.00,  I.00
53:    24.  1.50,  1.00,  1.00
56:    26,  2.75,  1.00,  1.00
57:    27,  7.25,  1.00,  1.00
58:    29,  8 00.  1.00,  1.00
59:    31.  9.00,  2.00,  1.00
60:    35,  3.00,  1.42,  1.00
61:    36,  7 00,  1.42,  1.00
62:    39,  0.00.  3.00,  1.00
63:    41,  0.75,  3.00,  1.00
64:    43,  1.50,  3.00.  1.00
65:    45.  3.25,  1.70,  1.00
66:    47.  3.60,  2.05,  1.00
67:    48,  3.60,  3.004  1.00
68:    50,  3 95,  2.25,  1.00
69:    52,  4.50,  2.45,  1.00
70:    53,  5.00.  3.00,  1.00
71:    55.  5.00,  2.50,  1.00
72     57,  5 50,  2.45,  1.00
73     58,  6 20,  3.00,  1.00
74     60,  5 90,  2.30,  1.00
```

camncontrol
e factors

element
definitians
(Card Type E)

noda1
coordinates
(Card Type F)

FIGURE 3-4

CARD IMAGES USED FOR INPUT
OF EXAMPLE PROBLEM

```
62.  6 40.  2 05.  1 00
63.  6 75.  1.70,  1 00
65.  0 00.  3.00.  1 00
73,  0 00.  5.00.  1 00
75.  0.75,  5.00.  1 00
77.  1.50.  4.00.  1 00
79.  3 20.  5.00.  1 00
81.  5 00.  5.00.  1 05
83.  6 70.  4 00.  1 00
85.  9 00.  4 00.  1 00
88.  5 00.  1.70,  1 00
92.  5 00.  1.00,  1 00
96.  5 00.  0.00.  1 00
100. 7 50.  4.00.  1 00
102. 0.00.  4.00.  1 00
107, 9 00.  6.00.  1 00
116. 0.00.  8.00.  1 00
118. 0.75.  8.00.  1 00
120. 1 50.  8.00.  1 00
122. 3.00,  8.00.  1 00
124. 5 00.  8.00.  1 00
126. 7 00.  8.00.  1 00
128. 9 00,  8.00.  1 00
132. 0 00.  9 50.  1 00
134. 0 75.  9.50,  1 00
9999/
```

nodal
coordinates
(Card Type F)

```
 5,   6,  25,  24
 6,   7,  26,  25
24,  25,  44,  43
26,  45,  44,  25
45,  50,  48,  44
48,  77.  43,   0
48,  79,  77.   0
48,  53,  81,   0
48.  81,  79,   0
 8.   9,  28,  27
 9.  10,  29,  78
27,  28,  64,  63
28,  29,  65,  64
63,  64,  58,  60
64,  65,  58,   0
53,  58,  81.   0
44.  48.  43.   0
58,  83,  81,   0
9999/
```

element
refinement
(Card Type H)

```
 1.   2,   2,   3,   0,  9.00,  4.00,  9.00,  0.00, 17.00,  0.00, 17.00,  4.00/
 2,   3,   2,   2,   0, 17.00,  4.00, 17.00,  0.00, 38.00,  0.00, 38.00,  4.00/
 3,   2,   2,   1,   0,  9.00,  8.00,  9.00,  4.00, 17.00,  4.00, 17.00,  8.00/
 4,   3,   2,   2,   0, 17.00,  8.00, 17.00,  4.00, 38.00,  4.00, 38.00,  8.00/
 5,   1,   4,   1,   0,  0.00, 32.00,  0.00,  9.50,  0.75,  9.50,  0.75, 32.00/
 6,   1,   4,   1,   0,  0.75, 32.00,  0.75,  9.50,  1.50,  8.00,  1.50, 32.00/
 7,   1,   4,   1,   0,  1.50, 32.00,  1.50,  8.00,  3.00,  8.00,  3.00, 32.00/
 8,   3,   4,   1,   0,  3.00, 32.00,  3.00,  8.00,  9.00,  8.00,  9.00, 32.00/
 9,   2,   4,   1,   0,  9.00, 32.00,  9.00,  8.00, 17.00,  8.00, 17.00, 32.00/
10,   3.   4.   2,   0, 17.00, 32.00, 17.00,  8.00, 38.00,  8.00, 38.00, 32.00/
11,   2,   4,   2,   0, 38.00,  8.00, 38.00,  0.00, 62.00,  0.00, 62.00,  8.00/
12,   2,   4,   2,   0, 38.00, 32.00, 38.00,  8.00, 62.00,  8.00, 62.00, 32.00/
9999/
```

automatic
grid
generator
(Card Type I)

```
 1,  13,  20,  32,  39,  66,  73,  108,  116,  129,  132/
9999/
```

element
renumbering
(Card Type-J)

FIGURE 3-4
(continued)

```
                          PROGRAM GEOGRD
                A FINITE ELEMENT GRID GENERATOR
                         DEVELOPED BY
                RESOURCE MANAGEMENTS ASSOCIATES
                LAFAYETTE, CALIF -- NOVEMBER 1982


           NETWORK FOR GEOGRD DOCUMENTATION


*****RUN CONTROL PARAMETERS*****

   PRINT OPTION(IPRT)          2
   PLOT NODES(IPNN)            0
   PLOT ELTS(IPEN)             0
   PLOT NETWORK(IPO)           1
   PARTIAL PLOTS(IPP)          0
   NETWORK REFINE(IRFN)        1
   GEOM INPUT(IGIN)            0
   GEOM OUTPUT(LUNIT)         61
   GENERATE NET(IGEN)          1
   NUM ST LINES(NXLZ)          0
   REORDERING OPTION(IRO)      1


*****SCALE FACTORS*****

   HORIZ SIZE(PLOT)             0.000
   VERT SIZE(PLOT)              0.000
   X SCALE(PLOT)                0.200
   Y SCALE(PLOT)                0.200
   ROTATION(PLOT)               0.000
   X OUTPUT SCALE               0.000
   Y OUTPUT SCALE               0.000



           SPECS FOR REFINED ELEMENTS

 ORC ELT      NODES
       3               5          6         25         24
       3               6          7         26         25
       8              24         25         44         43
       8              26         45         44         25
       9              43         50         48         44
      17              48         77         43          0
      17              40         79         77          0
      19              40         33         81          0
      18              48         81         79          0
       4               8          9         28         27
       4               9         10         29         28
      13              27         28         44         63
      13              28         29         63         64
      12              63         64         58         60
      12              64         65         58          0
      19              53         58         81          0
       9              44         48         43          0
      19              50         83         81          0

           NUMBER OF NEW ELEMENTS IS     18
           NUMBER OF NEW NODES  PTS IS     21
```

FIGURE 3-5

GEOGRD OUTPUT FROM
THE EXAMPLE PROBLEM

```
ELEMENT ORDER AFTER REFINEMENT

ORDER     NUMBER     NODES                                                  ZONE
    1          1         1     2     3    14    22    21    20    13           3
    2          2         3     4     5    15    24    23    22    14           3
    3          3        10    11    12    19    31    30    29    18           4
    4          4        20    21    22    33    41    40    39    32           3
    5          5        22    23    24    34    43    42    41    33           3
    6          6        48    49    50    52    55    54    53    51           3
    7          7        53    54    55    57    60    59    58    56           3
    8          8        29    30    31    72    65    37     0     0           4
    9          9        39    40    41    67    75    74    73    66           3
   10         10        41    42    43    68    77    76    75    67           3
   11         11        58    98   100    84    83    71     0     0           3
   12         12        45    87    88    86    55    52    50    47           5
   13         13        88    89    63    62    60    57    55    86           5
   14         14        26    91    92    90    88    87    45    35           5
   15         15        92    93    27    36    63    89    88    90           5
   16         16         7    95    96    94    92    91    26    16           5
   17         17        96    97     8    17    27    93    92    94           5
   18         18        65    72    31    38    85   103   102    99           4
   19         19        58    61    63    99   102   101   100    98           3
   20         20       100   101   102   104   107   106    83    84           1
   21         21        85   105   107   104   102   103     0     0           1
   22         22        73    74    75   109   118   117   116   108           3
   23         23        75    76    77   110   120   119   118   109           3
   24         24        77    78    79   111   122   121   120   110           3
   25         25        79    80    81   112   122   111     0     0           3
   26         26        81   113   124   123   122   112     0     0           1
   27         27        81    82    83   114   126   125   124   113           1
   28         28        83   106   107   115   128   127   126   114           1
   29         29       116   117   118   130   134   133   132   129           3
   30         30       118   119   120   131   134   130     0     0           3
   31         31         5   135     6   136    23   137    24    15           3
   32         32         6   138     7    16    26   139    25   136           3
   33         33        24   137    25   140    44   141    43    34           3
   34         34        26    35    43   142    44   140    25   139           3
   35         35        45    47    50    49    48   143    44   142           3
   36         36        48   144    77    68    43    46     0     0           3
   37         37        48    69    79    70    77   144     0     0           3
   38         38        48    51    53    70    81   143     0     0           3
   39         39        48   145    81    80    79    69     0     0           3
   40         40         8   146     9   147    28   148    27    17           3
   41         41         9   149    10    18    29   150    28   147           3
   42         42        27   148    28   151    64   152    63    36           3
   43         43        28   150    29    37    65   153    64   151           3
   44         44        63   152    64   154    58    59    60    62           3
   45         45        64   153    65    61    58   154     0     0           3
   46         46        53    56    58   155    81    70     0     0           3
   47         47        44   143    48    46    43   141     0     0           3
   40         48        53    71    83    82    81   155     0     0           3
```

FIGURE 3-5
(continued)

```
INPUTS FOR NETWORK GENERATION

INPUTS FOR SUBAREA IDENT     1

     HORIZ DIVISIONS =       2
     VERT DIVISIONS =        2
     MATERIAL CLASS =        3
     SHAPE(0=REC,1=TRI)      0

SUBAREA COORDINATES
     CORNER     X-CORD     Y-CORD      THICKNESS
          1       9 00       4 00       1 00
          2       9 00       0.00       1 00
          3      17 00       0 00       1 00
          4      17 00       4 00       1 00

INPUTS FOR SUBAREA IDENT     2

     HORIZ DIVISIONS =       3
     VERT DIVISIONS =        2
     MATERIAL CLASS =        2
     SHAPE(0=REC,1=TRI)      0

SUBAREA COORDINATES
     CORNER     X-CORD     Y-CORD      THICKNESS
          1      17 00       4 00       1 00
          2      17 00       0.00       1 00
          3      38.00       0.00       1 00
          4      38.00       4 00       1 00

INPUTS FOR SUBAREA IDENT     3

     HORIZ DIVISIONS =       2
     VERT DIVISIONS =        2
     MATERIAL CLASS =        1
     SHAPE(0=REC,1=TRI)      0

SUBAREA COORDINATES
     CORNER     X-CORD     Y-CORD      THICKNESS
          1       9 00       8.00       1.00
          7       9 00       4 00       1.00
          3      17 00       4 00       1.00
          4      17 00       8 00       1.00

INPUTS FOR SUBAREA IDENT     4

     HORIZ DIVISIONS =       3
     VERT DIVISIONS =        2
     MATERIAL CLASS =        [illegible]
     SHAPE(0=REC,1=TRI)      0

SUBAREA COORDINATES
     CORNER     X-CORD     Y-CORD      THICKNESS
          1      17 00       8.00       1 00
          2      17 00       4 00       1 00
          3      38.00       4 00       1 00
          4      38 00       8 00       1 00
```

FIGURE 3-5
(continued)

```
INPUTS FOR SUBAREA IDENT      5

     HORIZ DIVISIONS =        1
     VERT DIVISIONS =         4
     MATERIAL CLASS =         1
     SHAPE(0=REC,1=TRI)       0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD       THICKNESS
          1        0.00       32.00         1.00
          2        0.00        9.50         1.00
          3        0.75        9.50         1.00
          4        0.75       32.00         1.00

INPUTS FOR SUBAREA IDENT      6

     HORIZ DIVISIONS =        1
     VERT DIVISIONS =         4
     MATERIAL CLASS =         1
     SHAPE(0=REC,1=TRI)       0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD       THICKNESS
          1        0.75       32.00         1.00
          2        0.75        9.50         1.00
          3        1.50        8.00         1.00
          4        1.50       32.00         1.00

INPUTS FOR SUBAREA IDENT      7

     HORIZ DIVISIONS =        1
     VERT DIVISIONS =         4
     MATERIAL CLASS =         1
     SHAPE(0=REC,1=TRI)       0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD       THICKNESS
          1        1.50       32.00         1.00
          2        1.50        8.00         1.00
          3        3.00        8.00         1.00
          4        3.00       32.00         1.00

INPUTS FOR SUBAREA IDENT      8

     HORIZ DIVISIONS =        3
     VERT DIVISIONS =         4
     MATERIAL CLASS =         1
     SHAPE(0=REC,1=TRI)       0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD       THICKNESS
          1        3.00       32.00         1.00
          2        3.00        8.00         1.00
          3        9.00        8.00         1.00
          4        9.00       32.00         1.00
```

FIGURE 3-5
(continued)

```
INPUTS FOR SUBAREA IDENT      9

     HORIZ OIVISIONS =        2
     VERT OIVISIONS =         4
     MATERIAL CLASS =         1
     SHAPE(O=REC. 1=TRI)      0


SUBAREA COORDINATES
     CORNER      I-CORD      Y-CORD      THICKNESS
        1          9 00      32.00        1 00
        ■          Q 00       8. 00       1 GO
        3         17 00       a 00        ! 00
        4         17 00      32.00        1 00

INPUTS FOR SUBAREA IDENT      1Q

     HORIZ DIVISIONS =        3
     VERT DIVISIONS =         4
     MATERIAL CLASS =         2
     SHAPE(O=REC. 1=TRI)      0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD      THICKNESS
        I         17 00      32. 00       I. 00
        2         17 00       8. 00       1 00
        3         38. 00      8 00        I 00
        4         38 00      32.00        I 00

INPUTS FOR SUBAREA IDENT      11

     HORIZ DIVISIONS =        2
     VERT DIVISIONS =         4
     MATERIAL CLASS =         2
     SHAPE(O=REC. 1=TRI)      0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD      THICKNESS
        1         36.00       e. 00       1.00
        2         33. 00      0.00        1 00
        3         62. 00      0.00        1. 00
        4         62. 00      e. 00       1 00

INPUTS FOR SUBAREA IDENT      12

     HORIZ DIVISIONS =        2
     VERT DIVISIONS =         4
     MATERIAL CLASS =         2
     SHAPE(O=REC. 1=TRI)      0

SUBAREA COORDINATES
     CORNER      X-CORD      Y-CORD      THICKNESS
        I         38 00      32. 00       1 00
        -         38. CO      8 00        1 00
        3         62 00       a 00        1 00
        4         62 00      32.00        1 00
```

FIGURE 3-5
(continued)

NETWORK FOR GEOGRD DOCUMENTATION .. FREE FIELD FORMATS

ORDER	NUMBER	NODES								ZONE
1	1	1	2	3	14	22	21	20	13	3
2	2	3	4	5	15	24	23	22	14	3
3	3	10	11	12	19	31	30	23	18	4
4	4	20	21	27	33	41	40	39	32	3
5	5	22	23	24	34	43	42	41	33	3
6	6	48	49	50	52	55	54	53	51	3
7	7	53	54	55	57	60	59	58	56	3
8	8	29	30	31	72	65	37	0	0	4
3	9	39	40	41	67	75	74	73	66	3
10	10	41	42	43	60	77	76	75	67	3
11	11	58	98	100	84	33	71	0	0	3
12	12	45	87	88	86	55	52	50	47	5
13	13	88	89	63	62	00	57	55	86	5
14	14	26	91	92	90	98	87	45	35	5
15	15	92	93	27	36	63	89	88	90	5
15	16	7	95	96	94	92	91	26	16	5
17	17	96	97	8	17	27	93	92	94	5
18	18	65	72	31	38	85	103	102	99	4
19	19	58	61	65	99	102	101	100	90	3
20	20	100	101	102	104	107	106	93	84	1
21	21	95	105	107	104	102	103	0	0	1
22	22	73	74	75	109	118	117	116	108	3
23	23	75	76	77	110	120	119	118	109	3
24	24	77	78	79	111	122	121	120	110	3
25	25	79	80	91	112	122	111	0	0	3
26	26	81	113	124	123	122	112	0	0	1
27	27	61	82	83	114	126	125	124	113	1
28	28	83	106	107	115	128	127	126	114	1
29	29	116	117	118	130	134	133	132	129	3
30	30	118	119	120	131	134	135	0	0	3
31	31	5	135	6	136	25	137	24	15	3
32	32	6	138	7	16	26	139	25	136	3
33	33	24	137	25	140	44	141	43	34	3
34	34	26	35	45	142	44	140	25	139	3
35	35	45	47	50	49	48	143	44	147	3
36	36	40	144	77	60	43	46	0	0	3
37	37	40	69	79	70	77	144	0	0	3
38	38	48	51	53	70	81	145	0	0	3
39	39	48	143	81	80	79	69	0	0	3
40	40	8	146	9	147	20	148	27	17	3
41	41	9	149	10	18	29	150	28	147	3
42	42	27	148	28	151	64	152	63	36	3
43	43	28	150	29	37	55	153	64	151	3
44	44	63	152	54	154	53	59	60	62	3
45	45	64	153	65	51	58	154	0	0	3
46	46	53	56	59	155	61	0	0	0	3
47	47	44	143	48	46	43	141	0	0	3
48	48	58	71	33	52	31	155		0	3
49	49	85	38	31	152	163	160	157	156	3
50	50	157	160	163	154	165	[illegible]	159	158	3
51	51	31	19	12	168	164	166	163	162	3
52	52	163	166	169	170	171	167	165	164	3
53	53	159	161	165	181	182	178	173	172	2
54	54	173	178	182	183	184	179	175	174	2
55	55	175	177	184	185	186	180	177	176	2
56	59	185	147	171	170	171	187	182	181	2
57	57	192	187	191	192	193	123	194	193	2
58	58	194	158	193	194	195	189	186	105	2
59	59	123	115	107	202	203	200	197	196	1
[illegible]	60	197	200	203	204	205	201	199	198	1

FIGURE 3-5
(continued)

61	01	107	105	81)	156	157	206	203	202	1
62	67	203	206	157	158	159	207	205	204	1
63	63	199	201	205	217	218	214	209	208	2
64	64	209	214	218	219	220	213	211	210	[illegible]
65	65	211	211)	220	221	222	216	213	212	2
66	66	205	207	159	172	173	223	218	217	2
67	67	218	223	173	174	175	224	220	219	2
68	68	220	224	175	176	177	225	222	221	2
69	57	226	229	231	232	233	230	228	227	1
70	70	231	234	236	237	238	235	233	232	1
71	71	236	237	241	242	243	240	233	237	1
72	72	241	244	132	133	134	245	243	242	
73	-3	228	230	233	249	250	248	247	246	
74	74	233	235	238	252	2S3	251	250	249	1
75	75	238	240	243	255	256	254	2S3	252	1
76	7a	243	245	134	131	120	257	2S6	255	1
77	77	247	248	250	261	262	260	259	258	1
78	79	250	251	253	264	265	263	262	261	1
79	79	253	254	256	267	268	266	265	264	1
80	ao	256	257	120	121	122	269	263	267	1
81	81	259	260	262	279	280	276	271	270	1
82	82	271	276	280	281	282	277	273	272	1
83	83	273	277	282	233	284	279	275	274	1
84	84	262	263	265	288	289	285	280	279	1
85	85	280	285	289	290	291	286	282	2s1	1
86	86	282	286	291	292	293	287	284	283	1
87	87	265	266	268	297	298	294	289	288	1
88	88	289	294	298	299	300	295	291	290	1
89	89	291	295	300	301	302	296	293	292	1
90	90	268	269	122	123	124	303	298	297	1
91	91	298	303	124	125	126	304	300	299	1
92	92	300	304	126	127	128	305	302	301	1
93	93	275	278	284	312	313	310	307	306	1
94	94	307	310	313	314	315	311	309	308	1
95	95	284	287	293	318	319	316	313	312	1
96	96	313	316	319	320	321	317	315	314	1
97	97	293	296	302	324	325	[illegible]	319	318	1
98	98	319	322	325	326	327	323	321	320	1
99	99	302	305	128	196	197	328	325	324	1
100	100	325	328	197	198	199	329	327	326	1
101	101	309	311	315	339	340	336	331	330	2
102	102	331	336	340	341	342	337	333	332	2
103	103	333	337	342	343	344	338	335	334	2
104	134	315	317	321	346	349	345	340	339	2
105	105	340	345	349	350	351	346	347	341	2
106	106	342	346	351	352	353	347	344	343	2
107	137	321	323	327	357	358	354	349	348	2
108	108	349	354	358	359	360	3ss	351	350	2
109	109	351	355	360	361	362	356	353	352	2
110	110	327	329	199	208	209	363	358	357	2
111	111	358	363	209	210	211	364	360	359	[illegible]
112	112	360	364	211	212	213	365	362	361	[illegible]
113	113	213	216	222	372	373	370	367	366	[illegible]
114	114	367	370	373	374	375	37I	369	363	2
115	115	222	225	177	373	379	376	373	372	[illegible]
116	116	373	376	379	380	331	377	375	374	2
117	117	177	180	186	384	385	382	379	3-3	[illegible]
118	118	379	352	385	336	387	[illegible]	331	353	[illegible]
119	119	186	189	195	390	371	a;	335	381	[illegible]
120	120	385	388	391	23	393	337	387	386	2
121	121	335	338	344	400	401	398	395	394	[illegible]
122	122	395	398	401	402	403	399	397	396	
123	123	344	347	353	406	Ji7	404	401	400	
124	124	401	404	407	408	409	405	403	402	[illegible]
125	125	353	356	361	412	413	410	107	406	[illegible]
126	126	407	410	413	414	415	411	409	408	[illegible]
127	127	362	365	213	366	367	416	413	412	
128	128	413	416	367	368	359	41'	415	414	

FIGURE 3-5
(continued)

NETWORK FOR SEGORD DOCUMENTATION. FREE FIELD FORMATS

NODE	X-LOC	Y-LOC	THICK	NODE	X-LOC	Y-LOC	THICK
I	0 00	0 00	1 00	210	27 50	8 00	1 00
2	0 38	0 00	1 00	211	31 00	8 00	1 00
3	0 75	0 00	1 00	212	34 50	8 00	1 00
4	1 13	0 00	1 00	213	38 00	8 00	1 00
5	1 50	0 00	1 00	214	24 00	7 00	1 00
6	2.00	0 00	1 00	215	31 00	7 00	1 00
7	2.30	0 00	1 00	216	38 00	7 00	1 00
3	7 50	0 00	1 00	217	20 50	6 00	1 00
o	7 75	0 00	1 00	218	24 00	6 00	1 00
10	8 00	0 00	1 00	219	27 50	6 00	1 00
11	8 50	0 00	1 00	220	31 00	6 00	1 00
12	9 00	0 00	1.00	221	34 50	6 GO	1 00
13	0 00	0 SO	1 00	[illegible]	38 00	6 00	1 00
14	0 75	0 SO	1 00	223	24 00	5 00	1 00
1	1 50	0 30	1 00	224	31 00	5 00	1 00
16	2 60	0 60	1 00	225	38 00	5 00	1 00
17	7 40	0 60	1 00	226	0 00	32 00	1 00
13	8 00	0 50	1 00	227	0 38	32 00	1 00
19	9 00	1 00	1 00	228	0 75	32 00	1 00
23	0.00	1 00	1 00	229	0 00	29 19	1 00
21	0 38	1 00	1 00	230	0 75	29 19	1 00
22	0 75	1 00	1 00	231	0 00	26 38	1 00
23	1 13	1 00	1 00	232	0 38	26 38	1 00
24	1 50	1 00	1 00	233	0 7s	26 38	1 00
25	2 13	1 00	1 00	234	0 00	23 56	1 00
26	2 75	1 00	1 00	235	0 73	23 56	1 00
[illegible]	7 25	1 00	1 GO	236	0 00	20 73	1 00
28	7.63	1 00	1 00	237	0 38	20.73	1 00
29	8 00	1 00	1 00	238	0 7s	20 75	1 00
30	8 50	1 SO	1 00	239	0 00	17 94	1 00
31	9 00	2 00	1 00	240	0 73	17 94	1 00
32	0 00	2 00	1 00	241	0 00	15 13	1 00
33	0 75	2 00	1 00	242	0 30	15 13	I 00
34	1 50	2 00	1 00	243	0 75	15 13	1 00
35	3 00	1 42	I 00	244	0 00	12 31	I 00
34	7.00	1 42	1 00	245	0 7s	12 31	1 00
37	8 00	2.00	1 00	246	1 13	32 00	1 00
38	9 00	3 00	1 00	247	1 SO	37.00	1 00
33	0.00	3 00	1 00	248	1. 30	29 00	1 00
40	0.38	3 00	1 00	249	1 13	26 19	1 00
41	0 75	3 00	1 00	250	1 SO	26.00	1 00
42	1.13	3 00	1 00	251	1 50	27 00	1.00
43	1 50	3 00	1 00	252	1 13	20 38	1 00
44	2.33	2 35	1 00	253	1 50	20 00	1 00
45	3.25	1 70	1 00	254	1 SO	17 00	1 00
46	2 55	3 00	1 00	255	1 13	14 56	1 00
47	3 60	2 OS	1 00	256	1 SO	14 00	1 00
48	3 50	3 00	1 OC	2Y7	1 SO	11 00	1 00
49	3 77	2 63	1 00	258	2 25	32 00	1 00
50	3 95	2 25	1 00	259	3 00	32 00	1 00
51	4 30	3 00	1 00	260	3 00	29 00	1 00
52	4 50	2 45	1 00	261	2 25	26 00	1 00
53	5 00	3 00	1 00	262	3 00	26 00	1 00
54	5 00	2 75	1 00	263	3 00	23 00	1 30
55	5 00	2 50	1 03	264	2 25	20 00	1 30
56	5 60	3 00	1 00	265	3 00	20 GO	1 00
[illegible]	5 50	2 45	1 00	266	3 00	17 00	1 00
58	6 20	3 00	1 00	267	2 25	14 GO	1 00
59	6 05	2 65	1 00	268	3 00	14 00	1 00
60	5 [illegible]	2 30	1 00	269	3 00	11 00	I nn
61	7 10	3 00	1 00	270	4 CO	32 00	1 00
62	6 40	2 05	1 00	271	5 00	32 00	1 00
63	6 75	1 70	1 00	272	6 00	32 00	1 00
64	7 39	2 35	1 '3	273	7 00	32 00	1 00
53	8 00	3 03	i 00	274	8 00	32 00	1 00
66	0 00	4 00	1 00	275	9 00	32 00	! 00
47	0 75	4 GO	1 00	276	5 00	29 00	1 00
68	1 50	4 00	1 00	277	7 00	29 a0	1 00
69	3.40	4 00	1 00	278	9 00	29 00	1 00
70	5 00	4 00	1 00	279	4 00	26 00	1 00
71	6 45	4 00	1 30	280	5 00	26 00	1 00
72	9 50	2 50	1 00	281	6 00	25 00	1 00
[illegible]	0 00	5 00	1 00	282	7 00	26 GO	1 00
74	0 38	5 00	1 00	283	3 00	26 00	1 00
75	0 75	5 00	1 00	284	9 00	25 00	1 00
76	1 13	5 00	1 00	285	5 00	23 00	1 00
77	1.50	5 00	1 00	296	7 00	23 00	1 00
73	2.35	5 00	1 00	237	9 00	23 00	1 00
79	3 00	5 00	1 00	288	4 00	20 GO	I 00
80	4 10	7 00	1 03	289	5 05	20 00	1 00

FIGURE 3-5
(continued)

ai	3 00	5 00	1 00	290	6.00	20 00	1 00
82	5 85	5 00	1 00	291	7 00	20 00	1 00
83	6 70	5 00	1 00	292	8 00	20 00	I 00
84	7 10	4 50	I 00	293	9.00	20 00	1 00
85	9 CO	4 00	I 00	294	5.00	17 00	1 00
86	5 00	2 10	I 00	29Y	7 00	17 00	1 00
87	4 13	1 70	1 00	294	9 00	17 00	I 00
88	5 00	1 70	I 00	297	4 00	14 00	1 00
89	5 88	1 70	1 00	298	5 00	14 00	1 00
90	5 30	1 35	1 00	299	6.00	14 00	1 00
91	3 88	1 00	1 00	300	7 00	14 00	1 00
92	5 00	1 00	1 00	301	e.00	14 00	1 00
93	6 13	1 00	1 00	302	9.00	14 00	1 00
94	5 00	0 50	1 00	303	3.00	11 GO	I 00
9s	3 75	0 00	1 00	304	7 00	11 00	I 00
96	5 00	0.00	1 00	305	9.00	11 00	1 00
97	6 25	0 00	1 00	306	11.00	32 00	I 00
98	6 85	3.50	1 00	307	13.00	32 00	1 00
99	a 00	3 50	1 00	308	15.00	32 00	1 00
100	7 50	4 00	1 00	309	17.00	32 00	1 00
101	7 73	4 00	I 00	310	13.00	29 00	1 00
102	8 00	4 00	1 00	311	17.00	29 00	1 00
103	a SO	a 00	I 00	312	11.00	26 00	1 00
104	e 50	5 00	. 00	313	13.00	26 00	1 00
105	9 00	5 00	1 00	314	15.00	26 00	1 00
106	7 85	5 50	1 00	315	17.00	26 00	I 00
107	9 00	6 00	I 05	315	13.00	23 00	1 00
108	0 00	6 50	1 00	317	17.00	23 00	1 00
109	0 75	6 50	1 00	318	11.00	20 00	1 00
110	1 50	6 50	1 00	319	13.00	20 00	1 00
111	3 10	6 50	1 00	320	15.00	20 00	1 00
112	4 GO	6 50	I 00	321	17 00.	20 00	I 00
113	5 CO	6 50	1 00	322	13.00	17 00	1 00
114	6 85	6 50	1 00	323	17 00	17 00	I 00
115	9 00	7 00	1 00	324	11.00	14 GO	1 00
116	0 00	8 00	1 00	325	13.00	14 00	1 00
117	0 39	a 00	1 00	326	15.00	14 00	1 00
118	0 75	a 00	1.00	327	17 00	14 00	1 00
119	1 13	a 00	1 00	328	13.00	11 00	1 00
120	I 30	e 00	1 00	329	17 00	11 00	1 00
121	2 25	8 00	1 00	330	20.50	32 00	1 00
122	3 00	8 00	1 00	331	24.00	32 00	1 00
123	4 00	8 00	1 00	332	27. YO	32 00	I 00
124	5 00	a 00	1 00	333	31.00	32 00	1 00
125	6 00	a 00	1 00	334	34.50	32 00	1 00
126	7 no	e 00	1 00	335	38.00	32 00	1 00
127	8 00	8 00	1 00	336	24.00	29 00	1 00
129	9 GO	8 00	1 00	337	31.00	29 00	1 00
12?	0 00	8 75	1 00	339	38.00	29 00	1 00
130	0 75	e 7s	1 00	339	20.SO	26 00	1 00
131	1 13	a 75	1 00	340	24 00	26 GO	I 00
132	0 00	9 50	1 00	341	27 50	26 00	1 00
133	0 38	9 50	1 00	342	31.OS	26 00	I 00
134	0 75	9 50	1 00	343	34 50	26 00	1 00
135	1 75	0 00	1 00	344	38.00	26 00	1 00
136	2 06	0 SO	1 00	345	24 00	23 00	1 CO
137	1 81	1 00	1 00	346	31.00	23 00	I 00
139	2 25	0 00	1 00	347	38.00	23 00	1 00
139	2 44	1 00	1 00	348	20.SO	20 00	I 00
140	2 25	1 67	1 00	349	24.00	20 00	1 00
141	1 94	2 67	1 00	350	27 50	20 CO	1 00
142	2 ai	2 02	1 00	351	31.00	20 00	1 00
143	2 99	2 67	1 00	352	34 50	20 00	1 00
144	2 55	4 00	1 00	353	38.00	20 00	1 00
145	4 30	4 00	1 00	3s4	24 00	17 00	1.00
146	7 63	0 00	1 00	355	31.00	17 00	1 00
147	7 69	0 50	1 00	356	38.00	17 00	1 00
148	7 44	1 00	1 00	357	20.SO	14 00	1 00
149	7 88	0 00	1 00	358	24 00	14 00	I 00
lSO	7 a1	1 00	1 00	359	27 50	14 00	1 00
151	7 50	I 67	1 00	360	31.00	14 00	1 00
152	7 06	2 02	I 00	361	34 50	14 00	I 00
153	7 69	2 67	1 00	362	38.00	14 00	1 CO
154	6 79	2 67	1 00	363	24 00	11 00	1 00
155	5 60	4 00	1 00	364	31.00	11 00	1 00
15a	11 CO	4 00	1 00	365	38.00	11 00	1 00
!57	13 00	a 00	1 00	366	44 00	a 00	1 00
158	15 00	4 00	1 00	367	SO 00	3 00	1 00
159	17 00	4 00	I 00	368	56.00	8 GO	1 00
160	13 00	3 00	I 00	369	62.00	8 00	1 00

FIGURE 3-5
(continued)

```
161   17.00   3.00   1.00     370   50.00    7.00   1.00
162   11.00   2.00   1.00     371   62.00    7.00   1.00
163   13.00   2.00   1.00     372   44.00    6.00   1.00
164   13.00   2.00   1.00     373   50.00    6.00   1.00
165   17.00   2.00   1.00     374   56.00    6.00   1.00
166   13.00   1.00   1.00     375   62.00    6.00   1.00
167   17.00   1.00   1.00     376   50.00    5.00   1.00
168   11.00   0.00   1.00     377   62.00 .  5.00   1.00
169   13.00   0.00   1.00     378   44.00    4.00   1.00
170   15.00   0.00   1.00     379   50.00    4.00   1.00
171   17.00   0.00   1.00     380   56.00  . 4.00   1.00
172   20.50   4.00   1.00     381   62.00    4.00   1.00
173   24.00   4.00   1.00     382   50.00    3.00   1.00
174   27.50   4.00   1.00     383   62.00    3.00   1.00
175   31.00   4.00   1.00     384   44.00    2.00   1.00
174   34.50   4.00   1.00     385   50.00    2.00   1.00
177   38.00   4.00   1.00     386   56.00    2.00   1.00
178   24.00   3.00   1.00     387   62.00    2.00   1.00
179   31.00   3.00   1.00     388   50.00    1.00   1.00
180   38.00   3.00   1.00     389   62.00    1.00   1.00
181   20.50   2.00   1.00     390   44.00    0.00   1.00
182   24.00   2.00   1.00     391   30.00    0.00   1.00
183   27.50   2.00   1.00     392   56.00    0.00   1.00
184   31.00   2.00   1.00     393   62.00    0.00   1.00
185   34.50   2.00   1.00     394   44.00   32.00   1.00
186   38.00   2.00   1.00     395   50.00   32.00   1.00
187   24.00   1.00   1.00     396   56.00   32.00   1.00
188   31.00   1.00   1.00     397   62.00   32.00   1.00
189   33.00   1.00   1.00     398   50.00   29.00   1.00
190   20.50   0.00   1.00     399   62.00   29.00   1.00
191   24.00   0.00   1.00     400   44.00   26.00   1.00
192   27.50   0.00   1.00     401   50.00   26.00   1.00
193   31.00   0.00   1.00     402   56.00   26.00   1.00
194   34.50   0.00   1.00     403   62.00   26.00   1.00
195   38.00   0.00   1.00     404   50.00   23.00   1.00
196   11.00   8.00   1.00     405   62.00   23.00   1.00
197   13.00   8.00   1.00     406   44.00   20.00   1.00
198   15.00   8.00   1.00     407   50.00   20.00   1.00
199   17.03   8.00   1.00     408   56.00   20.00   1.00
200   13.00   7.00   1.00     409   67.00   20.00   1.00
201   17.00   7.00   1.00     410   50.00   17.00   1.00
202   11.00   6.00   1.00     411   62.00   17.00   1.00
203   13.00   6.00   1.00     412   44.00   14.00   1.00
204   15.00   6.00   1.00     413   50.00   14.00   1.00
205   17.00   6.00   1.00     414   56.00   14.00   1.00
206   13.00   5.00   1.00     413   62.00   14.00   1.00
207   17.00   5.00   1.00     416   50.00   11.00   1.00
208   20.50   8.00   1.00     417   62.00   11.00   1.00
209   24.00   8.00   1.00

FOR INITIAL ORDER. REORDERING SUM =   1050436

STARTING NODE = .    1

REORDERING SUM =    255892  BAND SUM =  -22842


SELECTED ELEMENT ORDER IS LISTED BELOW

    1     4     9    22    29    72    30    23    10     5
    2    74    36    37    24    80    47    33    31    39
   25    38    26    90    46    40    27    91    11    71
   73    79    87    88    35     6    34    32     7    12
   14    13    16    44    15    17    42    45    19    20
   28    92    89    43    40    41    21    18     8     3
   70    74    78    84    85    86    59    81    99    97
   95    49    51    69    73    77    81    82    83    93
   60    62   100    50    98    96    94    52    63    66
  110    53   107    56   104   101    64    67   111    54
  108    57   105   102    65    68   117    55   109    53
  106   103   113   113   127   117   125   119   123   121
  114   116   128   118   126   120   124   122

XMIN =      0.00
XMAX =     62.00
YMIN =      0.00
YMAX =     32.00
```

FIGURE 3-5
(continued)

CHAPTER 4

PROGRAM INPUT INSTRUCTIONS

Data for GEOGRO are input through the card reader and may or may not be augmented by a previously generated file (the file structure for GEOGRD is shown schematically in Figure 4-1). The first card is a comment which is printed and plotted, and the second card a list of program control variables. Next come the plot specifications, the element cards and the node cards. If network refinement, network generation, or element renumbering to be done, the card inputs for these activities follow the node cards.

The program has a number of options as explained below. Several options have to do with scaling the size of the plot. If values are specified for the horizontal and vertical plot size, the network will be scaled to fit within these bounds. This may result in a distortion of the plot, but will assure that the plot is contained on the plot page. If the sizes are left blank, the program will expect scale factors for the coordinates. These should be specified such that the inputs will fit into the desired space on the plot.

When preparing data for GEOGRD, the following items should be kept in mind:

1. The file written for geometric output is assumed to contain all element, coordinate and material zone data. For this reason all element type and width information must be on the element and coordinate cards when the final file is written. The output file is written on the specified logical unit.
2. Coordinate scale factors for scaling to prototype dimensions are included in GEOGRD, and may be used to scale coordinates prior to writing the geometric output file. If the scale factors are left blank, values of 1.0 are assumed.
3. The plotting scale factors are applied to the input coordinates independent of the prototype scale factors.
4. It is recommended that all inputs be made in the units of the source page plot; this will usually be inches or centimeters or some other convenient scale. Scaling to final prototype scales can then be done by specification of the appropriate scale factors in the simulation programs.

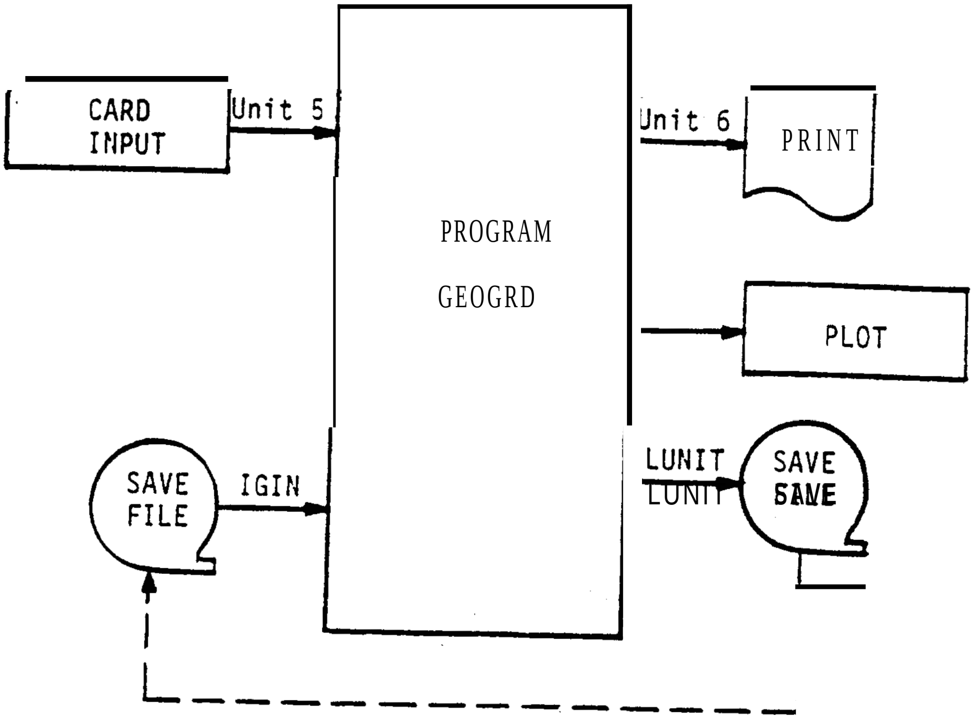


FIGURE 4-1

FILE ORGANIZATION
PROGRAM GEOGRD

5. When specifying the nodes which define an element, the user may input only the corner node numbers and the program will assign the midside numbers. If this is done, the specification of three nodes will imply a triangular element and four node numbers a quadrilateral element. The user must enter zeroes for the remaining node numbers and specify the material zone type in its proper location,

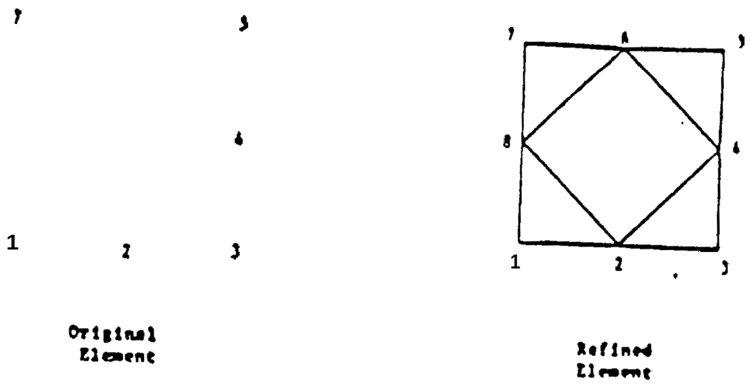
6. If an element side is straight, the user need only specify the coordinates of the corner nodes and the program will calculate the coordinates of the midside nodes.

OATA INPUT FORMATS

The following paragraphs sumnarize the exact card formats expected by GEOGRD. The user should follow this procedure exactly, and input the data in the same sequence as it is described. In all cases the program will expect to input this information on FORTRAN logical unit 5 unless otherwise noted. Finally, the reader is urged to review the input and output from the example problem if questions arise.

Please note that all inputs to GEOGRD are in free field format. This means that all data on a specified card image must be supplied, with individual values separated by blanks of commas. A slash (/) at the end of a line indicates the end of a record. If less than the proper number of items are input on a given card image, the program will look at the next card to complete its list. This is a common error in free field input, and must be checked carefully by the user.

Card Type	Input Sequence	FORTRAN Name	Description
A. Job Title			
	1	TITLE	Any 80 column comments; this comment will appear on both the Printed and plotted output.
B. Job Controls			
	1	IPRT	Enter 1 if node and element input data are to be echo printed. Enter 2 if both input data and the complete network specifications are to be printed; otherwise enter zero.
	2	IPNN	Enter 1 if node numbers are to be plotted; otherwise enter zero.
	3	IPEN	Enter 1 if element numbers are to be plotted; Enter 2 if the material types are to be plotted; enter 3 if both element numbers and element material types are to be plotted; otherwise enter zero.
	4	IPO	Enter 1 if only a network plot is to be drawn. Enter 2 if only a boundary is to be drawn. Enter 3 if both a network and boundary are to be drawn; otherwise enter zero.
	5	IPP	Enter 1 if the program is to produce a plot of a subsection of the network; otherwise enter zero. If a 1 is specified an additional card will be required as specified at Card Type D, below.
	6	IRFN	Enter a 1 if the program is to refine an existing network by subdivision of existing elements; otherwise enter zero. If a 1 is specified additional cards will be required as specified at Card Type H below (see Figure 4-2 for an explanation of network refinement).
	7	IGIN	If an existing network is to be input for processing, enter the number of the FORTRAN logical unit upon which it resides; otherwise enter zero.
	8	LUNIT	Enter the FORTRAN logical unit number upon which the results of the network processing are to be written. This file will serve as subsequent input to GEOGRD and GEODYN. If no file is to be written, enter zero.



Original Element

Refined Element

To refine the original element to the configuration shown, use the following input specifications:

8	1	2	0
2	3	4	0
8	6	7	0
6	8	2	4
6	4	5	0

The program will generate all other required information.

FIGURE 4-2

NETWORK REFINEMENT EXAMPLE

Card Type	Input Sequence	FORTRAN Name	Description
	9	IGEN	Enter 1 if a network (or network subsection) is to be generated from specification of its quadrilateral corner points; otherwise enter zero. A nonzero entry here will require inputs at Card Type I, below.
	10	NXZL	Enter the number of network line segments for which the program will internally calculate exact coordinates to insure a straight line of equal slope. An entry here will require additional input at Card Type G, below.
	11	IRO	Enter 1 if the program is to internally arrange the element order for a more efficient numeric solution. If a 1 is specified additional cards will be required as defined at Card Type J.
C. <u>Plot Scaling Factors</u>			
	1	HORIZ	Maximum horizontal size of plot, inches. If scale plot factors are used, enter zero.
	2	VERT	Maximum vertical size of plot, inches. If scale plot factors are used, enter zero.
	3	XSCALE	Plotting scale factor for X (horizontal) inputs; if HORIZ is not zero, set this value to zero.
	4	YSCALE	Plotting scale factor for Y (vertical) inputs; if VERT is not zero, set this value to zero.
	5	AR	Plot rotation in degrees from X axis (clockwise).
	6	XFACT	Prototype scale factor for X coordinates (assumed to be 1.0 if set to zero).
	7	YFACT	Prototype scale factor for Y coordinates (assumed to be 1.0 if set to zero).

Card Type	Input Sequence	FORTRAN Name	Description
D. **Subsection Plot Control** - omit if IPP (Card 8.5) = 0			
	1	NXPMIN	Node number of minimum X location in a partial network plot. If zero, taken as network minimum.
	2	NXPMAX	Node number of maximum X location in a partial network plot. If zero, taken as network maximum.
	3	NPYMIN	Node number of minimum Y location in a partial network plot. If zero, taken as network minimum.
	4	NYPMAX	Node number of a maximum Y location in a partial plot. If zero, taken as network maximum.
E. Element Definition			
	1	J	Element number
	2	IMAT(J)	Element type number (corresponds to soil zone specified for GEODYN).
	3-10	NOP(J,K)	Element node numbers; enter 6 (or 3) or 8 (or 4) numbers starting at any corner and moving counterclockwise around the element.
		...signal	the end of element data with 9999/ card.
F. Node Definition			
	1	J	Node number
	2	CORD(J,1)	X coordinate location
	3	CORD(J,2)	Y coordinate location
	4	WD(J)	Network width at node J; defaults to 1.0 if specified as zero,
		...signal	end of node data with 9999/ card.
G. Line Segment Coordinate Generation - NXZL (Card B.10) cards required, omit if NXZL=0.			
	1	NA	A corner node number at one end of a straight line segment.
	2	NB	The corner node number at the other end of a straight line segment.

Card Type	Input Sequence	FORTRAN Name	Description
	3-16	NIP	Up to 14 corner node numbers between nodes NA and NB for which the Y coordinate is to be interpolated using the input **values** of the X coordinate.

H. Element Refinement - IREN **(Card** 8.6) cards required, omit if IREN=0.

Card Type	Input Sequence	FORTRAN Name	Description
	1-4	NEW	Four node numbers (including trailing zero for triangle elements) from an existing element, either midside or corner, which are to become corner nodes for a refined element. See Figure 4-2 for a graphical description.

...signal end of **element** refinement data with 9999/ card.

I. Automatic Grid Generation - omit if IGEN (Card 8.9) = 0

Card Type	Input Sequence	FORTRAN Name	Description
	1	IBLK	A numeric designator for the section of the network to be generated.
	2	NXI	The number of subdivisions to be made along the X axis for the network to be generated.
	3	NYI	The number of subdivisions to be made along the Y axis for the network to be generated.
	4	ITP	The material type number to be assigned to the elements generated.
	5	ISHP	Enter 0 for generation of quadrilateral elements; enter 1 for generation of triangular elements.
	6	TC(1)	The X coordinate of the upper left corner of the area for which a network is to be generated.
	7	TC(2	The Y coordinate of the upper left corner of the area for which a network is to be generated.
	a	TC(3	The X coordinate of the lower left corner of the area for which a network is to be generated.

Card Type	Input Sequence	FORTRAN Name	Description
	9	TC(4)	The Y coordinate of the lower left corner of the area for which a network is to be generated.
	10	TC(5)	The X coordinate of the lower right corner of the area for which a network is to be generated.
	11	TC(6)	The Y coordinate of the lower right corner of the area for which a network is to be generated.
	12	TC(7)	The X coordinate of the upper right corner of the area for which a network is to be generated.
	13	TC(8)	The Y coordinate of the upper right corner of the area for which a network is to be generated.
	14	ELC(1)	The width of the network at the upper left corner (1.0 will be assumed if set to zero).
	15	ELC(2)	The width of the network at the lower left corner (1.0 will be assumed if set to zero).
	16	ELC(3)	The width of the network at the lower right corner (1.0 will be. assumed if set to zero).
	17	ELC(4)	The width of the network at the upper left corner (1.0 will be assumed if set to zero).

...signal end of grid generation with 9999/ card.

J. <u>Element Renumbering</u> - omit if IRO (Card 6.11) = 0

Card Type	Input Sequence	FORTRAN Name	Description
	1-50	NLIST	A list of node numbers (up to 50) from which the program will reorder the internal sequence of elements to obtain the most efficient operation of the simulation programs. As a general rule at least two starting locations should be tried, one at each end of the network. The end of a list is a blank card field.

APPENDIX G

GEODYN

Operating Instructions

OPERATING INSTRUCTIONS FOR THE
COMPUTER PROGRAM GEODYN

A Two-Dimensional Finite Element Program for Simulation of the Geothermal Freeze/Thaw Condition

by

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CHAPTER 1

INTRODUCTION

1.1 FOREWORD

Engineering analysis of problems in regions subject to freezing and thawing presents a number of interesting and difficult technical situations. From an analytical point of view, the general problem of the temperature distribution expected in a disturbed soil subject to the freeze/thaw cycle is one of the most difficult to analyze. To overcome this difficulty, Resource Management Associates (RMA), has undertaken the development of a general purpose numerical model which can be used by the experienced engineer or technician to develop accurate estimates of temperature behavior in freezing conditions. This document provides a description of the capabilities of the numerical model, called GEODYN, and explains both its technical basis and procedures necessary to use the associated computer program.

The program GEODYN is one of three codes that RMA has developed to analyze of freeze/thaw problems. The other two, GEOGRD and GEOPLT, are used to support GEOOYN, and are used as pre- and post-processors, respectively. GEOGRD is a stand alone program which can be used to develop the complicated finite element grids that are often required of prototype problems, while GEOPLT produces isotherm contour plots of GEODYN's results. Each of these programs has its own individual documentation.

1.2 PROGRAM CAPABILITIES

GEODYN is a FORTRAN coded, general purpose mathematical model for time-dependent analysis of two-dimensional geothermal problems. The program solves the equations of heat transfer including temperature-dependent latent heat effects, specified porous media convection, and ground surface/atmospheric heat transfers. GEOOYN utilizes the Galerkin finite element technique and can be coupled with computer graphics programs in a variety of output modes.

The program will accept two-dimensional Cartesian problems as well as two-dimensional axisymmetric problems. The region modeled may have straight or curved internal and/or external boundaries, with arbitrary material zones, soil stratigraphy and material anisotropies. The heat transfer mechanism included in the model includes both conduction and convection, as well as nonisothermal and nearly isothermal phase change. The program will accept a wide variety of boundary conditions including fixed temperatures (which may be time dependent), prescribed thermal fluxes and a full surface heat balance calculated from atmospheric parameters.

The primary output from the program consists of tabular listings of temperatures at particular locations as a function of time. The program also calculates and displays the spatial location Of particular isotherms (i.e., the freezing isotherm), and may output a file for subsequent graphical or statistical processing.

In its present form, GEODYN is considered to be relevant to at least the following types of problems:

Foundation Design - Analysis of short-term and long-term ground/foundation stability due to structure/soil thermal interaction, including construction disturbance effects.

Embankment Design - Analysis of embankment/subgrade thermal regime and its effect on embankment stability under external and internal loadings (ice forces, earthquake forces, foundation forces, thermal forces, gravity forces).

Slope/Thaw Plug Stability - Analysis of time-dependent slope thermal regime and its effect on slope movements.

Liquefaction Potential - Analysis of thaw/frost bulb development for determination of effects on liquefaction potential of soils.

Special Problems Related to Pipelines and Other Facilities

Thaw Settlement - Determine thaw configuration for thaw settlement effects on pipe stresses.

Frost Heave - Analysis of geothermal limits of frost heave including investigation of frost heave mitigation design techniques.

Pipeline Thermal-Hydraulic Analysis - Geothermal interface with pipeline thermal-hydraulic analysis.

Terrain Stability - Determine time-dependent thermal configurations for analysis of construction zone slope stability.

Right-of-way Disturbances - Analysis of thermal disturbance due to construction activities and operations on right-of-way thermal regime (thaw settlement and thermal erosion).

Right-of-Way Drainage - Determine effects of frost/thaw bulb development on subsurface and surface drainage across the ROW (including surface icing, surface and subsurface erosion).

Road Crossings - Determine effect of a (cold) pipe on potential road icings and evaluation of mitigative measures.

River Crossings - Analysis of frost/thaw bulb development effects on river crossings, including icing, scour, and pipe integrity,

Existing Facilities - Determine impact on existing facilities (structures, culverts, utilities, etc.) within pipe thermal influence zone.

Axisymmetric Problems - Analysis of artificial islands in the Arctic Coastal Zone and impact of exploratory drilling in a permafrost environment.

1.3 GOVERNING EQUATIONS

The two-dimensional form of the differential equation solved by the model can be written in Cartesian coordinates as:

$$\overset{(1)}{w\beta_1 \frac{\partial T}{\partial t}} + \overset{(2)}{w\beta_2 \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right)} - \overset{(3)}{\frac{\partial}{\partial x}\left(k_x w \frac{\partial T}{\partial x}\right)} - \overset{(4)}{\frac{\partial}{\partial y}\left(k_y w \frac{\partial T}{\partial y}\right)} + \overset{(5)}{w\sigma_1} - \overset{(6)}{w\sigma_2} = 0 \tag{1.1}$$

where T = temperature, °C

β_1 = the average volumetric heat capacity of the soil mass (kJ/m^3); this term is temperature dependent

β_2 = the volumetric heat capacity of water (kJ/m^3)

u, v = the components of Darcian water velocity in the x and y directions, respectively (m/hr)

K_x, K_y = thermal conductivity coefficients in the x and y directions, respectively (kJ/hr m °C); these terms are temperature dependent

w = the soil thickness normal to the x-y plane (m)

σ_1 = a thermal source or sink representing the effects of latent heat (kJ/hr m^3); this term is temperature dependent

σ_2 = a thermal source or sink term representing a thermal flux such as a surface heat flux or the flux resulting from the geothermal gradient (kJ/m)

Equation (1.1) represents a generalized, nonlinear statement of the equation describing the flow of heat in a saturated or unsaturated soil. In reviewing this equation, several comments concerning the assumptions made for each term are appropriate. First, in term (1) of Equation (1.1), the assumption is made that the heterogeneous soil-water matrix can be represented by a homogeneous approximation using a single volumetric heat capacity, β_1. In general, β_1 will be temperature dependent, and different values will be used if the local temperature is above or below the freezing temperature. In other words, β_1 is described in a stepwise fashion, with the step occurring at the phase transformation temperature.

Term (2) of Equation (1.1) represents the thermal effects of flowing water in the soil matrix, and is usually called the convection term. This term is derived directly from thermodynamic considerations and can have a profound effect on the behavior of a thermal regime, At the present time, it is assumed that all values of convective velocity are specified external to the model. If the temperature falls below freezing, the local water velocities are assumed to go to zero at that point. Terms (4) and (5) represent the diffusive transfer of heat according to the Fourier analogy. As with the soil properties, the diffusion coefficients are assumed to be stepwise temperature-dependent at the freeze temperature. It is the analyst's responsibility to specify the correct properties for the soil mass above and below the freeze point. Also, while not a general situation, it is easily seen that Equation (1.1) is formulated to simulate anisotropic diffusion properties in the x and y directions. This may be of particular interest in axisymmetric problems. The fifth term of Equation (1.1) represents the effects of latent heat. Proper formulation of this term is essential to the solution of the freeze/thaw problem, and a large number of alternative formulations have been tested. At the present time, this term is formulated as:

$$\sigma_1 = \frac{\lambda}{\Delta t} (m_1 - m_0) \qquad (1.2)$$

where σ_1 = the net effective heat source/sink term to represent the effects of the latent heat of fusion (kJ/hr m^3)

λ = the latent heat of fusion for the soil matrix (kJ/m^3)

At = some finite time interval between times t_0 and t_1 (hr

m_1 = the unfrozen moisture content of the soil matrix at the end of the time interval t_1 (fraction of total available unfrozen moisture for phase transformation)

m_0 = the unfrozen moisture content of the soil matrix at the beginning of the time interval t_0 (fraction of total available unfrozen moisture for phase transformation)

Finally, it is assumed that the unfrozen moisture content of a soil, m, can be approximated as a function of the soil temperature. This relationship has the form:

$$m = \lambda \left(\frac{\alpha}{\alpha + T_f - T} \right)^4 \text{ for } \quad T < T_f$$

and: (1.3)

$$m = 1.0 \qquad \text{for} \quad T \geq T_f$$

where T = the local temperature (°C)

T_f = the freezing temperature (°C)

The last term of Equation (1.1) represents the effects of heat fluxes. Such fluxes may either be specified by the analysis (i.e., the geothermal flux), or may result from a calculation of a surface heat balance. When done as a surface heat balance, the net surface energy balance flux term is approximated by the relationship:

$$Q_{NET} = Q_{SW} + Q_{NLW} + Q_{TURB} - Q_{EVAP} \tag{1.4}$$

where Q_{SW} = transmitted shortwave radiation flux

Q_{NLW} = transmitted net longwave radiation flux

Q_{TURB} = turbulent heat transmitted across the surface

Q_{EVAP} = evaporative heat flux leaving the boundary surface

In general the terms of Equation (1.4) are both surface temperature dependent and functions of one or more atmosphere variables. In order to calculate these terms, the user must supply appropriate time average values of the following meteorological parameters:

- Available incident solar radiation (kJ/day - m^2)
- Wind velocity (meters per hour)
- Evaporation flux (kJ/day m^2)
- Snow depth (m)
- Snow density (grams/cm^2)
- Air temperature (°C)
- Cloud cover (fraction of sky)

Evaluation of Equation (1.4) is completely integrated with the calculation of soil temperatures. Complete details of the formulas used to estimate component terms is provided in Appendix A of this document.

1.4 METHOD OF SOLUTION

To solve Equation (1.1), it is necessary to integrate the equation in both time and space. Except for very simple boundary conditions and material properties this is not possible by direct methods. It is therefore necessary to employ a numerical technique to obtain the desired solution. In the case of GEODYN, the isoparametric finite element method is used. In the process, Galerkin's criterion is used with the method of weighted residuals and the equations are integrated by Gaussian quadrature. The resulting set of equations is nonlinear and the final solution is found by the Newton-Raphson iteration technique.

To understand GEODYN, one should be aware of the procedure used to integrate spatially the governing equations. The first step in this process is to subdivide the region to be simulated into a number of subregions or subdomains called finite elements. These subdomains may have either triangular or quadrilateral shapes and may have curved boundaries or other irregular features. The corners and midside coordinates of each subdomain side are defined to be node points, and the output from the simulation is calculated in terms of the node point locations.

To produce the desired simulation, we first integrate Equation (1.1) over each subdomain (element) in terms of its nodal point values. The influence of all the subdomains is aggregated into a final set of algebraic equations to provide the numerical solution. The spatial integration is done by a process known as numerical integration. By using this technique any sort of function can be integrated over an area by making the assumption that:

$$\int_A f(T)\,dA = \sum_{i=1}^{n} w_i f(T)_i \qquad (1.5)$$

where $f(T)$ = the continuous function (Equation (1.1)) over the area "A"

$f(T)_i$ = the value of the function evaluated at a particular location, i, within the area "A"

w_i = a weighting factor associated with the particular location i

The particular locations where the components of Equation (1.5) are evaluated are called the Gauss points. The larger the number of Gauss points, the more complex f(T) can be and still achieve an exact or nearly exact integration of the function. GEODYN has a number of different options on the number of Gauss points and will automatically use the least number required for a particular problem. This is important as computer time increases with the number of Gauss points in the solution. At the present time, GEODYN may use 9, 16, 25 or 49 Gauss points for a quadrilateral and 7 or 16 points for a triangle.

The equations developed from the numerical integration are valid at all points in space at a particular instant in time. If a steady state solution is desired ($\partial T/\partial t \equiv 0$), the appropriate terms are set to zero and a solution is made of the equations. If a dynamic problem is specified, however, it is necessary to integrate Equation (1.1) in time as well as space. This is accomplished as follows. First, it is assumed that the value of T at a particular point varies over a discrete time interval according to the relationship:

$$T = T_1 + at + bt^{\alpha} \qquad (1.6)$$

where T_1 = the value of temperature at the beginning of the time step

T = the value of temperature at the time t

t = elapsed time from the beginning of the interval

a,b = coefficients

If Equation (1.6) is differentiated, we find:

$$\frac{\partial T}{\partial t} = a + \alpha b t^{\alpha-1} \qquad (1.7)$$

which can be substituted into Equation (1.6) to eliminate b and gives:

$$\frac{\partial T}{\partial t} = a + \frac{\alpha}{t}(T-T_1) - \alpha a \qquad (1.8)$$

We also know that at $t = 0$, $\partial T/\partial t = 1$, or $(\partial T/\partial t)_1 = a$. If this relationship is applied, and the subscript 2 is used to denote the value at the end of time interval (t = At), we find:

$$\left(\frac{\partial T}{\partial t}\right) = \frac{\alpha}{\Delta t}(T_2 - T_1) + (1 - \alpha)\left(\frac{\partial T}{\partial t}\right)_1 \qquad (1.9)$$

Note that if $\alpha = 1$, this reduces to the conventional linear integration scheme and if a = 2, the scheme is identical to the quadratic integration method. A value of $\alpha = 1.5$ has been found stable for large time staps and also to give good accuracy.

To incorporate Equation (1.9) into GEOOYN, we make use of the idea that our solution is to be valid at a particular instant in time (the end of the time step), and that complete information is available for T and its time derivative at the beginning of the time step. The solution is then marched through time in a series of discrete intervals (time steps) which are specified at the discretion of the user.

1.5 REPORT ORGANIZATION

This document is organized into four chapters. The four chapters are intended to provide the user of GEOOYN with the information needed to understand the program, assuming he is generally familiar with the solution of geothermal problems and has some experience with computer models and numerical simulation.

In format, the first chapter provides an overview of the model, the problems to which it can be applied, and gives a short introduction into the governing equations and the solution technique. Chapter 2 provides a description of the computer program, and Chapter 3 presents the results of an example problem which utilizes most of GEODYN's options. In Chapter 4, the detailed instructions for GEODYN's computer input are fully described. In addition to these four chapters, this report contains three appendices. Appendix A provides additional detail on the formulation of the surface heat balance terms, and Appendix B further develops the mathematical basis of the numerical model. Finally, Appendix C reproduces several test cases which compare GEODYN's numerical solution against known analytical solutions to phase change problems.

CHAPTER 2

PROGRAM ORGANIZATION AND DESCRIPTION

The computer program GEOOYN consists of a main routine, 19 active subroutines and a Block Data subroutine. All the routines are written in standard FORTRAN code, and no special system or library routines are needed. The logical organization of the code is shown in Figure 2-1, with the subroutines indicated in the order in which they would be called in a normal program execution. The paragraphs which follow provide a narrative description of the main routine and each of the active subroutines. The subroutine descriptions are provided in alphabetical order after the main routine, not the order shown in the figure.

Main Routine (GEODYN)

Program execution begins in the main routine with the initialization of program arrays for which lack of initialization could cause later trouble. Next, subroutine CGP is called to calculate normalized Gauss point factors which will be used later for spatial integration of the governing equations. Subroutine INPUT is then called to input and echo print all nondynamic run control variables and program data not associated with surface energy balance. Upon return from INPUT, subroutine IOSURF is called to input all data associated with the surface energy balance and/or user specified surface fluxes. If a final results file is to be output, the geometric data for the problem are written to logical unit IS5; if the problem is time dependent, subroutine PRINT will be called to echo print (on logical unit 6) the problem's initial conditions.

Subsequent to printing the initial conditions, the program enters the time loop. This loop is executed repeatedly for as many time steps as are specified by the user. At the top of this loop the program sets the current time step, updates several arrays in time, calls subroutine IODYN to update the specified temperature boundary conditions and decides if the problem is symmetrical or nonsymmetrical as a result of convective terms. With these operations complete, subroutine LOAD is called to form the cross reference between external node numbers and internal equation numbers; at this point the program enters the iteration loop.

Within the iteration loop, subroutine FRONT is called for a nonsymmnetric problem or subroutine FRONTS called for a symmetric problem. In either case, a solution update vector is calculated and the temperature arrays incremented by the latest solution. Subroutine CONVRG is then called to see if any nodes and/or elements can be dropped for subsequent iterations, and the most recent convergence history saved for later printing. The program continues to loop until either a

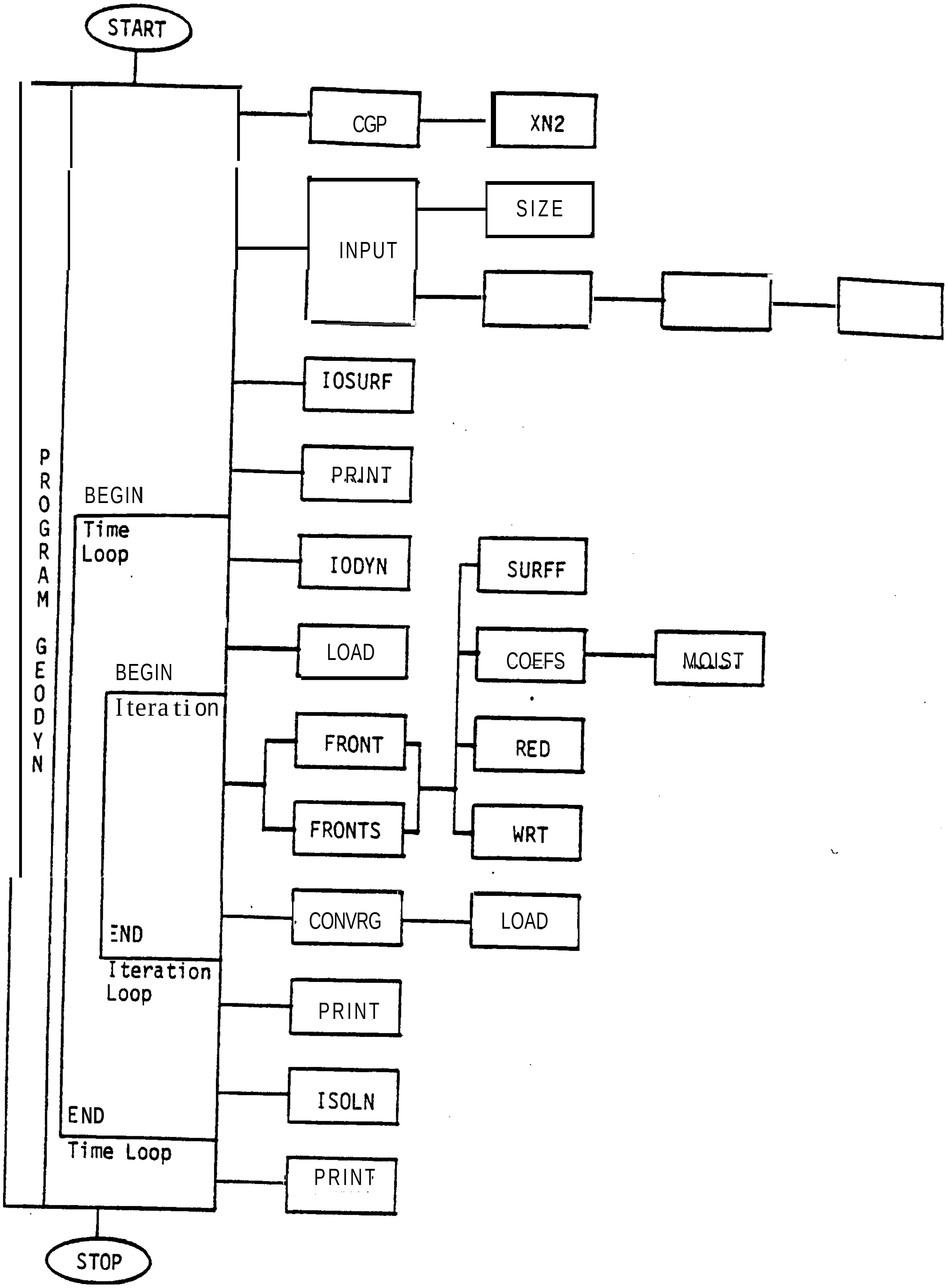


FIGURE 2-1

LOGICAL ORGANIZATION OF THE MAIN ROUTINES AND SUBROUTINES WHICH COMPRISE THE COMPUTER PROGRAM GEODYN converged solution is found or the user set iteration limit is reached. If a solution is found, the program will call subroutines PRINT to output the node point temperatures and subroutine ISOLN to compute and print the location of the freezing isotherm. Following this, a restart file will be written on unit IT if requested. If, at the iteration limit a solution is not found, the program may increase the number of potential Gauss points and re-enter the iteration loop; this process will be repeated until the user defined Gauss point limit is reached. If a converged solution cannot be found the program will output an error message and exit the time and iteration loops. If converged solutions are found the program simply repeats the above process until all time steps have been computed. In any case, after leaving the time loop, the convergence history for the entire computer run is output to the printer along with the time history of temperatures at certain user defined node points. Following this a message indicating the end of the run is printed and program execution stopped.

Subroutine ADJPT

As part of GEODYN's frontal solution scheme, the program needs to develop a list of the order in which elements can be eliminated to achieve the minimum frontwidth. Subroutine ADJPT is used with subroutines REORD and ORDER to calculate this list.

From a computational point of view, subroutine ADJPT prepares a matrix (ICON) of the nodes which are connected to a given node, and which are thus available for inclusion in the equation elimination procedure. This information is returned to subroutine ORDER where decisions are made on what adjacent nodes are then best brought into the elimination to get a minimum frontwidth.

Subroutine ADJPT is called from subroutine ORDER a variable number of times depending on the problem. and makes no 'further calls.

Subroutine CGP

Program GEODYN performs its required integrations via a process known as Gaussian Quadrature. This process is basically a method whereby a series of weighted components is summed to perform a numerical approximation of an exact integral. It is the function of subroutine CGP to calculate and store the necessary two dimensional factors as calculated from a much simpler set of one dimensional functions. (Note: two dimensional factors are multiples of one dimensional factors.) At present, subroutine CGP deals only with quadrilateral shapes; the factors for triangles are explicitly set in GEODYN's Block Data subroutine.

Computationally, CGP enters a loop the integration levels, and then copies appropriate one dimensional factors into temporary arrays. The actual shape function, weighting factors and derivatives are calculated by a call to function XN2 for a given location. Upon the return from XN2 the results of the calculations are stored in program arrays dimensioned in the common block GAUSS.

Subroutine CGP is called once in each program execution from the main program and makes further calls to function XN2.

Subroutine COEFS

As explained elsewhere, the finite element method performs spatial and temporal integration on an element by element basis and then aggregates the individual element contributions to find the final solution. The temporal and spatial integration of the governing equations for an individual element is the prime function of subroutine COEFS.

To perform the desired computations, the routine first decides if the element is a triangle or quadrilateral and then copies the appropriate shape functions and weighting factors into temporary program arrays. Next, the local element properties are estimated based on current temperatures, and then the code enters the loop on the individual Gauss points. Within this loop the first task is evaluation of the Jacobian and then the evaluation of the local state variables. Next, the right-hand-side (a vector) and the left-hand-side (a matrix) of terms needed by Newton-Raphson iteration scheme are formed by summing individual contributions on a Gauss point by Gauss point basis. Note that if the problem is symmetrical, COEFS recognizes this fact and the computational effort is reduced accordingly.

Upon completion of the basic element formulation process, COEFS checks to see if any atmospheric surface fluxes have been specified for this element. If they have their contribution is incorporated in the left and right hand sides matrices via numerical evaluation of the appropriate surface flux line integrals.

Following this, the global right-hand-side vector, R1, is updated for all active system equations. The global left-hand-side matrices are updated later in the calling routine (FRONT or FRONTS).

Subroutine COEFS is called from subroutine FRONT for a nonsymmetric problem or FRONTS for a symmetric problem for each active system element at every iteration cycle. It makes one further call to subroutine MOIST.

Subroutine CONVRG

Program GEODYN uses an iterative solution technique to solve its governing nonlinear equations. This technique completes a solution by making successive corrections to a previous solution. It is the function of subroutine CONVRG to inspect the solution correction vector, and to complete one of two tasks. First, CONVRG inspects the entire solution vector, and compares the maximum solution correction to the user specified convergence criterion. If all corrections are less than the limit, the solution is converged and control is returned to the point of the call. If the solution is not converged, CONVRG will inspect the solution to see if the equations defining any individual element have converged sufficiently to allow an entire element to be deleted on the next iteration.

Computationally, CONVRG begins with a loop on node points to check to overall convergence of the solution vector. In this process relevant statistics on the solution are saved for later printing. Assuming the solution has not converged, a loop is entered on the system of elements. If it is found that each node in an element has cbnverged, the element is eliminated from the system by modification of the array IMAT. Once all the elements have been checked, subroutine LOAD is called to reform the active set of system equations.

Subroutine CONVRG is called once in each iteration cycle from the main routine. Depending on the application, it may or may not call subroutine LOAL.

Subroutine FRONT (and FRONTS)

Subroutine FRONT and FRONTS are two nearly identical subroutines which, for all practical purposes, can be documented by this single description. The only difference between FRONT and FRONTS is that FRONT is capable of solviflg a nonsymnetric set of system equations, while FRONTS is designed to solve a symmetric set of equations, From a programming point of view, FRONTS is a slightly modified version of FRONT which recognizes and takes advantage of the symmetrical nature of the governing equations. The decisions to use FRONT or FRONTS is made in the main routine, and FRONTS is included in GEODYN primarily to reduce computer time where possible. In the paragraphs which follow, all references to FRONT will also be applicable to FRONTS.

Subroutine FRONT begins by initializing various program arrays, and then modifying the element/node connection array to indicate the last appearance of each node in the upcoming equation elimination process. Next, the global right-hand-side vector, R1, is initialized; a call is then made to subroutine SURFF which will produce a modification to R1 if surface fluxes are included in the problem.

The routine then enters a price of logic whereby the contribution of each active system element to the global system of equations is calculated by a call to subroutine COEFS. The order in which the element contributions are calculated and stored is provided in the array NFIXH which is either set by default or a call to the element reordering subroutines. FRONT then accumulates the node point (equation) contributions until a forward elimination can be done on a particular row and column. In this process, the results of the completed (intermediate) eliminations are saved via calls to subroutine WRT. This process is repeated until all system equations have been considered. At this point FRONT begins the back substitution on the system of reduced equations to find the final solution vector. This is done in a standard fashion, with calls to subroutine RED to retrieve the intermediate and previously stored values. Once the back substitution is complete, FRONT returns control to the main routine where the solution vector, Rl, is used to update the nodal temperatures.

Subroutine FRONT is called from the main routine for each cycle of iteration for each time step and it calls to subroutines SURFF, WRT and RED.

Subroutine INPUT

Subroutine INPUT has the function of reading into the computer most of the user specified data which does not change with time. Most data for INPUT comes from the card reader (logical unit 5) and is imnediately output to the line printer (logical unit 6) as a check. Subroutine INPUT makes few calculations of its own.

In a logical sense, INPUT reads and echo prints the Run Control Parameters, Numerical Solution Parameters and Time Control Parameters for each run (see Chapter 3 for examples of this output). Next, INPUT reads optional data such as the length of the simulation time steps, the parameters for sinusoidal boundary conditions and nodes that will have special printed output. Following this, INPUT reads the material zone properties, the geometric file produced by program GEOGRD, and any network update cards; if an axisymmetric problem has been defined, INPUT also makes the required adjustment to the system thickness inputs. Subsequently, INPUT calls subroutine SIZE to compute element sizes and subroutine REORD for element ordering. Next, depending on user options, INPUT will output to the printer the complete network definition of nodal coordinates and element connections. Finally, the routine reads the initial conditions and inputs the specified restart file, if any.

Subroutine INPUT is called once in each program execution from the main routine. It makes further calls to subroutine SIZE and optionally to subroutine REORD.

Subroutine IOOYN

Program GEODYN is designed to accept a wide variety of boundary conditions, some of which may be updated as the program marcnes through time. It is the function of subroutine IOOYN to input and specify those fixed value temperature boundary conditions which change with time.

From a logical point of view, this is done by reading the annual temperature cycles and information on how many boundary conditions are to be changed from the current specifications. New specifications are then loaded into the proper program arrays. Following this, sinusoidal temperature values are calculated and loaded, if specified, and all current values of specified temperature boundary conditions output to the line printer on a print cycle. Next, updated values of the specified convective velocities will be input and printed; the format of the convective output will depend on whether or not the convective velocities are uniform at all node points or vary from node Point to node point.

Subroutine IOOYN is. called once for each execution of GEODYN's time loop, and makes no further subroutine calls.

Subroutine IOSURF

Program GEOOYN can accommodate two types of surface fluxes, those calculated from atmospheric conditions and those specified by the user. It is the function of subroutine IOSURF to input to the program all the information necessary numerically evaluate both of these types of fluxes.

From a logical point of view, IOSURF begins by testing the user specified value of the number of nodes which are to have atmospheric fluxes. If it is greater than zero, the program will input and echo print all user definitions of the annual meteorologic cycle. This includes certain heat fluxes and meteorologic variables that are used in the calculation of the full surface heat balance. The reader is referred to Chapter 1 and Appendix A of this report for further details on GEODYN's surface energy balance.

Following their basic definition, the meteorologic variables are scaled by user defined factors and the final values output to the printer for review. Finally, IOSURF develops a list of the nodes which define the atmospheric interface, and will halt if the user has specified incorrect nodal definitions (not an outside boundary),

The second portion of IOSURF inputs and outputs the number and location of user specified constant surface fluxes. These may be applied to any of a networks outer boundaries, and can be used to represent such things as the earth's geothermal gradient. Following this, the program again develops a complete list of the nodes which define the flux boundary, and will halt if the user has provided an incorrect specification.

Subroutine IOSURF is called once in each program execution from the main program, and makes no further subroutine calls.

Subroutine ISOLN

As one of its program options, program GEOOYN will locate the position of the freezing isotherm. This option is intended to aid in the interpretation of results, and is done on an element side by element side basis. It is the function of subroutine ISOLN to perform the calculations ncessary to locate the freezing isotherm on an element side.

Computationally, ISOLN begins this process by entering a loop on active system elements. Within this loop, the maximum and minimum element nodal temperatures are checked, and only those elements which have temperatures above and below freezing are kept for further consideration. If an element has been selected, a loop is entered to determine which element side(s) contain the freezing isotherm. If an element side is selected, it is checked to see if this is the first occurence of the side in the search process. If it is, the program uses a Newtonian iteration scheme and the isoparametric shape functions to locate the exact position of the freezing isotherm on the element side. This procedure is necessary due to the nonlinear nature of both the geometric coordinates and the temperature values. At the conclusion of these computations the program prints the X and Y coordinates of the freezing isotherm, together with some information on the element side in which it was found.

Subroutine ISOLN is called by user option from the main program for each time step and makes no further calls.

Subroutine LOAD

As part of the bookkeeping design of GEODYN, it is necessary to create a cross reference array between internal equation numbers and external node numbers. Creation of this array, which is stored in array NBC in common block BLK3 is the sole job of subroutine LOAD.

To create the desired array, LOAD scans each active problem element and creates a list of potential active equations. Next, equations at the location of specified temperature boundary conditions are deleted, and the final cross reference list created. The total number of active equations is assigned the value NSZF, and this value is checked against the current program dimension limit IR1MAX. If NSZF IR1MAX a message is output to the printer and program execution halted.

In normal program operation, LOAD will be called once in the main program for each time step, and may or may not be called from subroutine CONVRG; calls from CONVRG are dependent on the dropping of node point equations. Subroutine LOAD makes no further subroutine calls.

Subroutine MOIST

In its current form, program GEOOYN estimates the frozen moisture content of a soil as a function of temperature from the relationship:

$$m = \lambda \left(\frac{\alpha}{\alpha + T_f - T}\right)^4 \quad ; \quad T \leq T_f$$

where m = the unfrozen moisture content

T_f = freezing temperature

T = local temperature

λ, α = soil property parameters

It is the function of subroutine MOIST to evaluate this equation and to find its derivative with respect to temperature.

Subroutine MOIST is called from subroutine COEFS for each Gauss point in the numerical integration loop and makes no further calls. Please note that if moisture functions other than that shown above are to be used in GEODYN, subroutine MOIST will need to be rewritten accordingly.

Subroutine ORDER

As part of GEODYN's frontal solution scheme, the program needs to develop a list of the order in which elements can be eliminated which will result in the minimum frontwidth. Subroutine ORDER is used with subroutines REORD and ADJPT to calculate this list.

Subroutine ORDER is a somewhat complicated bookkeeping algorithm which performs a pseudo equation elimination in an incremental fashion. In this process, ORDER inputs a list of user specified node points and begins the elimination process based on the implied element connections. When it gets to a point where it needs additional equations to continue the elimination process, it selects the best alternative from a list of potential nodes which has been prepared by a previous call to subroutine ADJPT. This process is repeated until all nodes have been considered, at which time control is returned to the calling routine, REORD, Please note that this procedure is a directed search, and will not always find the global optimum order for a given system of equations. Also, as presently coded, ORDER does not take account of boundary conditions; in some problems this may be a factor.

Subroutine ORDER is called from subroutine REORD. It is called once for each user specified list of starting node points and outputs an echo check of the data it reads. It makes a further call to subroutine ADJPT.

Subroutine PRINT

The function of subroutine PRINT is to output to the line printer, logical unit 6, the entire array of nodal temperatures. In addition, PRINT outputs information on the elapsed simulation time (hour, day, month and year) plus an indication of which nodes have specified temperature boundary conditions and the most recent convergence history.

Logically, PRINT begins by loading the boundary condition identifier array and printing the time data and information relating to the nature of the current problem (i.e., steady state or dynamic). Next, the temperature history is output, followed by a sumnary of current atmospheric conditions if a surface heat balance is included in the simulation. Following this the current convergence history is printed.

Subroutine PRINT is called at user specified time step intervals (NTSEG) in a dynamic simulation, as well as to print initial conditions or the results of a steady state problem. PRINT makes no further calls.

Subroutine RED

Subroutine RED is used as a virtual memory replacement for a tape or disk READ operation. Its function is to retrieve the values of the arrays LHS and QS and the scalar LQ which have been generated in the solution process and stored via a call to subroutine WRT. This is accomplished by declaring a large virtual storage area, common block FAKE, into which the desired values have been stored. At each call to RED the values in the comnon block FAKE are simply copied into the appropriate local arrays.

Subroutine RED is called from either subroutine FRONT or FRONTS for most problems, but may not be called at all for small problems.

Subroutine REORD

As a part of GEODYN's frontal solution technique, the program must be able to develop an element order which results in a minimum front width. It is the function of subroutine REORO, working with subroutines AOJPT and ORDER, to find such an order. The technique used in GEODYN cannot be proved to be optimal in all cases, but has given satisfactory results in a large number of widely varying situations.

From a logical standpoint, the process starts in subroutine REORD. As its first task, REORD computes a list of all nodes connected to all other nodes (array ICON) and then makes an initial estimate of the maximum effective front width or bandwidth. Next, REORD calls subroutine ORDER to generate a new order resulting from a starting sequence supplied by the user. Upon return from ORDER, REORD saves the best current order, and then either returns to ORDER for a new try or is signaled that all current trys are complete. In either case, once all trys are complete, REORD transforms the nodal order generated in ORDER into an equivalent element order, outputs a message, and returns to the point of the call,

Subroutine REORD is called once by user option from subroutine INPUT and makes a futher call to subroutine ORDER.

Subroutine SIZE

It is the purpose of subroutine SIZE to compute the areas of all finite elements active in the current problem. This is accomplished by numerically integrating a unit function over the element area. The results of this integration are saved in array XAREA, which is dimensioned in the common block BLK4.

Computationally, SIZE enters a loop for each problem element, Within this loop a determination is made as to whether the element is a triangle or quadrilateral, and approriate shape functions, Previously computed in subroutine CGP, are copied into temporary arrays. The unit function is then integrated by sumning the appropriate shape functions and Gauss point values.

Subroutine SIZE is called from subroutine INPUT once in each program execution and makes no futher subroutine calls.

Subroutine SURFF

Program GEODYN has the capability to simulate a full surface energy balance as outlined elsewhere. It is the function of subroutine SURFF to calculate the various factors and constants which are necessary to include the surface energy balance in the appropriate system equations. SURFF also computes the terms necessary to include the user specified constant flux terms in the simulation.

Computationally, SURFF begins by finding the interpolated values of the meteorologic parameters which have been input in subroutine IOSURF. Once this is complete, the routine enters a loop on the specified number of element sides (NSFI) which define the soil/atmosphere interface. Within this loop the left and right hand side terms of each component in the energy balance are individually evaluated and stored in program arrays for later use. At the conclusion of this process, the program will have available for later use, in subroutine COEFS, the aggregate of all the surface heat effects on an element side by element side basis.

Subroutine SURFF is called from subroutine FRONT (or FRONTS) once for each iteration, and makes no further subroutine calls.

Subroutine WRT

Subroutine WRT is used as a virtual memory replacement for a tape or disk WRITE operation. Its function is to save intermediate values of the arrays LHS and QS and tne scalar LQ which are generated in equation solution process by subroutines FRONT or FRONTS. This is accomplished by declaring a large virtual storage area, common block FAKE, into which current values are stored for later retrieval. The size of the virtual storage space is checked on each entry and the program will write a message and stop if the allocation is exceeded.

Subroutine WRT is called from either subroutine FRONT or FRONTS for most problems, but may not be called for small problems.

Subroutine (Function) XN2

Program GEOOYN uses Gaussian Quadrature to perform certain spatial integrations of its governing equations. This process entails the summing of a number of factors over the region of integration. These factors include the various finite element shape functions and their derivatives at the summation (Gauss) points. It is the purpose of function XN2 to evaluate the shape functions and X and Y derivative of the shape functions for either triangles or quadrilaterals of unit dimension at various Gauss points.

From a logical point of view, XNZ is composed of two similar pieces, one for evaluation of triangles and one for quadrilaterals. Upon entry, control is directed to the proper portion of the subroutine and the proper functional evaluation (shape function or derivative) via parameters supplied in the calling sequence. The desired calculations are then completed and control returned to the calling routine, CGP.

XN2 is called from subroutine CGP for each Gauss point in a quadrilateral for each level of integration and makes no further calls.

CHAPTER 3

EXAMPLE PROBLEM

PROBLEM DEFINITION

To demonstrate the operation of program GEODYN, and to aid users in the solution of new problems, a fairly large scale test problem is presented for review. Any user of GEODYN should review this problem carefully prior to using the code in order to understand its data requirements and to become familiar with what to expect in relation to the model's input and output.

The example problem represents a cold pipe in a large soil mass. The network for the problem is assumed to have been defined by the user and previously generated via the program GEOGRD (see example application in the GEOGRD documentation). A plot of the basic network showing the location of the pipe and the various material zones is reproduced in Figure 3-1. As can be seen in the figure, the network is symmetrical about the vertical axis of the pipe, has five material zones, and is assumed to have a ground/atmosphere interface in the indicated location. The problem is to be run without convection (all groundwater velocities equal to zero) and with a full surface heat balance along the ground surface. The geothermal gradient will be specified as a constant flux across the network's lower boundary.

The data necessary to run this problem generally divide into three groups; physical data, initial conditionlboundary condition data, and run control data. The physical data are needed to describe the physical characteristics of the problem and its environment. For this problem the physical data are primarily the material properties of the five network zones and the ambient atmospheric conditions. The values used for this problem are summarized in Tables 3-1 and 3-2 respectively, and are typical of inputs required for such a problem. Please note that the pipe has been given certain physical properties and will be simulated by a single specified temperature at its center and the indicated "equivalent thermal properties" from its center to its outer wall. This type of representation is only one of several alternative schemes that could have been used to represent the pipe (i.e., specified fluxes or specified wall temperatures), and it is the responsibility of the analyst to chose the method most suitable for a given problem.

Other data for this problem include definition of the initial conditions, which were set just above freezing at 0.056°C, the temperature at the center of the pipe of -12.22°C and the selection of the simulation time steps (two at 7,604 days and 15.208 days thereafter).

In addition to these data two other types of data have been specified that require knowledge of the network's node numbers, The first of these has to do with GEODYN'S element reordering option. This option, which should always be used, requires that the user provide a list of nodes from which the program can begin the reordering Operation, The reordering may be performed by the GEODYN program at the user's option. Since GEODYN's scheme cannot be guaranteed to be globally optional, the user may need to do a little experimentation with starting lists to find the best overall sequence.

In the example problem, the reordering option has been given two starting lists, one along the ground surface and one along the bottom of the network (see Figure 3-2 for definition of the node numbers). The program will process each of these lists, and save the best element order.

The second type of input data that requires knowledge of the network's numbering are the surface fluxes. As before, the reader is referred to Figure 3-2 for definition of the network node numbers. In this case, it can be seen in the figure that mid-side node numbers along the ground suface have been used to define the location of the ground/atmospheric interface, while the mid-side nodes along the bottom define the location of the geothermal flux,

All these data, plus other information and data necessary to operate GEOOYN are organized according to the specification provided in Chapter 4. An annotated computer listing of the GEOOYN input data file is reproduced in figure 3-3. The user is referred to the instructions provided in Chapter 4 for the exact definition of the various items shown in Figure 3-3.

RESULTS

Program GEOOYN was operated for six time steps using the network shown in Figure 3-1 and the input data file reproduced in Figure 3-3. The results from the simulation are reproduced in Figures 3-4 to 3-11, as explained below.

As its first task, GEODYN reads and echo prints all the various run control and system definition data as shown in Figure 3-4. The order and definition of this data follow exactly the order of input given in Chapter 4 and the user should always review this section of the output for confirmation of desired program inputs,

Next, since the element reordering option is in effect, the program will input and process the two starting lists provided by the user. The results of this operation are shown in Figure 3-5, where the specifications for the two starting lists are printed along with the final element order selected. The user should note that the second input list provided the best order, and if this network is to be used for additional runs the first list may be deleted from the input stream,

Following the output of the reordering information, if requested the program will output the complete definition of nodal coordinates and element/node connections as shown in Figure 3-6. This output should always be reviewed carefully at least once for any particular problem. In addition to its obvious use to reference the spatial location of nodes, this output also provides the element areas and the user should check for such things as zero or negative values. If such a value is found, a mistake has occurred in problem setup that must be corrected before going further. A common error which results in negative areas is numbering the nodes in a clockwise direction in the element definition.

If the program is to use a full surface heat balance, the next item of output is a sumnary of the annual meteorologic conditions as shown in Figure 3-7. This output shows both the original input values as well as the values which result after multiplication by user defined scale factors.

After printing the meteorologic inputs, the program will output the various local factors assigned to nodes (element sides) along the soil/atmospheric interface, as well as any fluxes specified as constant values (see Figure 3-8). The values shown here will be held constant throughout the entire computer run.

In any dynamic simulation, the next output will be a complete summary of the problems initial conditions as shown in Figure 3-9. This report simply lists all the node numbers in the network and shows the initial temperature values which have been assigned. Since the accuracy and stability of a problem's solution are often highly dependent on a correct definition of initial conditions, the user is urged to review these values quite carefully prior to beginning a significant simulation.

All of the above outputs have been produced by GEODYN prior to actually beginning any simulation. Before beginning any major simulations the user should produce and review this information to insure proper problem specification. Once a simulation is begun the program simply marches forward in time, with printed output produced at the user specified frequency. In the example problem, the simulation was run for six time steps, with the output produced on the last step as shown in Figure 3-10.

At the top of Figure 3-10, the program recaps the time of the output, and then prints a complete history of all the networks nodal temperatures. If a node has a specified temperature boundary condition the symbol (*) is printed next to its temperature. Next, if a full surface energy balance is being calculated, the program outputs a general recap of the current meteorologic conditions, and then a node by node display of current values across the atmospheric interface. The nodal values differ from the general conditions by their local factors, and show each of the various components of the energy balance. Please note that in this example there was a snow cover of 0.61 meters, and the energy balance was calculated from the heat transfer through the snow, not a simple sumnation of the various energy terms.

Following the energy balance terms, the program prints a sumnary of the most recent convergence history, and the coordinate location of the freezing isotherm. This last display shows not only the absolute X and Y locations, but the fractional location along the indicated element side and is intended to aid the user in preparing quick sumnaries of the results without using the plotting program GEOPLT.

The program's final output, Figure 3-11, provides a complete recap of the problems convergence history. This output summarizes the length of each simulation time step, the final maximum temperature correction, the number of active nodes in the last iteration, the integration level and the number of iterations necessary to converge the problem, The convergence history shown here is typical of what could be expected from this type of problem.

These figures give a good indication of what can be expected from the program, and demonstrate most of the program options. Not included are the output which results if individual node time-temperature histories are requested or any error messages which are self explanatory. Note that the program option to output a final results file (tape) for subsequent processing by the plotting program, GEOPLT, was implemented. The use of this file will be documented in the GEOPLT documentation where the results of this example application will be shown graphically.

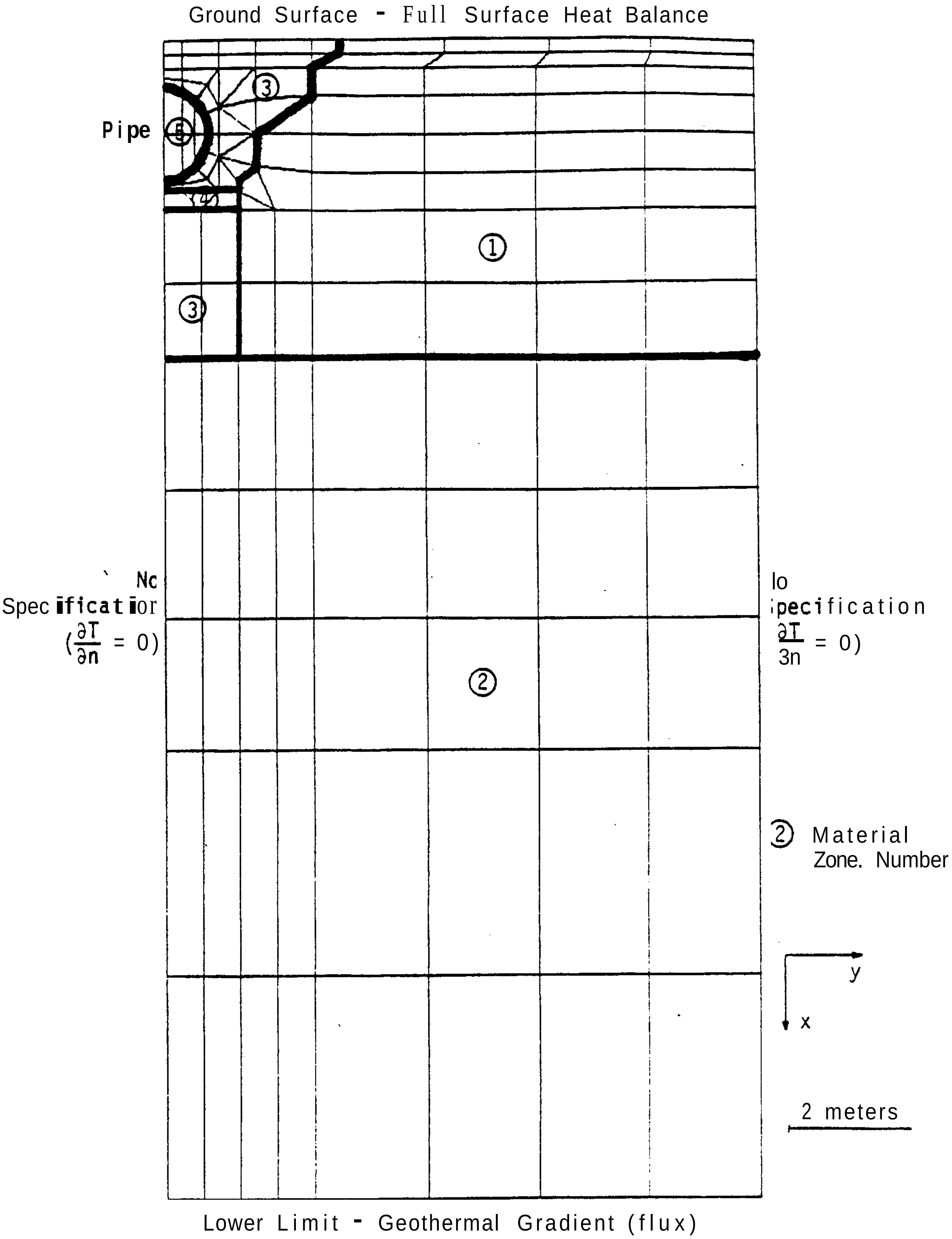


FIGURE **3-1**

GEODYN EXAMPLE PROBLEM **NETWORK** SHOWING
MATERIAL ZONES, LOCATION OF PIPE
AND **BOUNDARY CONDITIONS**

TABLE 3-1

ZONE MATERIAL PROPERTIES FOR GEODYN'S. EXAMPLE PROBLEM

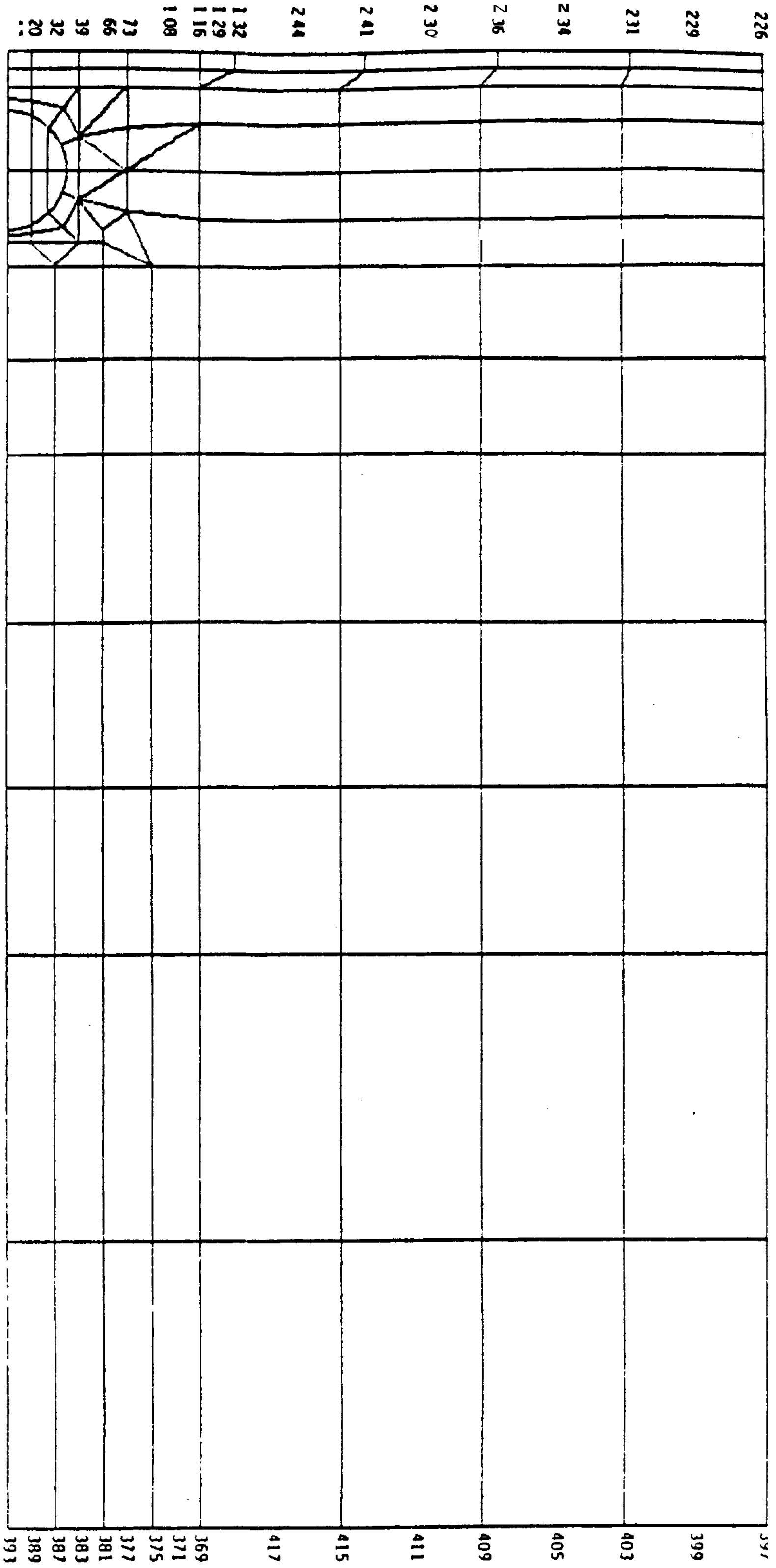
ZONE	X COND FROZEN (w/m°C)	Y COND FROZEN (w/m°C)	X COND THAWED (w/m°C)	Y COND THAWED (w/m°C)	SPEC Ht FROZEN (kJ/m³°C)	SPEC Ht FROZEN (kJ/m³°C)	LATENT HEAT (mJ/m³)
1	2.077	2.077	1.038	1.038	1944.900	3085.000	201.2
2	2.942	2.942	2.250	2.250	1810.800	2347.300	82.0
3	4.327	4.327	2.596	2.596	1676.700	2682.600	74.5
4	0.026	0.026	0.026	0.026	67.100	67.100	0.0
5	0.340	0.340	0.340	0.340	6.710	6.710	0.0

TABLE 3-2

METEOROLOGIC INPUTS FOR GEODYN'S EXAMPLE PROBLEM

MONTH	JULIAN DAY	SHORT WAVE (w/m²)	AIR TEMP (Deg C)	WIND (km/hr)	CLOUDS (frac)	EVAP (w/m²)	SNOW DEPTH (m)	SNOW DEN (gm/cc)
1	16.5	7.10	-25.00	4.67	0.60	0.00	0.49	0.18
2	45.0	31.27	-21.33	6.28	0.64	0.00	0.60	0.20
3	75.5	90.93	-13.05	8.21	0.60	0.00	0.61	0.20
4	105.0	165.17	-1.67	10.46	0.67	0.00	0.65	0.22
5	136.5	217.07	8.17	12.39	0.70	12.62	0.00	0.00
6	166.0	240.99	14.44	11.26	0.73	31.41	0.00	0.00
7	197.5	215.89	15.67	10.46	0.75	33.39	0.00	0.00
8	228.5	157.68	13.22	9.81	0.78	25.63	0.00	0.00
9	258.5	96.68	7.80	9.81	0.75	14.33	0.00	0.00
10	289.5	40.60	-4.33	8.69	0.80	0.00	0.00	0.00
11	319.0	12.48	-15.89	6.28	0.68	0.00	0.18	0.10
12	350.5	2.76	-22.17	5.15	0.70	0.00	0.41	0.17

Mid-Side Values Define
Network/Atmosphere Interface



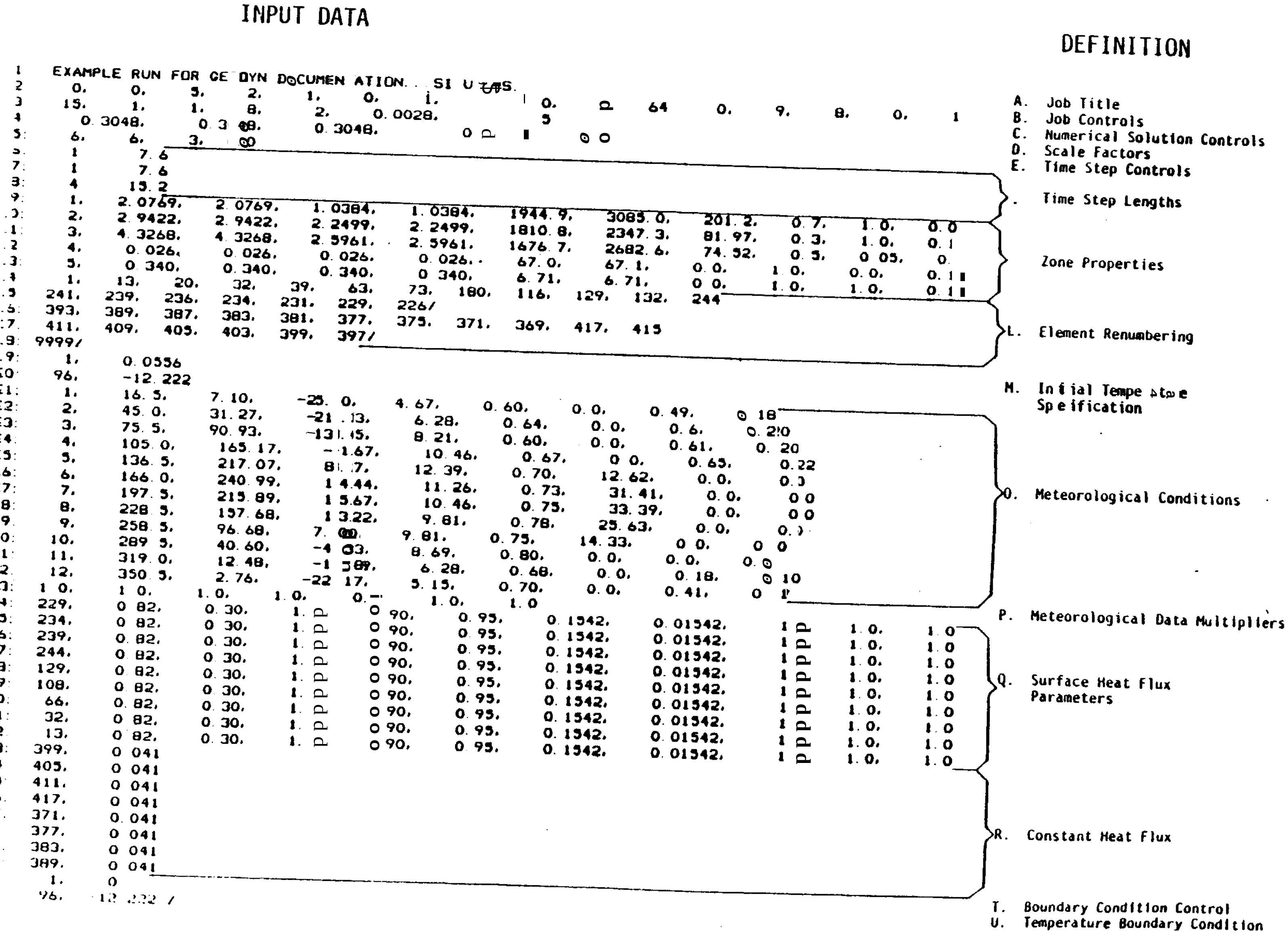
No Flux -
No Specification

No Flux -
No **Specification**

Mid-Sides Define **Location** of Specified Flux

FIGURE 3-2

GEODYN EXAMPLE PROBLEM **NETWORK**
WITH **SELECTED** NODE NUMBERS



INPUT DATA

DEFINITION

```
EXAMPLE RUN FOR GEODYN DOCUMENTATION. SI UNITS.
   0.      0.      5.      2.      1.      0.      1.      0.     0     64     0.     9.     8.     0.     1
  15.      1.      1.      8.      2.      0.0028.         5
     0.3048.     0.3048.      0.3048.                0 0    1    0 0
   6.      6.      3.     00
   1       7.6
   1       7.6
   4      15.2
   1.    2.0769,   2.0769,   1.0384,   1.0384,   1944.9,   3085.0,   201.2,   0.7,   1.0,    0.0
   2.    2.9422,   2.9422,   2.2499,   2.2499,   1810.8,   2347.3,   81.97,   0.3,   1.0,    0.1
   3.    4.3268,   4.3268,   2.5961,   2.5961,   1676.7,   2682.6,   74.52,   0.5,   0.05,   0.
   4.    0.026,    0.026,    0.026,    0.026,    67.0,     67.1,     0.0,     1.0,   0.0,    0.11
   5.    0.340,    0.340,    0.340,    0.340,    6.71,     6.71,     0.0,     1.0,   1.0,    0.11
   1.    13.   20.   32.   39.   63.   73.   180.   116.   129.   132.   244
 241.   239.  236.  234.  231.  229.  226/
 393.   389.  387.  383.  381.  377.  375.   371.   369.   417.   415
 411.   409.  405.  403.  399.  397/
9999/
   1.    0.0556
  96.   -12.222
   1.    16.5,    7.10,    -25.0,    4.67,    0.60,   0.0,     0.49,   0.18
   2.    45.0,    31.27,   -21.13,   6.28,    0.64,   0.0,     0.6,    0.20
   3.    75.5,    90.93,   -131.45,  8.21,    0.60,   0.0,     0.61,   0.20
   4.    105.0,   165.17,  -1.67,    10.46,   0.67,   0.0,     0.65,   0.22
   5.    136.5,   217.07,  81.7,     12.39,   0.70,   12.62,   0.0,    0.3
   6.    166.0,   240.99,  14.44,    11.26,   0.73,   31.41,   0.0,    0.0
   7.    197.5,   215.89,  15.67,    10.46,   0.75,   33.39,   0.0,    0.0
   8.    228.5,   157.68,  13.22,    9.81,    0.78,   25.63,   0.0,    0.0
   9.    258.5,   96.68,   7.00,     9.81,    0.75,   14.33,   0.0,    0.0
  10.    289.5,   40.60,   -4.03,    8.69,    0.80,   0.0,     0.0,    0.0
  11.    319.0,   12.48,   -1.589,   6.28,    0.68,   0.0,     0.18,   0.10
  12.    350.5,   2.76,    -22.17,   5.15,    0.70,   0.0,     0.41,   0.1
  1.0.   1.0.   1.0.   1.0.   0.   1.0.   1.0
 229.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 234.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 239.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 244.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 129.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 108.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
  66.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
  32.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
  13.    0.82,   0.30,   1.0   0.90,   0.95,   0.1542,   0.01542,   1.0   1.0,   1.0
 399.    0.041
 405.    0.041
 411.    0.041
 417.    0.041
 371.    0.041
 377.    0.041
 383.    0.041
 389.    0.041
   1.    0
  96.   -12.222 /
```

A. Job Title
B. Job Controls
C. Numerical Solution Controls
D. Scale Factors
E. Time Step Controls
. Time Step Lengths
Zone Properties
L. Element Renumbering
M. Initial Temperature Specification
O. Meteorological Conditions
P. Meteorological Data Multipliers
Q. Surface Heat Flux Parameters
R. Constant Heat Flux
T. Boundary Condition Control
U. Temperature Boundary Condition

FIGURE 3-3

CARD IMAGE INPUT TO GEODYN FOR EXAMPLE PROBLEM

```
                    PROGRAM GEODYN
           A FINITE ELEMENT FREEZ-THAW PROGRAM
                     DEVELOPED BY
            RESOURCE MANAGEMENTS ASSOCIATES
           LAFAYETTE, CALIF -- NOVEMBER 1982

     EXAMPLE RUN FOR GEODYN DOCUMENTATION   SI UNITS.

 INPUT/OUTPUT RUN CONTROL PARAMETERS

      NUMBER OF ELT CARDS(NCD)                    0
      NUMBER OF CORD CARDS(NPX)                   0
      NUMBER OF MATERIAL TYPES(NMAT)              5
      NUM OF INITIAL COND CARDS(IS1)              2
      OUTPUT PRINT OPTION(IPRT)                   1
      NUM SUMMARY PRINT NODES(NSPN)               0
      CALC OF FREEZING ISOTHRM(ISOC)              1
      INPUT GEOH FILE(LUNIT)                     60
      INPUT RESTART FILE(LI)                      0
      OUTPUT RESTART FILE(IT)                     0
      COMPLETE SAVE FILE(IS5)                    64
      NUM SIN/SURFACE NODES(ISINO)                0
      NUM SURFACE NODES(NSF1)                     9
      NUM CONST FLUX NODES(NSF2)                  8
      NUM TIME DEP B-C CROUP SPECS(NBCG)          0
      REORDERING OPTION(IRO)                      1

 NUMERICAL SOLUTION PARAMETERS

      MAX DYM ITERATIONS(MAXI)                        15
      MIN INTEGRATION LEVEL(MINGP)                     1
      MAX INTEGRATION LEVEL(MAXGP)                     1
      CYCLE FOR RELAX(NURF)                            8
      MAX TIME DIV(MAXSUB)                             2
      TEMP CONVRG LIMIT(CONVC)                    0.0028
      TIME INTEGRATION FACTOR(ALPHA)                 1.5

 SCALE FACTORS

      X SCALE =      0.305
      Y SCALE =      0.305
      W SCALE =      0.305
      U SCALE =      0.000
      V SCALE =      0.000

***THIS PROBLEM USES CARTESIAN COORDINATES***


 TIME CONTROL PARAHETERES

      NUMBER OF SOLUTION STEPS(NTIME)                 6
      PRINT INTERVAL(NTSEQ)                           6
      INPUT TIME STEPS(NVTS)                          3
      INITIAL TIME(TSTART)                          0 0

INPUT TIME STEPS (DAYS) AS FOLLOWS
 7 000       7.600      15.200      15.200      15.200      15.200

    ZONE MATERIAL PROPERTIES

      THERMAL CONDUCTIVITIES(W/M-C
      VOLUMETRIC SPECIFIC HEAT(KJ/M3-C)
      VOLUMETRIC LATENT HEAT(MJ/M3)

ZONE       FROZEN COND            THAWED COND          SP HEAT    SP HEAT     LATENT
      (X OR R)  (Y OR Z)   (X OR R)  (Y OR Z)       FROZEN     THAWED       HEAT      ALPHA       GAMMA     EPSILON
  1     2 077     2 a77      1 038     1 038     1944 900   3085 000      201.2      0.700       1 000       0 000
        2 942     2 942      2 250     2.250     1810 800   2347 300       82.0      0 300       1 030       0 100
  3     4 327     4 327      2 396     2 596     1676 700   2682 600       74 5      0 500       0 050       0 100
  1     0 026     0 026      0 024     0 026       67 000     67 100        0.0      1 000       0 000       0 100
        0 340     0 340      0 340     0 340        6 710      6.710        0.0      1 000       1 000       0 100

        MAX ELEMENT NUMBER =   128  MAX NODE NUMBER =   417
```

FIGURE 3-4

ECHO **PRINT** OF RUN CONTROL
AND MATERIAL PROPERTIES

```
          REORDERING OPTION HAS BEEN INVOKED

          STARTING NODES

   1    13    20    32    39    66    73   108   116   129   132   244   241   239   236   234
 231   229   726

          STARTING NODES

 393   389   387   383   381   377   373   371   369   417   415   411   409   405   403   399
 397

          SELECTED ELEMENT ORDER IS LISTED BELOW

            120       118       116       114       128       126       124       122       119       I17
            115       113       127       125       123       121        58        55        68        65
            112       109       104       103        57        34        67        64       111       108
            105       102        56        53        66        63       110       107       104       101
             52        50        61        60       100        90        96        94        51        49
             61        39        99        97        95        93        21        18         e         3
             28        20        92        e9        86        e3        19        11        45        43
             41        48        27        91        88        e3        at        46        26        90
             87        84        81        38        25        39        37        24        80        79
             78        77        38        47        44         7        42        40         6        35
             13        12        15        17        14        34        33        16        32        31
             23        10         5         2        30        74        75        74        73        22
              9        29         4         1        72        71        70        69
```

FIGURE 3-5

ECHO PRINT OF INFORMATION GENERATED IN
THE REORDERING OPTION

```
                         PROGRAM GEODYN
               A FINITE ELEMENT FREEZ-THAW PROGRAM
                          DEVELOPED BY
                  RESOURCE MANAGEMENTS ASSOCIATES
                LAFAYETTE, CALIF -- NOVEMBER 1982


            EXAMPLE RUN FOR GEODYN DOCUMENTATION...SI UNITS.

            FIXED NODAL COORDINATES ...

NODE   X-LOC   Y-LOC   THICK    NODE   X-LOC   Y-LOC   THICK    NODE   X-LOC   Y-LOC   THICK
      (METRE) (METRE) (METRE)         (METRE) (METRE) (METRE)         (METRE) (METRE) (METRE)
  1     0.00    0 00    0.3     140     0.69    0 51    0.3     279     1.22    7 92'   0.3
  2     0.11    0 00    0.3     141     0.59    0.82    0.3     200     1.52    7 92    0.3
  3     0.23    0 00    0.3     142     0.86    0.62    0.3     281     1.e3    7 92    0.3
  4     0.34    0 00    0.3     143     0.91    0.82    0.3     282     2.13    7 92    0.3
  5     0.46    0 00    0.3     144     0.70    1.22    0.3     283     2.44    7 92    0.3
  6     0.61    0 00    0.3     145     1.31    1 22    0.3     204     2.74    7 92    0.3
  7     0.76    0 00    0.3     146     2.32    0 00    0.3     285     1.52    7 01    0.3
  8     2.29    0 00    0.3     147     2.34    0.15    0.3     286     2.13    7 01    0 3
  9     2.36    0 00    0.3     148     2.27    0.30    0.3     287     2.74    7 01    0.3
 10     2.44    0 00    0.3     149     2.40    0.00    0.3     208     1.22    6 10    0.3
 11     2.s9    0 00    0.3     150     2.30    0.30    0.3     209     1.52    6.10    0.3
 12     2.74    0 00    0.3     151     2.29    0.51    0.3     290     1.e3    6 10    0.3
 13     0.00    0 15    0.3     152     2.15    0.62    0.3     291     2.13    6 10    0.3
 I4     0.23    0 15    0.3     153     2.34    0.82    0.3     292     2.44    6 10    0.3
 15     0.46    0 15    0.3     154     2.07    0.e2    0.3     293     2.74    6 10    0.3
 16     0.79    0 18    0.3     155     I.71    1.22    0.3     294     1.52    5 18    0.3
 17     2.26    0 18    0.3     156     3.35    1.22    0.3     295     2.13    5 18    0.3
 18     2.44    0 15    0.3     157     3.96    1.22    0.3     296     2.74    5 18    0.3
 19     2.74    0 30    0.3     158     4.s7    I.22    0.3     297     1.22    4 27    3.3
 20     0.00    0 30    0.3     159     5.18    1.22    0.3     298     1.52    4 27    0.3
 21     0 11    0 30    0.3     160     3.96    0.91    0.3     299     1.83    4 27    0 3
 22     0.23    0 30    0.3     161     5.18    0.91    0.3     300     2.13    4 27    0.3
 23     0.34    0 30    0.3     162     3.35    0.61    0.3     301     2.44    4 27    0.3
 24     0.46    0 30    0.3     163     3.96    0.61    0.3     302     2.74    4 27    0.3
 25     0.65    0 30    0.3     164     4.57    0.61    0.3     303     1.52    3 35    0.3
 26     0.94    0 30    0.3     165     5.18    0.61    0.3     304     2.13    3.35    0.3
 27     2.21    0 30    0.3     166     3.96    0.30    0.3     305     2.74    3 35    0.3
 20     2.32    0 30    0.3     167     5.18    0.30    0.3     306     3.35    9 75    0.3
 29     2.44    0 30    0.3     168     3.35    0.00    0.3     307     3.96    9 7s    0.3
 30     2.59    0 46    0.3     169     3.96    0.00    0.3     308     4.57    9 75    0.3
 31     2.74    0 61    0.3     170     4.57    0.00    0.3     309     5.10    9 75    0.3
 32     0.00    0 61    0.3     171     5.10    0.00    0.3     310     3.96    8 94    0.3
 33     0.23    0 61    0.3     172     6.25    1.22    0.3     311     5.I0    8 84    0 3
 34     0.46    0 61    0.3     173     7.32    1.22    0.3     312     3.35    7 92    0.3
 35     0.91    0 43    0.3     I74     8.30    1.22    0.3     313     3.96    7 92    0.3
 36     2.13    0 43    0.3     175     9.45    I.22    0.3     314     4.57    7 92    0.3
 37     2.44    0 61    0.3     176    10.s2    1.22    0.3     315     5.18    7 92    0.3
 38     2.74    0 91    0.3     177    11.58    1.22    0.3     316     3.96    7 01    0.3
 39     0 00    0 91    0.3     178     7.32    0.91    0.3     317     5.18    7 01    0.3
 40     0.11    0 91    0.3     179     9.45    0.91    0.3     310     3.35    6 10    0 3
 41     0.23    0 91    0.3     1BO    11.56    0.91    0.3     319     3.96    6 10    0.3
 42     0.34    0 91    0.3     181     6.25    0.61    0.3     320     4.57    6 10    0.3
 43     0.46    0 91    0.3     182     7.32    0.61    0.3     321     5.18    6 10    0.3
 44     0.72    0 72    0.3     183     9.38    0.61    0.3     322     3.96    5 18    0 3
 45     0.99    0 52    0.3     184     9.45    0 61    0.3     323     5.18    5 18    0 3
 46     0 78    0 91    0.3     185    10.52    0 61    0.3     324     3.35    4 27    0 3
 47     I.10    0 62    0.3     186    11.58    0.61    0.3     325     3.96    4 27    a 3
 48     1 10    0 91    0.3     187     7.32    0.30    0.3     326     4 57    4 27    0 3
 49     I.15    0 60    0.3     188     9.45    0.30    0.3     327     5.18    4 27    0 3
 50     1 20    3 69    0.3     189    11.50    0.30    0.3     320     3 96    3 35    0 3
 51     I.31    0 91    0.3     190     6.25    0.00    0.3     329     5.18    3 35    0 3
 52     1.37    0 75    0.3     191     7.32    0.00    0.3     330     6 25    9 75    0 3
 53     I.52    0 91    0.3     192     a.38    0.00    0.3     331     7 32    9 75    0 3
 54     I.s2    0 84    0.3     193     9.45    0.00    0.3     332     e.38    9 75    0.3
 55     1.52    0 76    0.3     194    10.52    0.00    0.3     333     9 45    9 75    0 3
 56     I.71    0 91    0.3     195    11.58    0 00    0.3     334    10.52    9 75    0.3
 57     1.68    0 75    0.3     196     3.35    2.44    0.3     335    11.58    9 75    5 3
 58     1.89    0 91    0.3     197     3.96    2.44    0.3     336     7.32    8 84    0 3
 59     I.84    0 81    0.3     198     4.57    2.44    0.3     337     9.45    e 84    3 3
 60     1 BO    0 70    0.3     199     5.19    2.44    0.3     338    11.58    e e4    5 3
 61     2.16    0 91    0.3     200     3.96    2.13    0.3     339     6.25    7 92    0 3
 62     1 95    0 62    0.3     20I     5.10    2.13    0.3     340     7.32    7 92    0 3
 63     2.06    0 52    0.3     202     3.35    1.e3    0 3     34I     8.38    7 92    5 3
 64     2.25    0 72    0.3     203     3.96    1.83    0.3     342     9 45    7 92    0 3
 65     2.44    0 91    0.3     204     4.57    1.e3    0.3     343    10.52    7 92    0 3
```

FIGURE 3-6

ECHO PRINT OF NODE AND
ELEMENT SPECIFICATIONS

66	0.00	1.22	0.3	205	5.18	1.83	0.3	344	11.58	7 92	0.3
67	0.23	1.22	0.3	206	3.96	1.52	0.3	745	7 32	7 01	0 3
68	0.46	1.22	0.3	207	5.18	1.52	0.3	346	9 45	7 01	0.3
69	1.04	1.22	0.3	208	6.25	2.44	0.3	347	11.58	7 01	0.3
70	1.52	1.22	0.3	209	7.32	2.44	0.3	348	6.25	6 10	0.3
71	1.97	1.22	0.3	210	8.38	2.44	0.3	349	7 32	6 10	0 3
72	2.59	0.76	0.3	211	9.45	2.44	0.3	350	e.38	6 10	0.3
73	0.00	1.52	0.3	212	10.52	2.44	0.3	351	9 45	6 10	0.3
74	0.11	I.52	0.3	213	11.58	2.44	0.3	352	10.52	6 10	0.3
75	0 23	1.52	0.3	214	7 32	2.13	0.3	353	11.50	6 10	0.3
76	0.34	I.52	0.3	215	9.45	2.13	0.3	354	7.32	5 18	0 3
77	0.46	I.52	0.3	216	11.58	2.13	0.3	355	9 45	5 18	0.3
78	0.72	1.52	0.3	217	6.25	1.E3	0.3	356	11.58	5 10	0.3
79	0.98	1.52	0.3	218	7.32	1.83	0.3	357	6.25	4 27	0.3
80	1.25	1.52	0.3	219	8.38	1.83	0.3	358	7.32	4 27	0.3
81	1.52	1.52	0.3	220	9.45	1.e3	0.3	359	8.38	4 27	0.3
82	I.78	1.52	0.3	221	10.52	1.83	0.3	360	9 45	4 27	0.3
83	2.04	1.52	0.3	222	11.58	1.83	0.3	361	10.52	4 27	0.3
a4	2.16	I.37	0.3	223	7.32	1.52	0.3	362	11.58	4 27	0.3
85	2.74	1.22	0.3	224	9.45	1.52	0.3	363	7.32	3 35	0.3
86	1.52	0.64	0.3	225	11.58	1.52	0.3	364	9.45	3 35	0 3
87	1.26	0.52	0.3	226	0.00	9.75	0.3	365	11.58	3 35	0.3
88	1.52	0.52	0.3	227	0.11	9.75	0.3	366	13.41	2 44	0.3
89	1.79	0.52	0.3	228	0.23	9.75	0.3	367	15.24	2 44	0.3
90	I.52	0.41	0.3	229	0.00	8.90	0.3	368	17.07	2 44	0.3
91	I.18	0.30	0.3	230	0.23	8.90	0.3	369	18.90	2 44	0.3
92	I.52	0.30	0 3	231	0.00	8.04	0.3	370	15.24	2 13	0.3
93	1.87	0.30	0.3	232	0.11	8.04	0.3	371	18.90	2 13	0.3
94	1.52	0 15	0.3	233	0.23	8.04	0.3	372	13.41	1 03	0 3
95	I.14	0.00	0.3	234	0.00	7.18	0.3	373	15.24	1 03	0 3
96	1.52	0.00	0.3	235	0.23	7.18	0.3	374	17.07	1 e3	0 3
97	1.90	0.00	0.3	236	0.00	6.32	0.3	375	18.90	1 e3	0.3
98	2.09	1.07	0.3	237	0.11	4.32	0.3	376	15.24	1 52	0.3
99	2.44	1.07	0.3	238	0.23	6.32	0.3	377	18.90	1 52	0.3
100	2.29	1.22	0.3	239	0.00	5.47	0.3	378	13.41	1 22	0.3
101	2.36	1.22	0.3	240	0.23	5.47	0.3	379	15.24	I 22	0.3
102	2.44	1.22	0.3	241	0.00	4.61	0.3	380	17.07	1 22	0.3
103	2.59	1.22	0.3	242	0.11	4.61	0.3	381	18.90	1 22	0.3
104	2.59	I.52	0.3	243	0.23	4.61	0.3	382	15.24	0 91	0.3
105	2.74	1.52	0.3	244	0.00	3.75	0.3	383	18.90	0 91	0.3
106	2.39	1.68	0.3	245	0.23	3.75	0.3	384	13.41	0 61	0.3
107	2.74	1.83	0.3	246	0.34	9 73	0.3	305	15.24	0 61	0.3
108	0.00	1.98	0.3	247	0.46	9 75	0.3	386	17.07	0 61	0 3
109	0.23	1.98	0.3	248	0.46	8.a4	0.3	307	18.90	0 61	0.3
110	0.46	1.98	0.3	249	0.34	7.98	0.3	388	15.24	0 30	0 3
111	0.94	1.98	0.3	250	0.46	7.92	0.3	309	18.90	0 30	0.3
112	1.22	1.98	0.3	251	0.44	7.01	0.3	390	13.41	0 00	0.3
113	1.52	1.98	0.3	252	0.34	6.21	0.3	391	15.24	0 00	0.3
114	2.09	1.98	0.3	253	0.46	6.10	0 3	392	17.07	0 00	0 3
115	2.74	2.13	0.3	254	0.46	5 18	0.3	393	18.90	0 00	0.3
116	0.00	2.44	0.3	255	0.34	4.44	0.3	394	13.41	9 75	0 3
117	0.11	2.44	0.3	256	0.46	4.27	0.3	395	15.24	9 75	0.3
118	0.23	2.44	0.3	257	0.46	3.35	0.3	394	17.07	9 75	0 3
119	0.34	2.44	0.3	258	0.69	9.75	0.3	397	18.90	9 75	0 3
120	0.46	2.44	0.3	259	0.91	9.75	0.3	398	15.24	a e4	0 3
121	0.69	2.44	0.3	260	0.91	8.e4	0.3	399	18.90	8 04	0 3
122	0.91	2.44	0.3	261	0.69	7.92	0.3	400	13.41	7 92	0 3
123	I.22	2 44	0.3	262	0.91	7 92	0.3	401	15.24	7 92	0 3
124	1.52	2.44	0.3	263	0.91	7.01	0.3	402	17.07	7 92	3 3
125	1 03	2.44	0.3	264	0.69	6.10	0.3	403	18.90	7 92	0 3
126	2.13	2.44	0.3	265	0.91	6.10	0.3	404	15.24	7 01	0 3
127	2.44	2.44	0.3	266	0.91	5.18	0.3	405	18 90	7 01	0 3
It8	2.74	2.44	0.3	267	0.69	4 27	0.3	406	13.41	6 10	0 3
129	0.00	2.67	0.3	268	0.91	4 27	0.3	407	15.24	6 10	0 3
130	0.23	2.67	0.3	269	0.91	3.35	0.3	408	17.07	6 10	0 3
131	0.34	2.67	0.3	270	1.22	9 75	0 3	409	18.90	6 LO	0.3
132	0.00	2.90	0.3	271	I.52	9.75	0.3	410	15.24	5 18	0 3
133	0.11	2.90	0 3	272	I.83	9.75	0.3	411	18.90	5 18	3 3
134	0.23	2.90	0.3	273	2.13	9.75	0.3	412	13.41	4 27	3 3
135	0.53	0.00	0 3	274	2.44	9 75	0.3	413	15.24	4 27	3 3
136	0.63	0.15	0 3	275	2.74	9.75	0 3	414	17 07	4 27	3 3
137	0 55	0.30	0.3	276	1.52	0 84	0.3	415	IS.90	4 27	0 3
138	0.69	0.00	0 3	277	2.13	8.04	0.3	416	15 24	3 35	3 3
139	0.74	0 30	0.3	278	2.74	8.84	0.3	417	IS.90	3 35	3 3

FIGURE **3-6**
(continued)

```
                         PROGRAM GEODYN
                 A FINITE ELEMENT FREEZ-THAW PROGRAM
                          DEVELOPED BY
                 RESOURCE MANAGEMENTS ASSOCIATES
                 LAFAYETTE, CALIF -- NOVEMBER 1982


             EXAMPLE RUN FOR GEODYN DOCUMENTATION...SI UNITS.

          NOOK CONNECTIONS AND MATERIAL NUMBERS...

ELEMENT      NODES(COUNTERCLOCKWISE)        ZONE  SEQ   AREA-M2    ELEMENT      NODES(COUNTERCLOCKWISE)        ZONE  SEQ   AREA-M2
    1   1   2   3  14  22  21  20  13     3   120    0.070          65 211 215 220 221 222 216 213 212     2    86   1 301
    2   3   4   5  15  24  23  22  I4     3   118    0.070          66 205 207 159 172 173 223 218 217     2    83   1.301
    3  10  11  12  19  31  30  29  18     4   116    0.139          67 218 223 173 174 175 224 220 219     2    19   I.301
    4  20  21  22  33  41  40  39  32     3   114    0.139          68 120 224 175 176 177 225 222 221     2    11   1.301
    5  22  23  24  34  43  42  41  33     3   128    0.139          69 226 229 231 232 233 230 228 227     I    45   0.392
    6  40  49  50  52  55  54  53  51     3   126    0.069          70 231 234 236 237 238 235 233 232     1    43   0.392
    7  53  54  55  57  60  59  58  56     3   124    0.057          71 236 239 241 242 243 240 230 237     1    41   0.392
    8  29  30  31  72  65  37   0   0     4   122    0.093          72 241 244 137 133 134 245 243 242     1    48   0.392
    9  39  40  41  67  75  74  73  66     3   119    0.139          73 220 230 233 249 250 240 247 24L     1    27   0.405
   10  41  42  43  68  77  76  71  67     3   117    0.139          74 233 235 230 252 2S3 251 250 249     I    91   0.403
   11  58  90 100  84  83  71   0   0     3   115    0.090          75 230 240 243 255 256 254 2S3 252     I    88   0.405
   12  45  07  88  86  55  52  SO  47     5   113    0.091          76 243 245 134 131 120 257 256 255     I    85   0.405
   13  88  09  63  62  60  57  55  86     5   127    0.091          77 247 240 250 261 262 260 259 250     1    82   0.836
   14  26  91  92  90  88  87  45  35     5   125    0.132          70 250 251 253 264 265 263 262 261     1    46   0.E36
   15  92  93  27  36  63  89  88  90     5   123    0.132          79 233 254 256 267 268 266 265 264     I    26   0.836
   16   7  95  96  94  92  91  26  16     5   121    0.224          80 256 257 120 121 122 269 260 267     1    90   0.836
   17  96  97   8  17  27  93  92  94     5    50    0 224          81 259 260 262 279 280 274 271 170     1    87   I 115
   10  65  72  31  38  85 103 102  99     4    53    0.139          82 271 276 280 281 282 277 273 272     I    64   1.115
   19  58  61  65  99 102 101 100  90     3    60    0.107          a3 273 277 202 283 284 270 275 274     I    81   1.115
   20 100 101 102 104 107 106  83  84     1    65    0.190          84 262 263 265 288 289 285 280 279     1    38   1.115
   21  85 105 107 104 102 103   0   0     1   112    0.093          85 280 205 209 290 291 206 282 281     I    25   I.115
   22  73  74  75 109 118 117 116 108     3   109    0.209          86 202 286 291 297 293 207 204 203     1    39   I.115
   23  75  76  77 110 120 119 110 109     3   106    0.209          87 265 266 260 297 290 294 289 288     1    37   1.115
   24  77  70  79 111 122 121 120 110     3   103    0.446          88 289 294 298 299 300 295 291 290     1    24   1.115
   25  79  80  81 112 122 111   0   0     3    57    0.251          89 291 295 300 301 302 294 293 292     1    EO   1.115
   26  81 113 124 123 122 112   0   0     1    54    0.279          90 268 269 122 123 124 303 290 297     I    79'  1.115
   27  81  82  87 114 126 125 124 113     I    67    0.516          91 298 303 124 125 126 304 300 299     I    70   1.115
   28  03 106 107 115 128 127 126 114     1    64    0.492          92 300 304 126 127 128 305 302 301     1    77   1.115
   29 116 117 110 130 134 133 132 129     3   111    0.105          93 775 278 284 312 313 310 307 306     1    36   2.23C
   30 118 119 120 131 134 130   0   0     3   108    0.052          94 307 310 313 314 311 311 309 300     1    47   2.23C
   31   5 135   6 136  25 137  24  15     3   105    0.052          95 294 207 293 318 319 316 313 312     1    44   2.23C
   32   6 138   7  16  26 139  25 136     3   102    0.049          96 313 31d 319 320 321 317 315 314     1     7   2.23C
   33  24 137  25 140  44 141  43  34     3    56    0.120          97 293 296 302 324 325 322 319 318     I    42   2.23C
   34  26  35  45 142  44 140  25 139     3    53    0.081          90 319 322 325 326 327 323 321 320     I    40   2.230
   35  45  47  50  49  40 143  44 142     3    66    0.093          99 302 305 128 194 197 320 325 324     1     6   2.23C
   36  48 144  77  68  43  44   0   0     3    63    0.195         100 325 328 197 198 199 329 327 326     1    35   2.23C
   37  48  69  79  70  77 144   0   0     3   110    0.158         101 309 311 315 339 340 336 331 330     2    13   3.902
   30  40  51  53  70  81 145   0   0     3   107    0.130         102 331 336 340 341 342 337 333 332     2    12   3 902
   39  48 145  ai  80  79  69   0   0     3   104    0.167         103 333 337 342 343 344 330 335 334     2    15   3 902
   40   8 146   9 147  20 140  27  17     3   101    0.026         104 315 317 321 340 349 345 340 339     2    17   3.902
   41   9 149  10  18  29 150  28 147     3    52    0.029         105 340 345 349 350 351 346 342 341     2    14   3 902
   42  27 148  28 151  64 152  63  36     3    50    0.057         106 342 346 351 352 353 347 344 343     2    34   3 902
   43  28 150  29  37  65 153 '64 151     3    62    0.082         107 321 323 327 357 3S8 354 349 348     2    33   3 902
   44  63 152  64 154  59  59  60  62     3    60    0.085         108 349 354 358 359 360 355 351 350     2    16   3 902
   45  64 153  65  61  58 154   0   0     3   100    0.034         109 351 355 360 361 362 356 353 352     2    32   3 902
   46  53  56  58 155  81  70   0   0     3    99    0.111         110 327 329 199 208 209 363 358 357     2    31   3.902
   47  44 143  40  46  43 141   0   0     3    96    0.063         111 358 363 209 210 211 364 360 359     2    23   3 902
   40  58  71  83  82  81 155   0   0     3    94    0.158         112 360 364 211 212 213 365 362 361     2    LO   3 902
   49  85  38  31 162 163 160 157 156     3    51    0.743         113 213 216 222 372 373 370 367 366     2     5   2 23C
   SO 157 160 163 164 165 161 159 158     3    49    0.743         114 367 370 373 374 375 371 369 368     2     2   2 23C
   51  31  19  12 168 169 166 163 162     3    61    0.743         115 222 225 177 378 379 376 373 372     2    30   2.23C
   52 163 166 169 170 171 167 165 164     3    59    0.743         116 373 376 379 380 381 377 375 374     2    76   2 23C
   53 159 161 165 181 182 170 173 172     2    99    I.301         117 177 180 186 384 385 382 379 378     2    75   2 23C
   54 173 178 182 183 104 179 175 174     2    97    1.301         110 379 382 385 386 387 383 381 380     2    74   2 23C
   55 175 179 184 185 186 180 177 176     2    95    I.301         119 186 189 195 390 391 388 385 384     2    73   2 23C
   56 165 167 171 190 191 187 182 181     2    93    1.301         120 385 388 391 392 393 389 387 386     2    22   2 23C
   57 182 187 191 192 193 188 184 183     2    21    1.301         121 335 338 344 400 401 398 395 394     7     9   6 689
   58 184 188 193 194 195 109 186 185     2    18    1.301         122 395 390 401 402 403 399 397 396     2    29   6 689
   59 128 115 107 202 203 200 197 196     1     8    0.743         123 344 347 353 406 407 404 401 400     2     4   b 689
   60 197 200 203 204 205 201 199 198     1     3    0.743         124 401 404 407 4CB 409 405 403 402     2          6 689
   61 107 105  85 156 157 206 203 202     1    28    0.743         125 353 356 362 412 413 410 407 406     2    72   6 689
   a2 203 206 157 158 139 207 205 204     1    20    0.743         126 407 410 413 414 415 411 409 408     2    71   6 689
   63 199 201 205 217 218 214 209 208     2    92    1.301         127 362 365 213 366 367 416 413 412     2    70   6 689
   64 209 214 218 219 220 215 211 210     2    89    1.301         128 413 416 367 368 369 417 415 414     2    69   6 639
```

FIGURE 3-6
(continued)

```
SUMMARY OF STANDARD MONTHLY AVED & METEOROLOGIC CONDITIONS

MONTH    DAY     S-WAVE    AIR TEMP     WIND    CLD CVR     EVAP   SNOW CVR   SNOW DEN
                 (W/M2)    (DEG(C)    (KM/HR)    (FRAC)   (W/M2)       (M)    (GM/CC)
  1      16.5      7.10     -25.00      4.67      0.60     0.00      0.49       0.18
  2      45.0     31.27     -21.33      6.28      0.64     0.00      0.60       0.20
  3      75.5     90.93     -13.05      8.21      0.60     0.00      0.61       0.20
  4     105.0    165.17      -1.67     10.46      0.67     0.00      0.65       0.22
  5     136.5    217.07       8.17     12.39      0.70    12.62      0.00       0.00
  6     166.0    240.99      14.44     11.26      0.73    31.41      0.00       0.00
  7     197.5    215.89      15.67     10.46      0.75    33.39      0.00       0.00
  8     228.5    157.68      13.22      9.81      0.78    25.63      0.00       0.00
  9     258.5     96.68       7.00      9.81      0.75    14.33      0.00       0.00
 10     289.5     40.60      -4.33      8.69      0.80     0.00      0.00       0.00
 11     319.0     12.48     -15.89      6.28      0.68     0.00      0.18       0.10
 12     350.5      2.76     -22.17      5.15      0.70     0.00      0.41       0.17

        MULT       1.00       1.00      1.00      1.00     0.40      1.00       1.00

SUMMARY OF MONTHLY METEOROLOGIC DATA FOR SURFACE ENERGY CALCULATIONS
AFTER MULTIPLICATION

MONTH    DAY     S-WAVE    AIR TEMP     WIND    CLD CVR     EVAP   SNOW CVR   SNOW DEN
                 (W/M2)    (DEG C)    (KM/HR)    (FRAC)   (W/M2)       (M)    (GM/CC)
  1      16.5      7.10     -25.00      4.67      0.60     0.00      0.49       0.18
  2      45.0     31.27     -21.33      6.28      0.64     0.00      0.60       0.20
  3      75.5     90.93     -13.05      8.21      0.60     0.00      0.61       0.20
  4     105.0    165.17      -1.67     10.46      0.67     0.00      0.65       0.22
  5     136.5    217.07       8.17     12.39      0.70     5.05      0.00       0.00
  6     166.0    240.99      14.44     11.26      0.73    12.56      0.00       0.00
  7     197.5    215.89      15.67     10.46      0.75    13.36      0.00       0.00
  8     228.5    157.68      13.22      9.81      0.78    10.25      0.00       0.00
  9     258.5     96.68       7.00      9.81      0.75     5.73      0.00       0.00
 10     289.5     40.60      -4.33      8.69      0.80     0.00      0.00       0.00
 11     319.0     12.48     -15.89      6.28      0.68     0.00      0.18       0.10
 12     350.5      2.76     -22.17      5.15      0.70     0.00      0.41       0.17
```

FIGURE 3-7

ECHO PRINT OF STANDARD
METEOROLOGIC CONDITIONS

```
    SUMMARY OF METEOROL G IC F CTORS FOR SURFACE NODES

   NODE     SURF ALB     SNOW ALB     VIEW FAC     SURF EM      SNOW EM      SURF RUF     SNOW RUF     EVAP FACT    DEEP FACT
             (FRAC)       (FRAC)       (FRAC)       (FRAC)       (FRAC)         (M)          (M)         (FRAC)       (FRAC)
1   229       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
2   234       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
3   239       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
4   244       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
5   129       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
6   108       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
7    66       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
8    32       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00
9    13       0.82         0.30         1.00         0.90         0.95         0.15         0.02         1.00         1.00

  NUMBER OF CONSTANT F>UX BO△D DY NODES IS     8

   NODE      FLUX
    NUM     (W/M2)
    399     0.041
    405     0.041
    411     0.041
    417     0.041
    371     0.041
    377     0.041
    383     0.041
    389     0.041
```

FIGURE 3-8

ECHO PRINT OF NODAL VALUES USED IN THE SURFACE ENERGY BALANCE

```
                                    EXAMPLE RUN FOR GEODYN DOCUMENTATION...SI UNITS. .

      ***THIS PROBLEM USES CARTESIAN COORDINATES***
                                                              INITIAL CONDITIONS

         TIME STEP      0 OF     6
         TIME STEP IS  7.60(DAYS)
         RESULTS AT     0.00(HRS)      0.00(DAYS)      0.00(MOS)      0 00(YRS)

            THE SYMBOL • DENOTES A SPECIFIED VALUE

NODE    TEMP   NODE     TEMP   NODE    TEMP   NODE    TEMP   NODE    TEMP
   I   0.056    85    0 056    169    0.056   253    0.056   337    0.056
   2   0 056    86    0 056    170    0.056   254    0.056   338    0.056
   3   0 056    87    0 056    171    0.056   255    0.056   339    0.056
   4   0.056    88    0 056    172    0.056   256    0.056   340    0.056
   5   0.056    89    0 056    173    0.056   257    0.056   341    0.056
   6   0.056    90    0 056    17.4   0.056   258    0.056   342    0.056
   7   0 056    91    0 056    175    0.056   759    0.056   343    0.056
   8   0.056    92    0 056    I76    0.056   260    0.056   344    0.056
   9   0.056    93    0 056    177    0.056   261    0.056   345    0.056
  10   0.056    94    0 056    178    0.056   267    0.056   346    0.056
  11   0 056    95    0 056    179    0.056   263    0.056   347    0.056
  12   0.056    96  -12.222    180    0.056   264    0.056   348    0.056
  13   0 056    97    0 056    181    0.056   265    0.056   349    0.OS6
  14   0.056    98    0 056    182    0.056   266    0.056   350    0.056
  15   0.056    99    0 056    183    0.056   267    0.056   351    0.056
  16   0.056   100    0 056    184    0.056   268    0.056   352    0.056
  17   0 056   101    0 056    185    0.056   269    0.056   353    0.056
  18   0.056   102    0.056    186    0.036   270    0.056   354    0.056
  19   0 056   103    0.056    187    0.056   271    0.056   355    0.056
  20   0.056   104    0.056    188    0.056   272    0.056   356    0.056
  21   0 056   105    0.056    189    0.056   273    0.056   357    0.056
  22   0 056   106    0.056    190    0.056   274    0.056   358    0.056
  23   0.056   107    0.056    191    0.056   275    0.056   359    0.056
  24   0 056    08    0.056    192    0.056   276    0.056   360    0.056
  25   0.056    09    0.056    193    0.056   277    0.056   36I    0.056
  26   0.056    10    0.056    194    0.056   278    0.056   362    0.056
  27   0.056    11    0.056    195    0.056   279    0.056   363    0.056
  28   0.056    12    0.056    196    0.056   280    0.056   364    0.056
  29   0.056    13    0.056    197    0.056   281    0.056   365    0.056
  30   0.056    14    0.056    198    0.056   282    0.056   366    0.056
  31   0.056    15    0.056    199    0.056   283    0.056   367    0.056
  32   0.056    16    0.056    200    0.056   284    0.056   368    0.056
  33   0.056   117    0.056    201    0.056   285    0.056   369    0.056
  34   0.056   118    0.056    202    0.056   286    0.056   370    0.056
  35   0 056   119    0.056    203    0.056   287    0.056   371    0.056
  36   0.056   120    0.056    204    0.056   288    0.056   372    0.056
  37   0 056   121    0.056    205    0.056   289    0.056   373    0.056
  38   0 056   122    0.056    206    0.056   290    0.056   374    0.056
  39   0.056   123    0.056    207    0.056   291    0.056   375    0.056
  40   0 056   124    0.056    208    0.056   292    0.056   376    0.056
  41   0.056   125    0.056    209    0.056   293    0.056   377    0.056
  42   0.056   126    0.056    210    0.056   294    0.056   378    0.056
  43   0 056   127    0.056    211    0.056   295    0.056   379    0.056
  44   0.056   128    0.056    212    0.056   296    0.056   380    0.056
  45   0.056   129    0.056    213    0.056   297    0.056   381    0.056
  46   0.056   130    0.056    214    0.056   298    0.056   382    0.056
  47   0.056   131    0.056    215    0.056   299    0.056   383    0.056
  48   0.056   132    0.056    216    0.056   300    0.056   384    0.056
  49   0.056   133    0.056    217    0.056   301    0.056   385    0.056
  50   0.056   134    0.056    218    0.056   302    0.056   386    0.056
  51   0.056   135    0.056    219    0.056   303    0.056   387    0.056
  52   0.056   136    0 056    220    0.056   304    0.056   388    0.056
  53   0.056   137    0.056    221    0.056   305    0.056   389    0.056
  54   0.056   138    0.OS6    222    0.056   306    0.056   390    0.056
  55   0.056   139    0.056    223    0.056   307    0.056   391    0.056
  56   0.056   140    0.056    224    0.056   308    0.056   392    0.056
  57   0.056   141    0.056    225    0.056   309    0.056   393    0.056
  58   0 056   I42    0.056    226    0.056   310    0.056   394    0.056
  59   0 056   143    0 056    227    0.056   311    0 056   395    0.056
  60   0.056   144    0.056    228    0.056   312    0.056   396    0.056
```

FIGURE **3-9**

SUMMARY OF INITIAL CONDITIONS

```
61    0.056   145   0.056   229   0.056   313   0.036   397   0.056
67    0.056   146   0.056   230   0.056   314   0.056   398   0.056
63    0.056   147   0.056   231   0.056   315   0.056   399   0.056
64    0.056   148   0.056   232   0.056   316   0.056   400   0.056
65    0.056   149   0.056   233   0.056   317   0.056   401   0.056
66    0.056   1S0   0.056   234   0.056   318   0.056   402   0.056
67    0.056   151   0.056   235   0.056   319   0.056   403   0.056
68    0.056   Is2   0.056   236   0.056   320   0.056   404   0.056
69    0.056   153   0.056   237   0.056   323   0.056   405   0.056
70    0.056   154   0 056   238   0.056   322   0.056   406   0.056
71    0.056   155   0.056   239   0.056   323   0.056   407   0.056
72    0.056   156   0.056   240   0.056   324   0.056   400   0.056
73    0.056   157   0.056   241   0.056   315   0.056   409   0.056
74    0.056   158   0 056   242   0.056   326   0.056   410   0.056
75    0.056   159   0.056   243   0.056   327   0.056   411   0.056
76    0.056   160   0.056   244   0.056   328   0.054   412   0.056
77    0.056   161   0.056   245   0.056   319   0.056   413   0.056
78    0.056   162   0.056   246   0.056   330   0.056   414   0.056
79    0.056   163   0.056   247   0.056   331   0.056   415   0.056
e0    0.056   164   0.056   240   0.056   332   0.056   416   0.056
81    0.056   165   0.056   249   0.056   333   0.056   417   0.054
82    0 056   166   0.056   250   0.056   334   0.056
e3    0.056   167   0.056   251   0.016   335   0.056
e4    0.056   168   0.056   252   0.056   336   0.056


  NODE     TEMP       DTDT
    96    -12.22   0.000E-01
```

FIGURE 3-9
(continued)

```
                                         EXAMPLE RUN FOR GEODYN DOCUMENTATION...SI UNITS.

          ***THIS PROBLEM USES CARTESIAN COORDINATES***

             TIME STEP     6 OF     6
             TIME STEP IS 15.20(DAYS)
             RESULTS AT  1824.0(HRS)    76.00(DAYS)      2.50(MOS)      0.21(YRS)

                THE SYMBOL * DENOTES A SPECIFIED VALUE

NODE      TEMP   NODE     TEMP   NODE     TEMP   NODE     TEMP   NODE     TEMP
   1   -0 256     85    0.032    169    0.046    253   -0.002    337    0.056
   2   -0 188     86   -0.682    170    0.049    254   -0.003    338    0.057
   3   -0 120     87   -1.072    171    0.051    255   -0.014    339    0.055
   4   -0 065     88   -1.505    172    0.054    256   -0.003    340    0.055
   5   -0 040     89   -1.066    173    0.055    257   -0.001    341    0.056
   4   -0 053     90   -2.268    174    0.055    258    0.003    342    0.056
   7   -0 055     91   -2.215    175    0.056    259    0.007    343    0.056
   8   -0 064     92   -3.327    176    0.056    260    0.007    344    0.057
   9   -0 083     93   -2.214    177    0.057    261    0.003    345    0.055
  10   -0 080     94   -7 230    178    0.055    262    0.007    346    0.056
  11   -0 016     95   -2.687    179    0.056    263    0.007    347    0.057
  12    0 040     96  -12.222*   180    0.057    264    0.003    348    0.055
  15   -0 256     97   -2.685    181    0.053    265    0.007    349    0.055
  14   -0 119     98   -0.004    182    0.055    266    0.007    350    0.056
  15   -0.039     99    0.000    183    0.055    267    0.001    351    0.056
  16   -0 134    100    0.002    184    0 056    269    0.008    352    0.056
  17   -0 154    101    0.003    185    0.056    269    0.004    353    0.057
  18   -0 073    102    0.001    186    0.057    270    0.015    354    0.055
  19    3 041    103    0.020    187    0.053    271    0.022    355    0.056
  20   -5 255    104    0.021    188    0.056    272    0.028    356    0.057
  21   -0 187    105    0.028    189    0.057    273    0.033    357    0.055
[illegible] [illegible] 106    0.016    190    0.053    274    0.038    358    0.035
  23   -3 302    107    0.027    191    0 055    275    0 042    359    0.055
  24   -0 034    108   -0.249    192    0 055    276    0.022    360    0.056
  25   -3 042    109   -0.113    193    0.056    277    0.033    361    0.056
  26    0 001    110   -0.025    194    0.056    278    0.042    362    0.057
  27    0 006    111    0.000    195    0.057    279    0.015    363    0.055
  28   -0 057    112    0.001    196    0.040    280    0.022    364    0.056
  29   -0 049    113    0.004    197    0.047    281    0.028    365    0.057
  30    0 005    114    0.013    198    0.050    202    0.033    366    0.059
  31    0 040    115    0.029    199    0.053    283    0.038    367    0.065
  32   -0 253    116   -0.245    200    0.046    284    0.042    360    0.080
  33   -0 116    117   -0.178    201    0.053    285    0.021    369    0.106
  34   -0 030    118   -0.107    202    0.039    286    0.033    370    0.065
  35   -0 075    119   -0.052    203    0.046    287    0.042    371    0.106
  36   -0 081    120   -0.022    204    0.050    288    0.014    372    0.059
  37   -0 014    121   -0.002    205    0.052    289    0.021    373    0.065
  38    0 037    122    0.000    206    0.046    290    0.027    374    0.080
  39   -0 251    123    0.005    207    0.052    291    0.033    375    0.106
  40   -0 183    124    0.009    208    0.054    292    0.038    376    0 065
  41   -3 114    125    0.014    209    0.055    293    0.041    377    0.106
  42   -0 058    126    0.020    210    0.055    294    0.021    378    0.059
  43   -0 026    127    0.026    211    0.056    295    0.032    379    0.065
  44   -0 015    128    0.031    212    0.056    296    0.041    380    0.080
  45   -3 097    129   -0.247    213    0.057    297    0.014    381    0.106
  46   -0 507    130   -0.105    214    0.055    290    0.020    382    0.065
  47   -0 082    131   -0.947    215    0.056    299    0.026    383    0.106
  48   -0 017    132   -0.286    216    0.057    300    0.031    384    0.059
  49   -0 343    133   -0.178    217    0.054    301    0.035    385    0.065
  50   -0 081    134   -0.090    218    0.055    302    0.039    386    0.080
  51   -0 026    133   -0.041    219    0.055    303    0.016    387    0.106
  52   -0 072    136   -0.042    220    0.056    304    0.027    388    0 065
  53   -0 030    137   -0.032    221    0.056    305    0.036    389    0.106
  54   -3 050    138   -0.038    222    0.057    306    0.048    390    0.059
  55   -0 075    139   -0 027    223    0.055    307    0.051    391    0.065
  56   -0 027    140   -0.017    224    0.056    308    0.053    392    0.080
  57   -0 369    141   -0 014    225    0.057    309    0.055    393    0.106
  58   -0 018    142   -0 033    226   -0.306    310    0.051    394    0.059
  59   -3 047    143   -0 017    227   -0.162    311    0.055    395    0.065
  60   -0 087    144   -0.002    220   -0.053    312    0.048    396    0.080
  61   -0 009    145   -0.003    229   -0.306    313    0.051    397    0 106
  62   -0 080    146   -0 065    230   -0.053    314    0.053    398    0.065
  63   -0 100    147   -0.089    231   -0.306    315    0.055    399    0.106
  64   -0 018    148   -0 033    232   -0.162    316    0.051    400    0.059
  65   -3 003    149   -0.078    233   -0.053    317    0.055    401    0.065
```

FIGURE 3-10

SIMULATION OUTPUT AT TIME STEP SIX

```
 66  -0.251    150  -0.051    234  -0.306    318   0.047    402   0.080
 67  -0.114    151  -0.026    235  -0.053    319   0.051    403   0.106
 68  -0.025    152  -0.041    236  -0.306    320   0.053    404   0.065
 69  -0.003    153  -0.008    237  -0.167    321   0.054    405   0.106
 70  -0.007    154  -0.022    238  -0.054    322   0.051    406   0.059
 71  -0.001    155  -0.002    239  -0.307    323   0.054    407   0.063
 72   0.015    156   0.041    240  -0.053    324   0.046    408   0.080
 73  -0.251    157   0.041    241  -0.302    325   0.050    409   0.106
 74  -0.182    158   0.049    242  -0.162    326   0.052    410   0.065
 75  -0.113    159   0.051    243  -0.060    327   0.054    411   0.106
 76  -0.057    160   0.045    244  -0.309    328   0.048    412   0.059
 77  -0.025    161   0.051    245  -0.046    329   0.054    413   0.065
 78  -0.004    162   0.042    246  -0.012    330   0.055    414   0.080
 79  -0.001    163   0.046    247  -0.002    331   0.055    415   0.106
 80   0.000    164   0.049    248  -0.002    332   0.056    416   0.065
 81  -0.001    165   0.051    249  -0.012    333   0.056    417   0.106
 82   0.001    166   0.046    250  -0.002    334   0.056
 83   0.003    167   0.051    251  -0.002    335   0.057
 84   0.002    168   0.043    252  -0.012    336   0.035


      CURRENT METEOROLOGIC CONDITIONS

           SHORT WAVE(W/M2)                 92.19
           LONG WAVE(W/M2)                 166.74
           AIR TEMP(DEG C)                 -12.86
           WIND SPEED(KM/HR)                 8.25
           CLOUD COVER(FRAC)                 0.60
           EVAP. FLUX(W/M2)                  0.00
           SNOW DEPTH(M)                     0.61
           SNOW DENS(GM/CC)                  0.20

      NODAL VALUES-SURFACE ENERGY BALANCE

       NODE      G NET      DG/DT     EQ TEMP      TEMP      SH WV    L WV-IN   L WV-OUT     EVAP      TURB
               KJ/M2/HR              (DEG C)    (DEG C)    (W/M2)    (W/M2)     (W/M2)    (W/M2)    (W/M2)
  1   229      -9.26     -0.38      -13.76      -0.31      64.53     166.74      0.00      0.00      0.00
  2   234      -9.26     -0.38      -13.74      -0.31      64.53     166.74      0.00      0.00      0.00
  3   239      -9.76     -0.38      -13.76      -0.31      64.53     166.74      0.00      0.00      0.00
  4   244      -9.25     -0.38      -13.76      -0.31      64.33     166.74      0.00      0.00      0.00
  5   129      -9.30     -0.38      -13.76      -0.25      64.33     164.74      0.00      0.00      0.00
  6   108      -9.30     -0.38      -13.76      -0.25      64.53     144.74      0.00      0.00      0.00
  7    66      -9.29     -0.38      -13.76      -0.25      64.53     166.74      0.00      0.00      0.00
  8    32      -9.29     -0.38      -13.76      -0.25      64.53     166.74      0.00      0.00      0.03
  9    13      -9.29     -0.38      -13.76      -0.21      64.33     166.74      0.00      0.00      0.00


          CONVERGENCE HISTORY

ITER   NODES      AVG COR       MAX COR     NODE
  1     416       0.0059        0.0404      108
  2     416       0.0002        0.0020      257

          LOCATION OF    0.00 ISOTHERM

       ELT   MID NODE     X-CORD      Y-CORD       FRAC
  1     3         1       2.633       0.000       0.637
  2     3        30       2.574       0.440       0.355
  3     8        72       2.470       0.883       0.897
  4    11        98       2.182       1.139       0.738
  5    11        71       1.973       1.247       0.453
  6    14        91       0.038       0.305       0.000
  7    14        35       0.039       0.306       0.994
  8    15        93       2.209       0.305       0.999
  9    15        36       2.206       0.310       0.024
 10    16        16       0.838       0.304       0.003
 11    17        17       2.211       0.302       0.996
 12    19        99       2.438       1.039       0.527
 13    24       111       0.932       2.171       0.707
 14    24       121       0.738       2.438       0.385
 15    25       112       1.446       1.640       0.127
 16    26       113       1.524       1.595       0.078
 17    27        82       1.673       1.524       0.287
 18    32       139       0.834       0.305       0.020
 19    40       148       2.717       0.305       0.937
 20    77       261       0.540       7.924       0.181
 21    77       258       0.537       9.754       0.824
 22    78       264       0.526       6.096       0.150
 23    79       267       0.622       4.267       0.361
```

FIGURE 3-10
(continued)

```
                CONVERGENCE SUMMARY FOR THE COMPLETE RUN

STEP    DAYS     DELT     MX CHG       NODES     INT LV     IT NUM
  1      7.6      7.6     0.0018        179         1         14
  2     15.2      7.6    -0.0010        199         1          6
  3     30.4     15.2     0.0013        157         1          5
  4     43.6     15.2    -0.0012        183         1          4
  5     60.8     15.2    -0.0014        209         1          4
  6     76.0     15.2     0.0020        416         1          7


****************************************  RUN COMPLETE  ****************************************
```

FIGURE 3-11

CONVERGENCE HISTORY FOR THE EXAMPLE PROBLEM

CHAPTER 4

PROGRAM INPUT INSTRUCTIONS

The input data for program **GEOOYN** are read from the card reader (logical unit **5)** and output to the line printer (logical unit 6). The program may be run on a completely stand alone basis by card image input or may read files previously generated by itself or by the network generator, GEOGRD. **A** schematic description of the file units which may be used by **GEODYN** is shown in Figure 4-1.

DATA INPUT FORMATS

The following paragraphs summarize the exact card formats expected by **GEODYN**. The user should follow this sequence exactly and input the data in the same order as it is described. In all cases the program will expect to input this information on **FORTRAN** logical unit **5** unless otherwise noted. Finally, the reader *is* urged to review the nput and output from the example problem if questions arise.

Please note that all inputs to **GEODYN** are in free f eld format. This means that all data on a specified **card** image **must** be supplied, with individual values separated by blanks or commas. **A** slash (/) at the end of a line indicates the end of record and may be used to advantage in some cases. If less than the proper number of items are input on a given card image, the program will look at the next card to complete its list. This is a common error in free field Input, and must be checked carefully **by** the user.

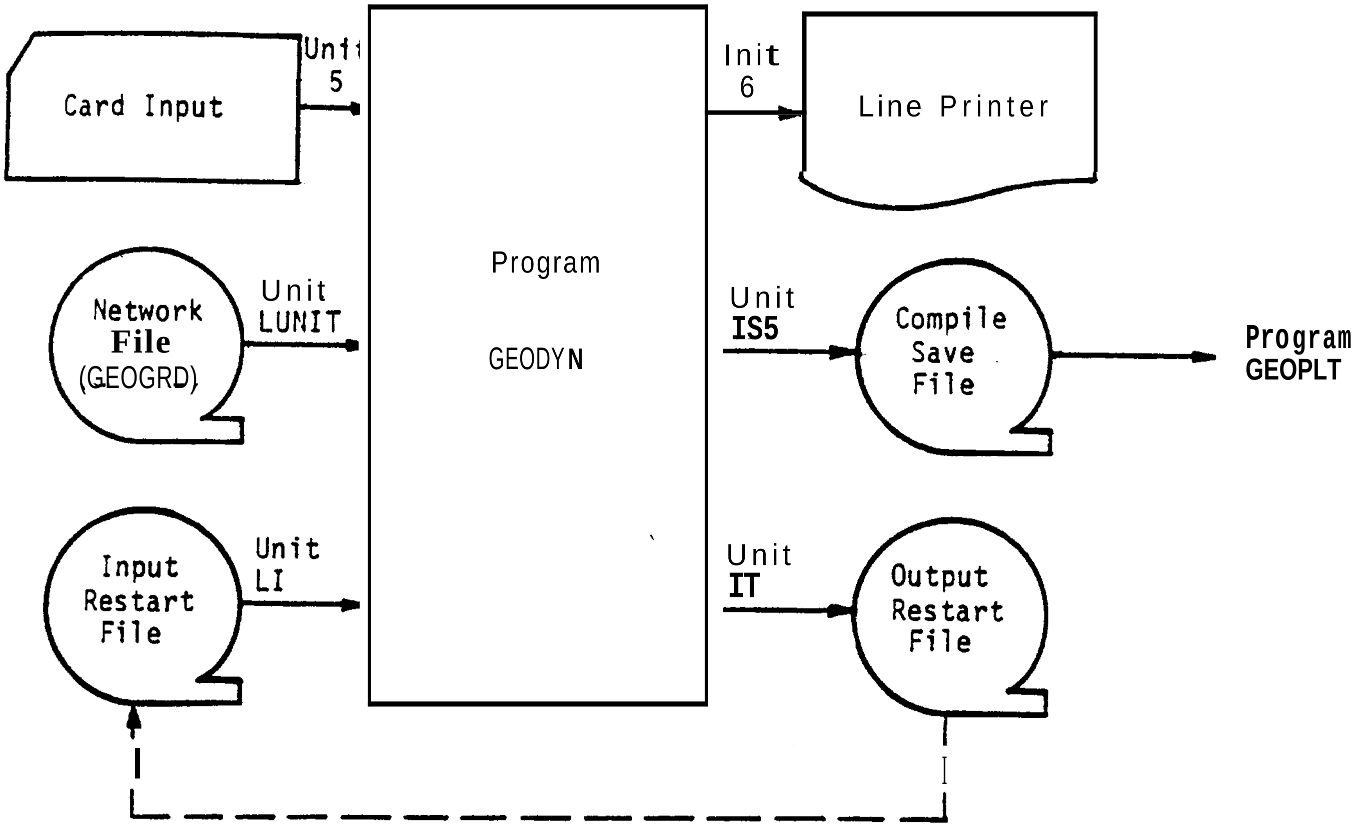


FIGURE 4-1

FILE ORGANIZATION FOR GEODYN PROGRAM

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
A.	**Job Title**		
	1	TITLE	Header label ; any 80 column Comment.
B.	Job Controls		
	1	NCD .	Number of element defining cards to be read from the card reader. This number may be zero if a GEOGRD file is input.
	2	NPX	Number of nodes whose spatial coordinates are to be explicitly input. Only the corner nodes need be explicitly input, as mid-side node locations, if not user-specified, are determined by linear interpolation. This number may be zero if a GEOGRD file is used.
	3	NMAT	Number of material zones. (Each unique combination of values for frozen and thawed thermal conductivities and heat capacities, and latent heat characteristics constitutes a unique material zone.) NMAT cannot exceed 20 and must be at least one.
	4	IS1	Enter the number of cards to be read to define the initial temperature conditions. The entire network will be initialized to the first value input before subsequent cards are read. If a zero is entered, no cards will be read. . If -1 or -2 is entered, a card of Type N will be required. If IS1<0, the initial conditions will be calculated from the expression $T=T_1+(T_2-T_1)e^{-kl}$ where $l = x$ if IS1=-1 and $l = y$ if IS1=-2. T_1, T_2 and k are input on Card Type N, below.
	5	IPRT	If IPRT is nonzero, the nodal coordinates, nodal connections, and element areas, will be printed. If IPRT equals zero, this portion of the network description will not be printed, but computations are unaffected
	6	NSPN	Enter the number of nodes for which a summary time history of temperatures is to be output at the end of the computer run. The list of node numbers is input on Card Type H.
	7	ISOC	Enter 1 if the program is to calculate and output the location of the freezing isotherm; otherwise enter zero.

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	8	LUNIT	Enter the FORTRAN logical unit number for the input file generated by GEOGRD; if no file is available, enter zero.
	9	LI	Enter the FORTRAN logical unit number for the input restart file; this file will have been written by a previous GEODYN run and written on unit IT, below.
	10	IT	Enter the FORTRAN logical unit number for output of the restart file; this file will contain all the information necessary to restart the simulation at the end of the final time step of the current simulation.
	11	IS5	Enter the FORTRAN logical unit number for output of a complete time history of results from this simulation. This file can be used. for post processing for such things as time histories or contour plotting. This is the input file for program GEOPLT.
	12	ISINO	Enter the number of surface boundary nodes at which an annual sinusoidal temperature variation will be imposed, These nodes will be the last ISINO node numbers assigned for boundary condition specifications and are input on Card Type T.
	13	NSF1	Enter the number of element sides (faces) which define the network interface for a full surface energy balance computation. The data required by a positive value are input on Card Types 0, P and Q.
	14	NSF2	Enter the number of element sides (faces) which are to receive a specified thermal flux. The node numbers are input on Card Type R.
	15	NBCG	Enter the number of annual profiles of temperature which may be used to define time dependent boundary conditions. If this value is greater than zero, NBCG of Card Type S will be required.
	16	IRO	If the program is to internally reorder the system elements, enter 1; otherwise enter zero. The node numbers from which to begin reordering are input on Card Type L.

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
C. Numerical Solution Controls			
	1	MAXI	The maximum number of Newtonian iterations for a given time step for a given level of numerical integration; $\leq$ 25.
	2	MINGP	The minimum level of numerical integration to be used for this problem. This value must be between 1 and 5, and is usually 1. MINGP must be $\leq$ MAXGP, below.
	3	MAXGP	The maximum level of numerical integration to be used for this problem. This value must be between 1 and 5 and is usually 2. MAXGP must be $\geq$ MINGP, above.
	4	NURF	The iteration number at which the program will apply an under relaxation factor of 0.5 for the Newtonian iteration scheme; normally this value is set to zero and under relaxation is not needed. If convergence problems develop, set NURF to 8.
	5	MAXSUB	The program will automatically halve the time step specified by the user if a stable solution cannot be reached. MAXSUB is the maximum number of times the time step increment will be halved.
	6	CONVC	The temperature convergence criteria, °C. The problem is considered converged if this limit is reached. The program will terminate execution on an error stop if this limit is exceeded by a factor of ten on the final iteration.
	7	ALPHA	This factor is used in the time integration scheme, and has a value between 1.0 and 2.0. Normally this value is set at 1.0 or 1.5, with 1.5 the recommended value. This is the value α in Equation (1.6).
D. Scale Factors			
	1	XSCALE	X-direction (or r direction) inputs for nodal locations will be multiplied by this factor to convert input values to meters.
	2	YSCALE	Same as XSCALE, but for y-direction (or z direction).

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	3	WSCALE	Same as XSCALE, but multiplies thickness inputs for a Cartesian system. NOTE: To operate GEODYN in cylindrical coordinates, set WSCALE to 0.0. The program will then shift to cylindrical coordinates with the origin at r = 0.0.
	4	USCALE	Scale factor for x or r direction groundwater velocities to convert input to m/hr.
	5	VSCALE	Scale factor for y or z direction groundwater velocities to convert input to m/hr.
E.	Time Step Controls		
	1	NTIME	Number of time steps for this simulation.
	2	NTSEG	Frequency of printout, in number of time steps (if NTSEG = 1, printout will be generated every time step).
	3	NVTS	The number of different time step increments to be read on Card Type F.
	4	TSTART	Starting time (days) for this run. If a restart file is used this value will be overwritten.
F.	Time Step Length - NVTS (Card E.3) cards required		
	1	N	Number of time steps
	2	DELTX	Time step size(s) (days). If set equal to zero, then the steady-state solution is calculated, and MAXI should be set equal to 1 to avoid duplicate calculations.
G.	Sinusoidal Temperature Boundary Condition - omit if ISINO (Card B.12)=0		
	1	TMEAN	Base temperature for sinusoid (equals mean annual temperature when AMP1 equals AMP2).
	2	AMP1	Summertime sinusoid amplitude (difference between highest desired temperature and TMEAN).
	3	AMP2	Winter sinusoid amplitude (difference between TMEAN and lowest desired temperature).
	4	PHASE	Phase in days, different from zero if start of simulation is other than January 1 of any year.

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION

H. Time History Summaries - Omit if NSPN (Card 8.6) = 0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	ISPN	Up to 12 node numbers for which complete time history summaries will be printed at the end of the computer run.

I. Zone Properties - NMAT (Card 6.3) cards required

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	J	Material zone number - corresponds to element zone definitions.
	2	ORT(J,1)	Frozen thermal conductivity in the x or r direction (W/m°C).
	3	ORT(J,2)	Frozen thermal conductivity in the y or z direction (W/m°C).
	4	ORT(J,3)	Thawed thermal conductivity in the x or r direction (W/m°C).
	5	ORT(J,4)	Thawed thermal conductivity in the y or z direction (W/m°C).
	6	ORT(J,5)	Frozen volumetric heat capacity (kJ/m^3°C).
	7	ORT(J,6)	Thawed volumetric heat capacity (kJ/m^3°C).
	8	HEATL(J)	The heat of fusion for this type element (mJ/m^3).
	9	ALPE(J)	The value of α in the soil moisture/temperature function of this type of material, °C. (See Equation (1.3).)
	10	GAME(J)	The fraction of the soil moisture not frozen isothermally for this type of material. (See Equazion (1.3).)
	11	EPSE(J	The temperature range over which the isothermal release of latent heat will be approximated, °C. (See Figure C-6.)

J. Node Definitions - NPX (Card 8.2) cards required, omit if NPX=0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
J	1	J	Node number.
	2	CORD(J,1)	X or r coordinate location.
	3	CORD(J,2)	Y or z coordinate location.
	4	WD(J)	The width of the network at this location (Cartesian coordinates only), If zero is entered, unit width will be assumed.

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
K.	Element Definition - NCD (Card 8.1) cards required, omit if NCD=0.		
	1	J	The element number
	2-9	NOP(J,K)	Six or eight node numbers, starting at a corner node and going counterclockwise around the element (remember to zero fill for triangles).
	10	IMAT(J)	Corresponding material zone number. Setting this to zero implies a null element and it effectively alters the grid network without having to pull out the corresponding cards. This number should correspond to the zone properties entered on Card Type 1.
L.	Element Renumbering - enter as many node lists as desired and terminate with a 9999/ card image, omit if IRO (Card 8.16) = 0		
	1-50	NLIST	A list of node points (up to 50) from which the program will reorder the internal sequence of elements to obtain the most efficient operation of the simulation programs. As a general rule at least two starting lists should be tried, one at each end of the network. The end of a list is a zero value.
M.	Initial Temperature Specification - IS1 (Card 8.4) cards required, omit if IS1 is less or equal to zero		
	1	J	Node number
	2	TOLD(J,1)	Initial temperature at node 3. All nodes will be set to the first value input before reading subsequent inputs.
N.	Initial Temperature Relationship - one card required, omit if IS1 (Card 8.4) is less than zero.		
	1	T1	The initial condition temperature at coordinate distance of infinity, °C.
	2	T2	The initial condition temperature at coordinate distance of zero, °C.
	3	XK	An exponential decay factor to transition from T2 to T1 with distance, m^{-1}. The definition of how these data are used to define initial condition is provided in the description of IS1.

NOTE: Input Card Types O, P and Q only if a full surface energy balance is to be calculated (NSF1>0).

O. Meteorological Conditions - twelve cards required if NSF1 (Card 8.13) is greater than 0, omit if NSF1=0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	N	Month ($1 \le N \le 12$).
	2	DOM(N)	Day of year corresponding to this month ($1 \le DOM(N) \le 365$).
	3	QSW(N)	The short wave solar radiation for this month (W/m^2).
	4	TAIR(N)	The air temperature for this month (°C).
	5	WSPD(N)	The wind speed for this month (km/hr).
	6	CLDCV(N)	The fractional cloud cover for this month ($0.0 \le CLDCV(N) \le 1.0$).
	7	EVPRT(N)	The evapotranspiration flux for this month (W/m^2).
	8	SDEP(N)	The snow depth for this month (m).
	9	SDEN(N)	The snow density for this month (gm/cc).

P. Meteorological Data Multipliers - one card required if NSF1 (Card 8.13) is greater than 0, omit if NSF1=0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	CVF1(1)	A uniform multiplier to be applied to the values of QSW(N) (Card 6.3).
	2	CVF1(2)	A uniform multiplier to be applied to the values of TAIR(N) (Card 8.4).
	3	CVF1(3)	A uniform multiplier to be applied to the values of WSPD(N) (Card 8.5).
	4	CVF1(4)	A uniform multiplier to be applied to the values of CLDCVR(N) (Card 8.6).
	5	CVF1(5)	A uniform multiplier to be applied to the values of EVPRT(N) (Card 8.7).
	6	CVF1(6)	A uniform multiplier to be applied to the values of SDEP(N) (Card 8.8).
	7	CVF1(7)	A uniform multiplier to be applied to the values of SDEN(N) (Card 8.9).

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION

Q. **Surface Heat Flux** Parameters - NSFl (Card 8.13) cards required, omit if NSF1=0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	NLIST1(J,2)	The mid-side node number of an element face (side) which is to be included in a surface energy balance calculation,
	2	ALGND(J)	The short wave radiation albedo for this face when snow free (fraction).
	3	ALSNO(J)	The short wave albedo for this face when snow covered (fraction).
	4	VFACT(J)	The shortwave view factor for this face (fraction).
	5	EMGND(J)	The long wave back radiation emissivity for this face when snow free (fraction).
	6	EMSNO(J)	The long wave back radiation emissivity for this face when snow covered (fraction).
	7	RBARE(J)	The surface roughness for this face when snow free (m).
	8	RSNOW(J)	The surface roughness for this face when snow covered (m).
	9	EFACT(J)	The ratio of the monthly evapotranspiration flux to the evapotranspiration flux to be assigned to this element fact (fraction).
	10	TFACT(J)	The ratio of the monthly snow depth to the snow depth to be assigned to this element face (fraction).
	11	DFACT(J)	The ratio of the monthly snow density to the snow density to be assigned to this element face (fraction).

R. Constant Heat Flux - **NSF2** (Card 6.14) **cards** required, omit if NSF2=0

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION
	1	NLIST2(N,2)	The mid-side node number of an element face across which a flux is to be specified.
	2	FLUXC(N)	The constant flux to be applied across the element face. A positive value is an input and a negative value is a withdrawal (W/m^2),

CARD TYPE	INPUT SEQUENCE	FORTRAN NAME	DESCRIPTION

NOTE: Input Card Type S only if time dependent annual schedules are to be input to define boundary conditions (NBCG>0).

S. Time Dependent Boundary Conditions - one card required if NBCG (Card 8.15) is greater than zero, omit if NBCG=0

	1	M	The time series order number. This will be used for reference purposes later when the boundary conditions are input.
	2	N	The number of day-temperature pairs which define the annual temperature schedule.
	3-22	TBC,VBC (N pairs)	The Julian day, TBC, and the associated temperature value. At least two pairs must be input, with 0 < TBC ≤ 365, Up to 20 pairs may be used—to define an annual sequence.

T. Boundary Condition Control - one card required (**see** notes following Card Type V description)

	1	NBX	The number of temperature boundary condition cards to be read.
	2	NVEL	The number of nodal velocity component cards to be read.

U. Temperature Boundary Conditions - NBX (Card T.1) required) (see notes following **Card** Type V description)

			The node number where a boundary condition is to be applied.
	2	TNEW(J,1)	The boundary condition value (°C).
	3	IG	The group number for this boundary condition. This value corresponds to input 1 on Card Type S. Enter zero if the value of TNEW(J,1) Is to be used as the boundary conditic

V. Flow Velocity Boundary Conditions - **NVEL** (Card T.2) required (see following notes)

	1	N	The node number where flow velocities are to be assigned.
	2	UX	The convective velocity to be assigned to node N. The value input will be multiplied by USCALE input on Card Type 0, above.
	3	VX	The convective velocity to be assigned to node N. The value input will be multiplied by VSCALE input on Card Type O, above.

Notes for proper boundary condition Specification.

1) The set of Card Types T, U, and V can be repeated for as many time steps as desired. After the set of inputs is exhausted, the program will continue to use the last values read. Please note the temperature boundary conditions and/or convective velocities may be time dependent. If, for example, one wished to change only velocities and leave the temperatures alone, the proper speciffcation would be NBX=0 and NVEL>0.

2) The first set of inputs <u>must</u> encompass the total list of nodes for which boundary conditions are to be specified. After the first set, subsequent sets need only contain values that are to be changed; previously specified values will remain at their current levels.

3) After the first set of inputs, a value of NBX = -1 will result in a single card input (Card Type U) which will be applied to all nodes which are designated as boundary condition nodes.

4) A value of NVEL = -1 will result in a single card Input (Card Type V) which will be applied to all nodes in the network.

5) If the IG on Card Type U is >0, the annual specification (Card Type S) will override any input values.

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APPENDIX A

SURFACE HEAT BALANCE

A.1 INTRODUCTION

This chapter discusses the formulation of the surface energy balance used in GEODYN. Part or all of each component of the energy balance is calculated as a function of a climate variable that is expressed as an explicit function of time (i.e., solar radiation, cloud cover, air temperature, wind speed, local evaporation rate, and snow depth and density). As presently formulated, selection of the full surface energy balance option in GEODYN will invoke piece-wise linear temporal interpolation of the appropriate average monthly values of the following seven meteorological parameters:

- Incident solar radiation (W/m^2)
- Wind velocity (km/hr)
- Evaporation flux (W/m^2)
- Snow depth (m)
- Snow density ($grams/cm^3$)
- Air temperature (°C)
- Cloud cover (fraction of sky)

Computation of the net surface heat flux is completely integrated with the calculation of soil temperatures. It is solved simultaneously with the heat conduction problem in a fully implicit manner. Nonlinear terms arising from back radiation and latent heat effects are included in iteration schemes. Snow cover effects are modeled by calculating an energy balance across the snow depth and solving for the equilibrium snow surface temperature. This temperature is used to estimate a heat flux through the snow based on an assumed linear temperature distribution in the snow and the local value of the snow/ground interface temperature.

A.2 SURFACE ENERGY BALANCE

The net surface energy balance flux term is approximated by the relationship:

$$Q_{NET} = Q_{SW} - Q_{NLW} + Q_{TURB} - Q_{EVAP} \qquad (A.1)$$

where Q_{SW} = net shortwave radiation flux

Q_{NLW} = net 'longwave radiation flux

Q_{TURB} = net turbulent heat exchange across the surface

Q_{EVAP} = net evaporative heat flux leaving the boundary surface

Shortwave Radiation

The available shortwave radiation transmitted across a surface is specified explicitly according to the relationship:

$$Q_{sw} = \alpha V_f F_{sw}(t) \qquad (A.2)$$

where α = surface absorption coefficient, time dependent

V_f = view factor accounting for shading effects, independent of time

$F_{sw}(t)$ = total incoming shortwave flux, time dependent

Appropriate summer and winter surface absorptivities for incoming solar radiation are specified on a monthly basis. Bifferent values are read in for each surface grid point and values between grid points are linearly interpolated. $F_{sw}(t)$ is the explicit incoming solar radiation function. The variable, V_f, view factor, is a fractional modifier for available solar radiation that accounts for shading effects.

Colsenga and List (1964) give detailed information on how to calculate inconing solar radiation on clear days. Scott (1964) provides a correction for cloud cover. In general, the measured and calculated values of solar radiation agree well, Alternatively, The National Weather Service and Titus (1969), publish measured solar radiation tor several locations in Alaska and Canada. These values can be used directly or corrected for small changes in latitude for a given location.

Longwave Radiation

Outgoing longwave radiation is simulated according to the well known Stefan-801tzmann relationship:

$$Q_{l} = \varepsilon \sigma T_s^4 \qquad (A.3)$$

where ε = the longwave emissivity of the surface

σ = the Stefan-Boltzmann constant, (5.7×10^{-8} W/m^2 °K^{-4})

T_s = the surface temperature (°K)

Values of ε are tire dependent and are read in for each grid point just as for the shortwave absorptivities.

If clouds are present, additional radiation is emitted by water and ice particles at the bottom of the clouds. Low clouds emit more radiation than high clouds, the farmer being in general warmer and denser than the latter, furthermore, the extent of cloud cover has an influence on the incoming longwave radiation transmitted to a surface. Since the amount of radiation from the central part of the sky is dominant, clouds near the horizon do not influence radiation as much as clouds in the central part of the sky. However, in many practical cases, cloud types are not recorded, therefore, an approximate correction for cloud cover has to be taken into account. If a certain cloud type is associated with a certain cloud cover, a functional relationship such as $f(c) = 1. + .17c^2$ has been derived (TVA, 1972). The atmospheric radiation from a cloudy sky usng a formula proposed by Swinbank is presently employed in the surface heat balance algorithm to account for incoming longwave radiation according to the relationship:

$$Q_{ILW} = 0.91 \times 10^{-5} \varepsilon T_s^6 f(c) (1-Ra) \qquad (A.4)$$

where Q_{ILW} = incoming longwave radiation (W/m^2)

ε = Stefan-Boltzmann constant (5.7×10^{-8} W/m^2 °K^{-4})

T_s = dry bulb air temperature (°K)

$f(c)$ = $1. + 0.17C^2$, cloudiness correction for atmospheric radiation

Ra = 0.05, reflectivity of a surface incident longwave radiation

Convection

The heat transferred by convection between the air and ground surface is calculated in the conventional manner according to the relationship:

$$QTURB = h(T_s - T_a) \tag{A.5}$$

where h = the local convection heat transfer coefficient (W/m^2-°C)

T_s = the surface temperature (°C)

T_a = the local air temperature, time dependent (° C)

The air is assumed to act as an infinite sink at any given time and the surface temperature is calculated implicitly at each step 'by the program. The convective heat transfer coefficient is calculated from the Colburn analogy which is a classical heat and momentum flux relationship that assumes neutrally stable atmospheric conditions.

This analogy was used since it accounts for local variations in wind speed and surface roughness and gives values of h that are representative of "mean" conditions between stable and unstable atnospheric conditions during nighttime and daytime. The Colburn analogy is written as:

$$h = C_f \cdot \rho C_p \cdot (P_r)^{-2/3} W_s \tag{A.6}$$

where C_f = a drag coefficient dependent on surface roughness

ρ = the density of air (Kg/m^3 at °C)

C_p = the heat capacity of air (Kcal/kg at °C)

P_r = the Prandtl Number of air

W_s = the wind speed (km/hr)

GEODYN uses the correlation for the drag coefficient presented by Schlicting determined in a study of drag caused by vegetation on the earth's surface:

$$C_f = [2.5 \ln (1.6/R) + 5.]^{-2} \qquad (A.7)$$

where R = the surface aerodynamic roughness (m)

R is time dependent and may also be varied from node point to node point in the finite element grid.

Evaporative Heat Effects

Surface evaporative heat gains and losses, Q_{EVAP}, at the surface are included in the program in an explicit form. Explicitly evaporative heat losses are provided by the user with the evaporation function that specifies the surface evaporation rate in the summer months to account for best estimates of evapotranspiration.

Snow Cover

Snow cover is one of the more important factors affecting the surface heat balance. Snow cover is simulated as discussed earlier. Whenever snow is on the ground, surface parameters are automatically switched to represent a snow cover. Thermal conductivity of the snow is calculated based on the formula:

$$K = 1.68 \cdot (P_s)^2 \qquad (A.8)$$

where K = the snow thermal conductivity (W/m^2-°C)

P_s = the snow density in (gm/cc)

Both the snow depth and snow density are explicitly specified by the user. Bilello (1969) publishes a correlation that can be used to estimate the snow density based on air temperature and wind speed. The snow's volumetric heat capacity is neglected during all heat transfer calculations. Snow cover effects are terminated when specified snow depth decreases to 0.006 m. The depth and density, respectively, of the snow cover may be varied across the entire simulation grid using the dimensionless variables in the program input.

A.3 SUMMARY AND USE

Past experience has shown that where sparse meteorological data exists for thermally sensitive areas, it is necessary to "calibrate" a model to site specific conditions. **GEODYN** has been specifically formulated to provide this capability. Each of the climatic variables may be multiplied by a dimensionless factor to facilitate micro-climate calibration of the model or to permit a sensitivity study of climatic variability.

Climatic data for the surface heat balance is input in average monthly values beginning with the month of January. The user may specify any desired starting point for a simulation (i.e., a summer start capability.) as **well** as request a restart point to continue a previously run simulation.

APPENDIX B

GOVERNING EQUATIONS AND SOLUTION TECHNIQUE

B.1 INTRODUCTION

The intent of this chapter is to describe the technical basis for the mathematical model and computer program GEODYN. The purpose of the model is to predict temperature distributions in a soil mass which may or may not undergo a phase change and which may or may not possess a convective component. This discussion is focused on the two dimensional version of the model and uses the finite element method of numerical approximation. The governing equation is derived from the classic concept of conservation of energy and accommodates both surface fluxes and specified boundary conditions.

As presently programmed 'GEODYN provides a generalized two dimensional, nonlinear, time dependent solution for a statement of conservation of thermal energy in terms of temperature. A solution is produced in response to a number of user specified boundary conditions and/or source and sink terms, and the program will accept arbitrarily defined material and thermal properties. The output from the model is a set of temporal histories of temperature over the spatial domain being simulated.

The solution technique employs the finite element method of numerical approximation to achieve a solution to the governing differential equation. To develop this solution, we first present the governing differential equation which has been derived in the classical manner for an infinitessimal elemental volume. Next, we discuss some of the basic concepts of the finite elenent method, and how it can be applied to the governing equations. Included in this discussion is an explanation of how the governing equations will be integrated in both space and time, Finally, since the final set of equations is nonlinear, a brief summary of the nonlinear solution algorithm is presented.

8.2 GOVERNING DIFFERENTIAL EQUATION

The two-dimensional form of the differential equation solved by GEODYN can be written in Cartesian coordinates as:

$$w\beta_1 \frac{\partial T}{\partial t} + w\beta_2 \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial x}\left(K_x w \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y w \frac{\partial T}{\partial y}\right)$$

$$+ w\sigma_1 - w\sigma_2 = 0 \qquad (B\text{-}1)$$

where T = temperature, °C

β_1 = the average volumetric heat capacity of the soil mass (kJ/m^3); this term is temperature dependent

β_2 = the volumtric heat capacity of water (kJ/m^3)

u,v = the components of Darcian water velocity in the x and y directions, respectively (m/hr)

K_x, K_y = thermal conductivity coefficients in the x and y directions, respectively, ($kJ/m\text{-}hr\text{-}°C$); these terms are temperature dependent

w = the soil thickness normal to the *x-y* plane (m)

σ_1 = a thermal source or sink representing the effects of latent heat ($kJ/hr\text{-}m^3$); this term is temperature dependent

σ_2 = a thermal source or sink term representing a thermal flux such as a surface heat flux or the flux resulting from the geothermal gradient ($kJ/hr\text{-}m^3$)

Equation 8-1 represents a generalized, nonlinear statement of the equation describing the flow of heat in a saturated or unsaturated soil. In reviewing this equation, it is nonlinear because of the temperature dependence of the thermal conductivity of terms, K_x and K_y, the coefficient β_1, and the phase change term, σ_2. The **numerical** approximations used for each term, **plus** the method used to integrate Equation 8-1 in both space and time are presented in the following paragraphs.

8.3 THE FINITE ELEMENT METHOD

Within the limits of present knowledge, analytic **solutions** to Equation **(8-1)** can be found for only **a** limited set of boundary conditions and thermal properties. For this reason, GEODYN uses a numerical solution technique to approximate Equation (B-1) under a much wider set of conditions; in this case we have chosen the so-called Finite Element Method (FEM) of numerical solution.

The Finite Element Method is a numerical. technique suitable for solving differential equations of the type derived for the thermal balance relationship. It differs from the finite difference method in that it assumes a continuous description of state variables as opposed to values defined only at specific points. In a general sense, the finite element is said to provide an "exact" answer to an approximation of the problem, whereas finite differences provide an approximate answer to the "exact" problem. From the user's point of view, the FEM offers simplified data input and provides a great deal of flexibility in problem definition.

The method was first applied by structural analysts seeking the solution to complex problems in stress analysis of a continuum. The initial applications were in the aerospace industry where the resistance capability of continuous aircraft skins had to be maximized in keeping with the overall objective of weight minimization.

In the FEM, a continuum is represented by a series of discrete polygons each interconnected at a finite number of locations called nodal points. These nodal points are directly equivalent to joints in structural problems and the elements are equivalent to beams and columns. In the first applications, the elements were allowed to respond in only restricted and simple displacement patterns such that continuity was maintained along element faces, but force transfer was allowed only at the nodes. With the system thus approximated, the method of assemblage of elements and solutions of the governing equations was exactly that of conventional structural analysis.

The mid-1960's saw a rapid expansion of the finite element into many structural problems such as plate bending, axisymmetric structures, solid systems, and shell structures. The procedure was also generalized and solutions were developed for nonstructural problems such as electric fields and pore pressures. Simultaneously the method was applied to nonlinear and time dependent problems in elasticity and from these problems experience was built up allowing the systematic solution of nonlinear problems.

More recently, the method has been applied as a special form of the method of weighted residuals in which the governing equations are satisfied in an area integral sense. This process removes the need for a functional and allows solution of equations for which there are no convenient functionals.

The first step in the application of the FEM is the construction of acceptable single element approximation to the physical system. A suitable element will have an approximating function with the same number of independent variables as the number of node points. The approximation must be such that the variation of the approximating function along the boundary of an element exactly matches that of an adjacent element.

For example, a triangular element with nodal (corner) point degrees of freedom at the vertices must have a linear approximating function. The necessary condition is met because the function is linear along the sides of the element and the adjacent elements match exactly. If mid-side nodes are used, a quadratic approximating function may be used, as is the case in GEODYN.

A necessary condition for solution of the equations is that the fundamental equations do not contain derivatives two orders higher than those that match across the element boundary. Also, the function must be capable of representing a constant value of the function or its derivatives which may be present in the integral equation describing the element.

As an example, consider a region as shown in Figure B-1. Over each triangular element the state variables of the governing equations are allowed to vary in a prespecified form and elements are interconnected only at nodal points.

In the conceptual representation of the region, let the nodal points be the vertices of the triangles. Then for a typical triangle (i, j, k) a linear approximation for a state variable, ϕ, may be written as:

$$\phi = \langle N_i, N_j, N_k \rangle \begin{Bmatrix} \phi_i \\ \phi_j \\ \phi_k \end{Bmatrix} \tag{B-2}$$

or

$$\phi = \langle N \rangle \{\phi_e\} \tag{B-3}$$

in which N_i is a linear function of the coordinate system such that N_i = unity at node i and zero at nodes j and k. A similar relationship exists for N_j and N_k. N_i is the so-called "shape function", or basis functions. In all finite element applications the shape functions have the same definition, i.e.,

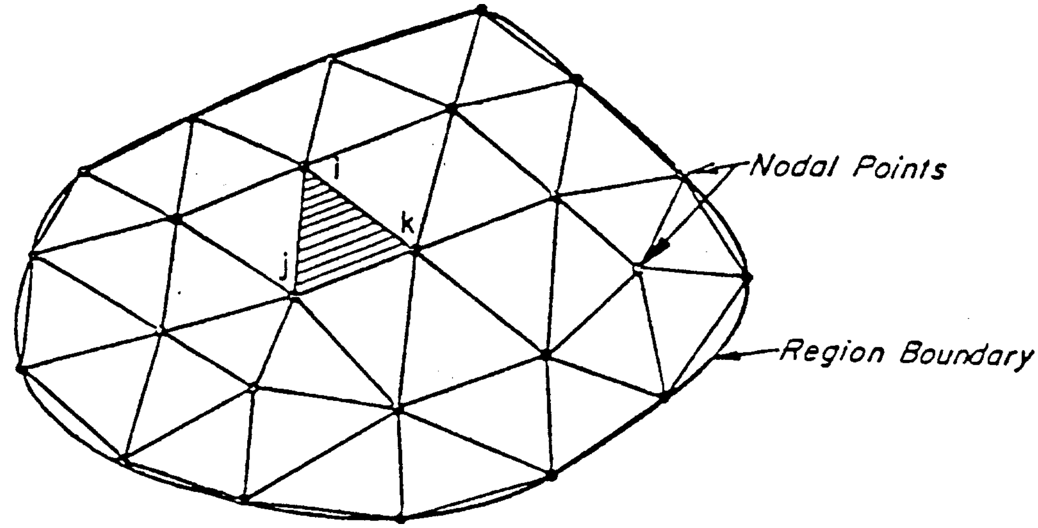


FIGURE B-1

FINITE ELEMENT REPRESENTATION
OF A REGION

N_i is continuous over the element, and

$$N_i = \begin{cases} 1 \text{ at node } i \\ 0 \text{ at all other nodes} \end{cases}$$

The coefficients of the shape functions are all known functions of the element geometry. For example, in an element with vertices at locations (0,0) (2,0) (0,2) as shown in Figure B-2. (A 45-degree triangle with base length equal 2). The shape functions are:

$$N_1 = 1/2\ (2-x-y)$$

$$N_2 = 1/2\ x \qquad \text{(B-4)}$$

$$N_3 = 1/2\ y$$

Similar functions may be written for the general linear triangle i, j, k, i.e.,

$$N_i = a_i + b_i x + c_i y \qquad \text{(B-5)}$$

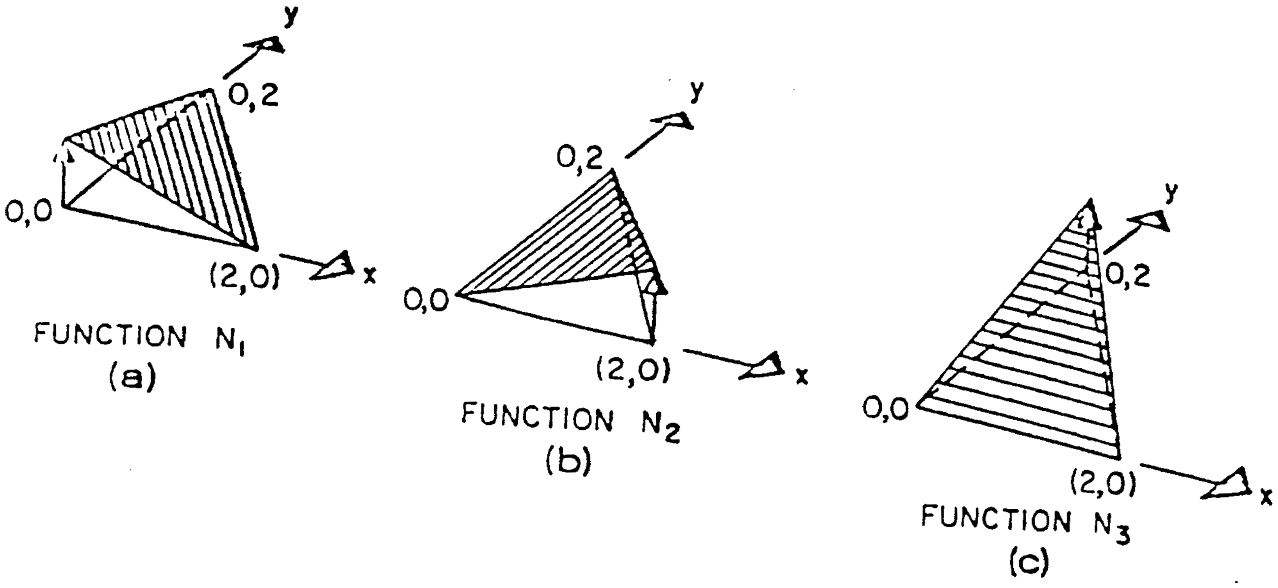
where a_i, b_i, c_i are purely geometric constants,

In GEODYN we use a more complicated, quadratic shape function. In one dimension the quadratic shape functions have the form indicated in Figure R-3. While the form of the quadratic shape function shown in Figure B-3 are' somewhat more complicated than the linear shape functions, a7l the ideas and definitions used with the linear functions are directly applicable to the quadratic formulation.

In developing the spatial approximation to the problem, it may be said that the continuous function, Equation B-1, has been replaced by a new, piecewise continuous function which is defined in terns of the values at the nodal points. To obtain a solution to the equations, we make use of the method of weighted residuals which restates the basic differential equation, $h = f(\phi,x,y)$ in terms of an error function and weighting function, w.

Ideally, the error function should be identically zero at all points. If this is the case, the integral for all weighting functions will be zero, or:

$$\iint w\ h\ dA = 0 \qquad \text{(B-6)}$$



FUNCTION N_1
(a)

FUNCTION N_2
(b)

FUNCTION N_3
(c)

FIGURE B-2

SHAPE FUNCTIONS FOR A 45° TRIANGLE

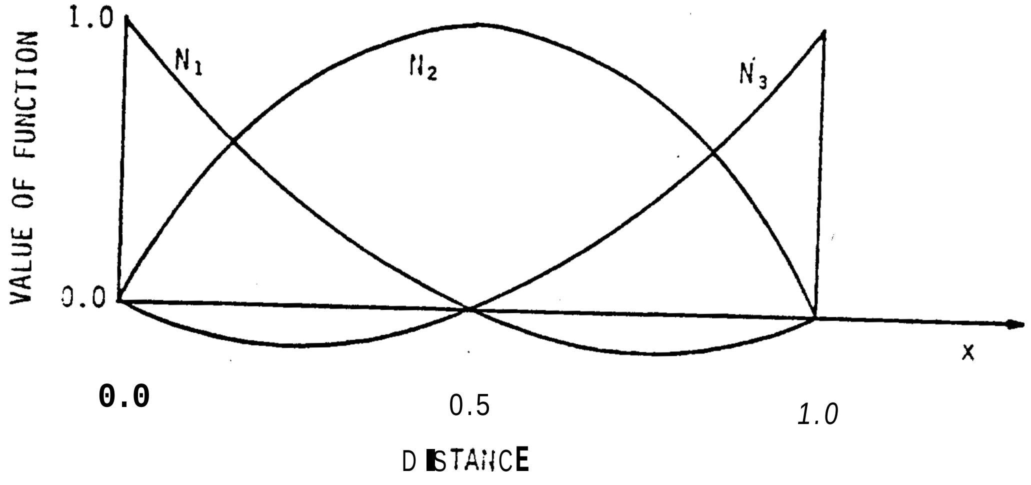


FIGURE 3-3

ONE DIMENSIONAL QUADRATIC
SHAPE FUNCTION

Then for a finite element approximation with n degrees of freedom, the single integral may be replaced by n integrals with independent weighting functions:

$$\iint w_n h \, dA = 0 \qquad (B-7)$$

where w_n represents the shape function associated with a degree of freedom. If the weighting function is defined to be equal to the shape function ($w = N$), there results what is known as the Galerkin method of weighted residuals which is the most accurate overall form.

In the complete formulation the contribution from a single finite element will be to all degrees of freedom (nodes) for that element and the total system will be a set of equations representing the sum of these contributions. This contribution to the equations may be written $\iint N \, h \, dA$ where N is the vector of shape functions for all degrees of freedom of the element.

The final step in the process is the assemblage and solution of the set. of simultaneous equations representing the system. The equations must be integrated and summed for each nodal point.

Figure B-4(a) shows a typical system consisting of six elements. The element is connected to the nodes as listed below:

ELEMENT	NODES		
1	1	4	3
2	1	2	4
3	4	2	5
4	3	4	6
5	4	7	6
6	4	5	7

If the three contributions are formed in terms of global coordinates, they can be added in the appropriate space of the global matrix. **Figure B-4(b)** shows the form of the six elements before addition and Figure B-4(c) the final form where non-zero elements are shaded.

After the equations are completely formed the boundary conditions must be inserted. These usually consist of specifying values of ϕ or its derivative at one or more nodes on the boundary of the region. Present values of ϕ may be inserted as an overriding equation replacing the previously formed equations or by eliminating the equation by direct

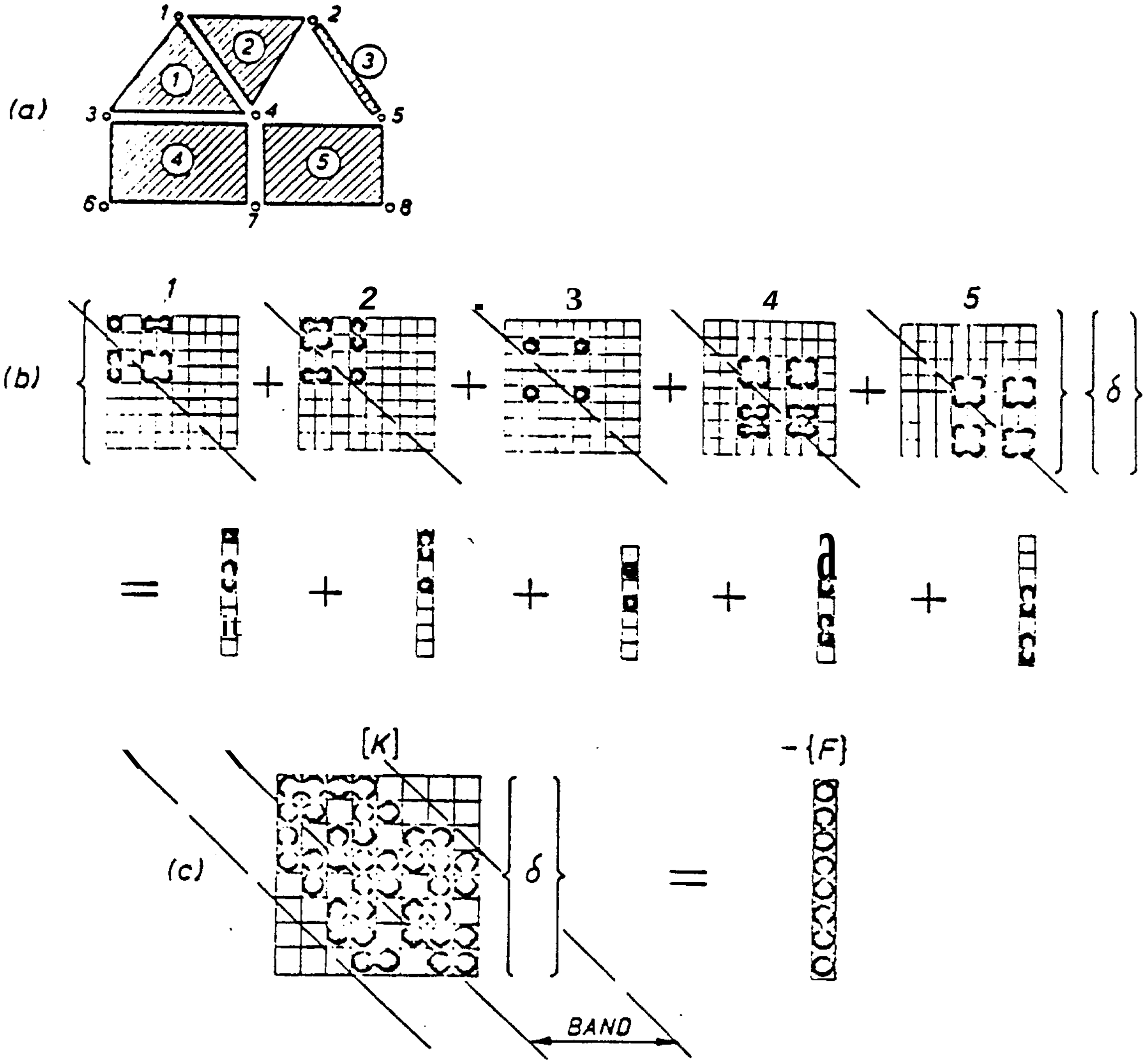


FIGURE B-4

TYPICAL FIVE ELEMENT **SYSTEM**

substitution of the specified value into the remaining equations. Values of the derivative of ϕ must be inserted by evaluating their influence on the right-hand side vector. The final step is the solution of linear simultaneous equations for the unknown nodal values of ϕ.

6.4 APPLICATION OF THE FINITE ELEMENT METHOD TO GEODYN

To develop a proper mathematical form for the application of the finite element method to Equation (B-1), we shall take advantage of Galerkin's technique which is a particular form of the method of weighted residuals. The idea behind this approach is that if a trial function (shape function) satisfying the boundary conditions is written for a differential equation, there may be some error. Mathematically, if a function is of the form $\delta(x,y,\phi) = 0$, and we assume a solution $g(x,y,\phi)$, then:

$$g(x,y,\phi) = R \neq 0 \qquad \text{(B-8)}$$

where

R = the solution residual or error

The best trial solution will be one that, in some sense, reduces the residual (error) to a minimum at all points. One obvious way to achieve this is to formulate the problem such that:

$$\iint \Omega R \, dxdy = 0 \qquad \text{(B-9)}$$

where Ω is any function of the coordinates x and y. This general procedure is known as the method of weighted residuals, and if the weighting function, Ω, is made equal to the shape functions defining the trial functions, the technique is called the Galerkin's method. For example, employing the normal finite element definition for variables, we can write:

$$\phi(x,y,t) = \langle N \rangle_i \; \{\phi_e\}_i \qquad \text{(B-10)}$$

where $\phi(x,y,t)$ = the value of ϕ at an arbitrary point in time and space in element i

$\langle N \rangle_i$ = the finite element shape (a row vector)

$\{\phi_e\}_i$ = the values of ϕ at the nodal points of element i (a column vector)

If Galerkin's method is applied to Equation (B-10) we obtain:

$$\iint \langle N\rangle_i \, \phi \, dxdy = 0 \qquad \text{(B-11)}$$

Equation (B-11) is the generalized statement for the application of Galerkin's method to the state variables of finite element i. This definition results in one independent equation for each nodal point for each element. In the final solution the contribution from all elements are combined for each nodal point and solved as one set of equations.

The final statement of the finite element model is developed as follows. First, for each element in the system the Galerkin method is applied to Equation (B-1). This leads to the general form:

$$\iint_A \langle N\rangle \{w\beta_1 \frac{\partial T}{\partial t} + w\beta_2 (u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) - \frac{\partial}{\partial x}(K_x w \frac{\partial T}{\partial x})$$

$$- \frac{\partial}{\partial y}(K_y w \frac{\partial T}{\partial y}) + w\sigma_1 - w\sigma_2\} \, dxdy = 0 \qquad \text{(B-12)}$$

where all terms have been previously defined. Next, to achieve the necessary inter-element consistency in the order of the approximation, we shall reduce the second order derivatives of Equation (B-12) to first order terms by an application of Green's transformation. This is accomplished by writing the identity, for example:

$$\iint_A \langle N\rangle \frac{\partial}{\partial x}(K_x w \frac{\partial T}{\partial x}) \equiv \oint \langle N\rangle w K_x \frac{\partial T}{\partial x} dy - \iint_A w K_x \langle N_{,x}\rangle \frac{\partial T}{\partial x} dxdy \qquad \text{(B-13)}$$

where $\langle N_{,x}\rangle$ is the derivative of the shape function $\langle N\rangle$ with respect to x.

When the relationships of the type shown in Equation (B-13) are substituted into Equation (B-12), we arrive at the general statement of the finite element form of the governing equation for GEODYN:

$$\iint w\,[\langle N\rangle\,\{\beta_1\frac{\partial T}{\partial t}+\beta_2\,(u\,\frac{\partial T}{\partial x}+v\,\frac{\partial T}{\partial y})+\sigma_1+\sigma_2\}+K_x\langle N_{,x}\rangle\,\frac{\partial T}{\partial x}$$

$$+\,K_y\langle N_{,y}\rangle\,\frac{\partial T}{\partial y}\,]\,dxdy-\oint wK_x\langle N\rangle\,\frac{\partial T}{\partial x}\,dy-\oint wK_y\langle N\rangle\,\frac{\partial T}{\partial y}\,dx=0 \qquad (B\text{-}14)$$

In Equation (B-14) it should be recognized that for all interior element boundaries the line integrals exactly cancel and their net influence at any node is zero, For external element boundaries, however, these terms do not cancel and appropriate boundary conditions must be specified or assumed. Equation (B-14) is the final form of the thermal equation and is the expression coded for solution in the computer code. The equation is numerically integrated for each element in the problem and a system of linear, simultaneous equations developed. These are then integrated in tine to provide the desired temporal and spatial description for temperature. The situation is further complicated by the nonlinear nature of several of the terms in Equation (B-14) as is explained below. Within the context of GEODYN'S formulation, two sources of discontinous nonlinearity exist. These are the step function changes in the material properties which are assumed to take place at the freezing temperature and the isothermal release of a large fraction of latent heat. Since no modeling technique which assumes a .continuous description of system variables (i.e., GEODYN) can easily accommodate discontinuous functions, it was necessary to find appropriate continuous approximations to the discontinuous functions. The way this was done is explained below.

The approach taken to approximate the discontinuous material properties (i.e., specific heat and thermal conductivity) is io use the linear distribution of material properties between the corner node points of any finite element. This approximation is schematically represented in one dimension in Figure (B-5). It should be recognized that this distribution can be fairly complicated in a two-dimensional element, and changes with time, temperature, and within the solution process itself. The approximation shown in Figure B-5 is the most satisfactory approach tested thus far and has been retained in the present versions of GEODYH.

A second source of nonlinearity arises from the release of latent heat. Recalling that the effects of latent heat are calculated from the expression:

$$\sigma_1=\frac{\lambda}{\Delta t}\,(m_1-m_0) \qquad (3\text{-}15)$$

where σ_1 = the net effective heat source/sink term to represent the effects of the latent heat of fusion (kJ/hr m^3)

λ = the latent heat of fusion for the soil matrix (kJ/m^3)

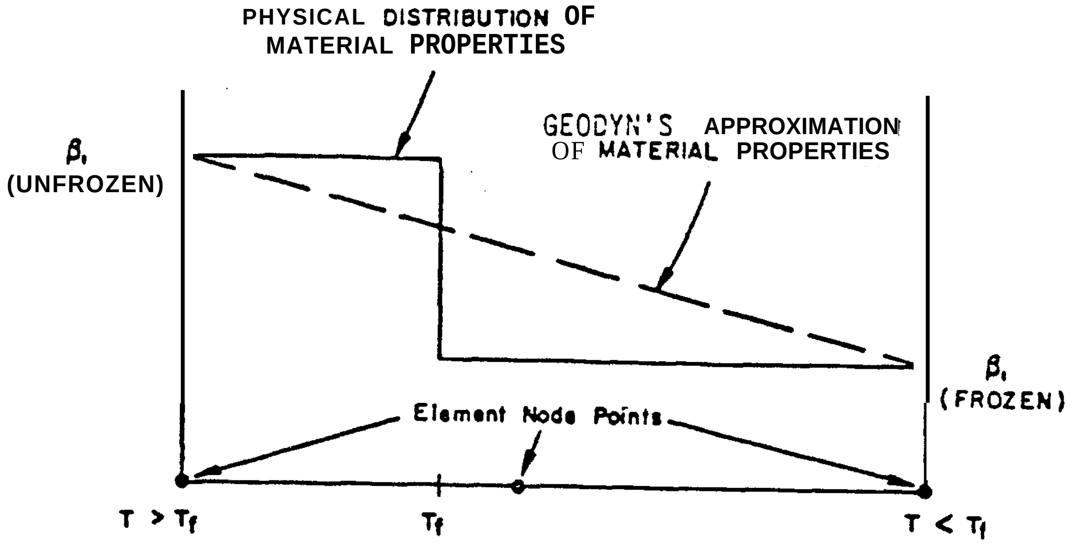


FIGURE 8-5

SCHEMATIC REPRESENTATION OF GEODYN'S APPROXIMATION OF TEMPERATURE DEPENDENT MATERIAL PROPERTIES - ONE DIMENSION

Δt = some finite time interval between times t_0 and t_1 (hr)

m_1 = the unfrozen moisture content of the soil matrix at the end of the time interval t_1 (fraction of total available unfrozen moisture for phase transformation)

m_0 = the unfrozen moisture content of the soil matrix at the beginning of the time interval t_0 (fraction of total available unfrozen moisture for phase transformation)

Also, it is assumed that the unfrozen moisture content of a soil, m, can be approximated as a function of the soil temperature. This relationship has the form:

$$m = \gamma\left(\frac{\alpha}{\alpha+T_f-T}\right)^4 \text{ for } \quad T < T_f$$

(B-16)

$$m = 1.0 \qquad \text{for} \quad T \geq T_f$$

It can be seen from Equation (8-16) that the fraction $(1.0-\gamma)$ of the latent heat is assumed to be released isothermally. To overcome this problem, GEODYN makes the assumption that the isothermal range can be approximated by a narrow linear range as suggested in Figure B-6. In practice, the finite offset range, ε, can be specified to a small value (i.e., 0.1°F) depending on the nature of the soil and the value of γ.

where γ = the fraction of the soil moisture not frozen isothermally at the freezing temperature (fraction)

T_f = the freezing temperature, °C

T = the local temperature, °C

α = a coefficient characteristic of a particular soil

Equations (8-15) and (E-16) have been incorporated into GEODYN. The sign of σ_1 depends on whether the soil is heating or cooling. For example, if the soil is heating, m_1 will be greater than m_0, and the effects of latent heat will tend to slow the temperature rise. In the form written, σ enters as a positive number, which is correct. The reverse argument holds true for cooling, and the appropriate sign is automatically generated by Equation (B-15). The nonlinearity introduced into Equation (B-14) by Equation (B-15) is easily seen. The final tern of Equation (8-14) is the surface flux term. These terms may enter Equation (8-14) either as known and specified values or as functions of the surface heat flux. When formulated as functions of the meteorologi-

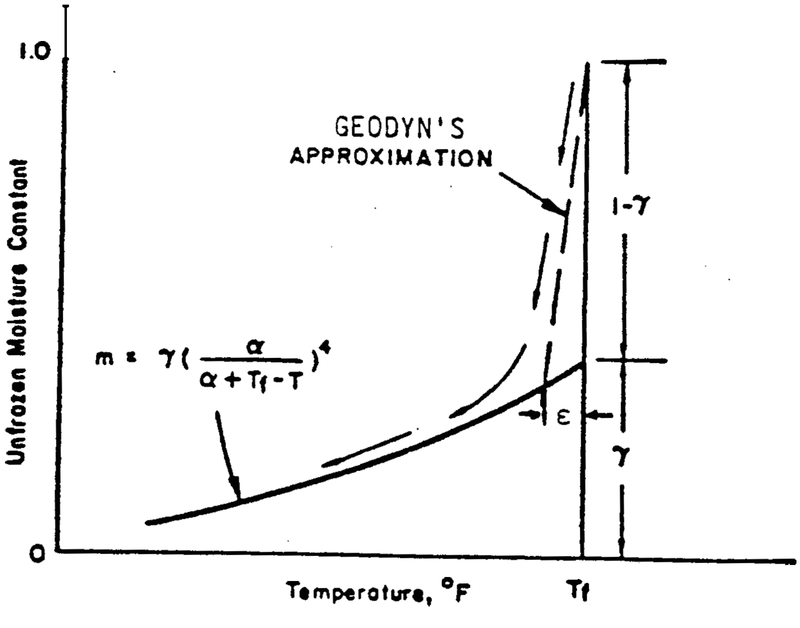


FIGURE B-6

SCHEMATIC REPRESENTATION OF GEODYN'S
APPROXIMATION TO THE ISOTHERMAL
RELEASE OF LATENT HEAT

cal variables and surface temperatures such terms enter the formulation in the general form:

$$\sigma_2 = aT_s + bT_s^n + c \qquad (B\text{-}16a)$$

where T_s is the local surface temperature, and a, b, c and n are constants which depend on the meteorologic conditions and the empirical formulas chosen for surface heat exchange.

8.5 INTEGRATION IN TIME

Equation (B-14) is valid at all points in space at a particular instant in time. If a steady state solution is desired ($\partial T/\partial t \equiv 0$), the appropriate terms are set to zero and a single solution made of the equations. If a dynamic problem is specified, however, it is necessary to integrate Equation (B-14) in time as well as space. This is accomplished as follows. First, it is assumed that the value of T at a particular point varies over a discrete time interval according to the relationship:

$$T = T_1 + at + bt^{\alpha} \qquad (B\text{-}17)$$

where T_1 = the value of T at the beginning of the time step

T = the value of T at the time t

t = elapsed time from the beginning of the interval

a,b = coefficients

If Equation (B-17) is differentiated, we find:

$$\frac{\partial T}{\partial t} = a + \alpha b t^{\alpha - 1} \qquad (B\text{-}18)$$

which can be substituted into Equation (8-17) to eliminate b:

$$\frac{\partial T}{\partial t} = a + \frac{\alpha}{t}(T - T_1) - \alpha a \qquad (B\text{-}19)$$

We also know that at $t = 0$, $\partial T/\partial t = a$, or $(\partial T/\partial t)_1 = a$. If this relationship is applied, and the subscript 2 is used to denote the value at the end of time interval ($t = \Delta t$), we find:

$$\left(\frac{\partial T}{\partial t}\right)_2 = \frac{\alpha}{\Delta t}(T_2 - T_1) + (1 - \alpha)\left(\frac{\partial T}{\partial t}\right)_1 \qquad \text{(B-20)}$$

Note that if $a = 1$, this reduces to a conventional linear integration scheme and if $\alpha = 2$, the scheme is identical to the quadratic integration method. A value of $a = 1.5$ has been found stable for large time steps and also to give good accuracy.

To incorporate this expression into GEODYN, we make use of the idea that our solution is to be valid at a particular instant in time (the end of the time step), and that complete information is available for T and its time derivative at the beginning of the time step. This being the case, Equation (-20) can be rearranged as:

$$\left(\frac{\partial T}{\partial t}\right)_2 = \frac{\alpha}{\Delta t} T_2 + (1 - \alpha)\left(\frac{\partial T}{\partial t}\right)_1 - \frac{\alpha}{\Delta t} T_1 \qquad \text{(B-21)}$$

or:

$$\left(\frac{\partial T}{\partial t}\right)_2 = \frac{\alpha}{\Delta t} T_2 + p \qquad \text{(B-22)}$$

where $P = (1 - a)(\partial T/\partial t)_1 - \alpha/\Delta t\ T_1$

p = known values at time 2 for time 1

This expression, Equation (B-22) can be substituted directly into Equation (B-14) with the result that the equation is formulated completely in terms of values of T at the end of the time step. Once the solution for T has been found, the value of the time derivation, Equation (B-21) can be calculated in a recursive fashion. The values of T and its time derivative thus become the "**old**" values used to define p for the next time interval.

B.6 INTEGRATION IN SPACE

It can be seen that Equation (8-14) implies a system of integral equations which must be evaluated in the solution process. For reasons of speed and efficiency, these equations are integrated numerically rather than analytically in GEODYM. A brief explanation of numerical integration is as follows.

The process of numerical integration is the evaluation of the function at specified locations within an element and then multiplying the value of the function by appropriate weighting factors and summing the result, i.e.,

$$\iint_A g\,(x,y)\,dxdy \cong \sum_{i=1}^{q} \Omega_i\, g\,(x_i,y_i) \qquad (B\text{-}23)$$

where Ω_i = a specified weighting factor

x_i, y_i = the specified coordinate locations for evaluation of g

q = the number of integration points

In this process, x_i and y_i are invariant with respect to actual shape of the element. Appropriate numbers of points and their locations for given orders of error are available in the literature. In GEODYN a three-point scheme is used on linear elements, with higher order schemes used on triangles and quadrilaterals. Typical locations and weighting factors for two dimensional elements in GEODYN are indicated in Figure (B-7).

B.7 CURVED ELEMENTS

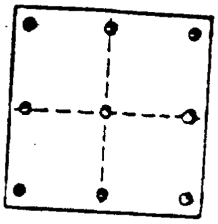
GEODYN has the added feature that the sides of any of its elements (linear, triangular, or quadrilateral) ray take on a curved shape. This is accomplished by means of a coordinate transforcation as outlined below.

Recalling that basic finite element definition takes the form $\phi = \langle N\rangle\{\phi^e\}$, it seems logical to consider the idea that the coordinates of an element could also be expressed in terms of a shape function, say $\langle N'\rangle$, and its specified coordinate points. If this is the case we can write:

$$x = \langle N'\rangle\,\{x^e\} \qquad (B\text{-}24)$$

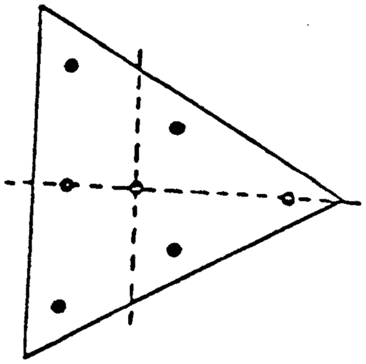
$$y = \langle N'\rangle\,\{y^e\} \qquad (B\text{-}25)$$

When the shape functions for the coordinates are equal to the shape functions for the state variables ($\langle N'\rangle = \langle N\rangle$) the elements are said to be iroparametric; this is the case in GEODYN.



(x_i, y_i)	Ω_i
$(0,0)$	16/81
$\left(\pm\sqrt{\frac{3}{5}}h, \pm\sqrt{\frac{3}{5}}h\right)$	25/324
$\left(0, \pm\sqrt{\frac{3}{5}}h\right)$	10/81
$\left(\pm\sqrt{\frac{3}{5}}h, 0\right)$	10/81

Numerical Integration
For Quadralaterals



(x_i, y_i)	Ω_i
$(0,0)$	270/1200
$\left(\left(\frac{\sqrt{15}+1}{7}\right)h, 0\right)$	$\frac{155-\sqrt{15}}{1200}$
$\left(\left(\frac{-\sqrt{15}+1}{14}\right)h, \pm\left(\frac{\sqrt{15}+1}{14}\right)\sqrt{3}h\right)$	
$\left(\left(-\frac{\sqrt{15}-1}{7}\right)h, 0\right)$	$\frac{155+\sqrt{15}}{1200}$
$\left(\left(\frac{\sqrt{15}-1}{14}\right)h, \pm\left(\frac{\sqrt{15}-1}{14}\right)\sqrt{3}h\right)$	

Numerical Integration
For Triangles

FIGURE B - 7

NUMERICAL INTEGRATION RELATIONSHIPS

Next, we wish to develop the expressions ncessary to transform the arbitrarily specified, curved sided elements into a standard form in order that we may carry out an efficient solution to the problem. To do this, we recognize first that two transformations are necessary. Since $\langle N \rangle$ is defined in terms of the local coordinates, the first transformation is necessary to devise a means expressing the global derivatives in terms of the local derivatives. The Second transformation is used to define the surface over which the numerical integration is to be carried out.

For example, consider a set of local coordinates (associated with the numerical integration elements) ξ, η, and a corresponding set of global coordinates x and y. By usual rules of partial differentiation the ξ derivative of the shape function is:

$$\frac{\partial N_i}{\partial \xi} = \frac{\partial N_i}{\partial x}\frac{\partial x}{\partial \xi} + \frac{\partial N_i}{\partial y}\frac{\partial y}{\partial \xi} \tag{B-26}$$

If this process is carried out for all terms in two dicensions, in matrix form we have the expression:

$$\left\{\begin{matrix} \dfrac{\partial N_i}{\partial \xi} \\ \\ \dfrac{\partial N_i}{\partial \eta} \end{matrix}\right\} = \begin{bmatrix} \dfrac{\partial x}{\partial \xi} & \dfrac{\partial y}{\partial \xi} \\ \\ \dfrac{\partial x}{\partial \eta} & \dfrac{\partial y}{\partial \eta} \end{bmatrix} \left\{\begin{matrix} \dfrac{\partial N_i}{\partial x} \\ \\ \dfrac{\partial N_i}{\partial y} \end{matrix}\right\} = [J] \left\{\begin{matrix} \dfrac{\partial N_i}{\partial x} \\ \\ \dfrac{\partial N_i}{\partial y} \end{matrix}\right\} \tag{B-27}$$

The left-hand side can be evaluated as the functions of N_i and are specified in local coordinates. Further, as x and y are explicitly given by the relation defining the curvilinear coordinates, the matrix [J] can be found explicitly in terms of the local coordinates. This matrix is known as the Jacobian matrix.

To find the global derivatives we invert [J] and write:

$$\left\{\begin{matrix} \dfrac{\partial N_i}{\partial x} \\ \dfrac{\partial N_i}{\partial y} \end{matrix}\right\} = [J]^{-1} \left\{\begin{matrix} \dfrac{\partial N_i}{\partial \xi} \\ \dfrac{\partial N_i}{\partial \eta} \end{matrix}\right\} \tag{6-23}$$

In terms of the shape function defining the coordinate transformation we have:

$$[J] = \begin{bmatrix} \Sigma \frac{\partial N'_i}{\partial \xi} x_i & \Sigma \frac{\partial N'_i}{\partial \xi} y_i \\ \Sigma \frac{\partial N'_i}{\partial \eta} x_i & \Sigma \frac{\partial N'_i}{\partial \eta} y_i \end{bmatrix} \qquad \text{(B-29)}$$

or

$$[J] = \begin{bmatrix} \frac{\partial N'_1}{\partial \xi} & \frac{\partial N'_2}{\partial \xi} & \cdots \\ \frac{\partial N'_1}{\partial \eta} & \frac{\partial N'_2}{\partial \eta} & \cdots \end{bmatrix} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} \qquad \text{(B-30)}$$

or, in the case of a two dimensional element:

$$[J] = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \qquad \text{(B-31)}$$

For which we can find the expression:

$$[J]^{-1} = \frac{1}{\det [J]} \begin{bmatrix} J_{22} & -J_{12} \\ -J_{21} & J_{11} \end{bmatrix} \qquad \text{(B-32)}$$

and $\det [J] = J_{11} \; J_{22} - J_{12} \; J_{21}$

To transform the variables and the region with respect to the integration is a process which involves the determinant of [J]. For instance:

$$dxdy = \det\ [J]\ d\xi\ d\eta \tag{B-33}$$

This type of transformation is valid irrespective of the number of coordinates used. For its justification the reader is referred to standard mathematical texts.

We have now reduced the evaluation of the element properties to that of finding integrals of the form:

$$\int_{-1}^{1}\int_{-1}^{1} [G(\xi,\eta,\zeta,)]\ d\xi\ d\eta \tag{B-34}$$

If the curvilinear coordinates are of the normalized type. Indeed, the integration is carried out within the normalized area and not in the complicated distorted shape, thus accounting for the simple integration limits.

B.8 NONLINEAR SOLUTION TECHNIQUES

In its initial phases, the Finite Element method was used strictly for linear problems but stress analysts soon become interested in solving for stresses in materials with nonlinear stress-strain response curves. Research and development led to two basic approaches to these nonlinear problems: incremental methods and single step iterative methods.

In the first approach the physics of the system are recognized and the structure is assumed to be loaded in small increments. A linear solution with modified properties is made at each solution step. The advantage of this method is that it eliminates uncertainties about uniqueness of the solution by modeling the physical process. However, making the solution steps small enough can make the computer time prohibitive for some problems.

Using the second approach a succession of linear solutions are made which approximate the full problem. Between each solution the properties of the system are varied depending on the particular iterative technique employed. For the geothermal problem no simple physical interpretation of nonlinearity is possible and the Method of Successive **Approximations** must be **used.**

In general terms, the finite element formulation for the geothermal equations can be written as:

$$[K]\ \{T_n\} + [D(T)]\ \{T_n\} - \{R\} = 0 \qquad (8\text{-}35)$$

where $[K]$ = the contribution of linear terms

$[D(T)]$ = the contribution of nonlinear terms

$\{T_n\}$ = a generalized variable vector

$\{R\}$ = a right-hand side vector

To solve these equations, GEODYN employs the so-called Newton-Raphson iteration procedure. To do this, the Newton-Raphson procedure replaces Equation (8-35) with a derivative approach based upon the error of the first solution. If an error function f is defined as:

$$\{f^m\} = [K]\ \{T_n^m\} + [D(T^m)]\ \{T_n^m\} - \{R\}$$

and solution is based upon solving for the correction, AT, to the previous solution, then:

$$[J^m]\ \{\Delta T_n^{m+1}\} = \{f^m\}$$

where $\{u_n^{m+1}\} = \{u_n^m + \Delta u_n^{m+1}\}$

and $\left[J_{ij}^m\right] = \left[\dfrac{\partial f_i^m}{\partial T_j}\right]$

$[J^m]$ is the so-called Jacobian of the system at step m, and terms of this matrix indicate the instantaneous slope of the functions f with respect to changes in each of the variables. Actual solution thus consists of evaluating all the error functions $\{f\}$, and computing the corrections to $\{T\}$ based upon the instantaneous slopes to eliminate all the errors.

Graphically the Newton-Raphson procedure may be represented in one degree of freedom with values of f following the curve 0-0 (see Figure 8-8), by the following steps:

1. Point 1 represents the initial guess T_i
2. Point 2 represents the value of the function f for T_i
3. Point 3 represents the adjusted value of T based upon the slope at 2
4. Point 4 represents the adjusted value of f etc. until convergence is achieved at point 9

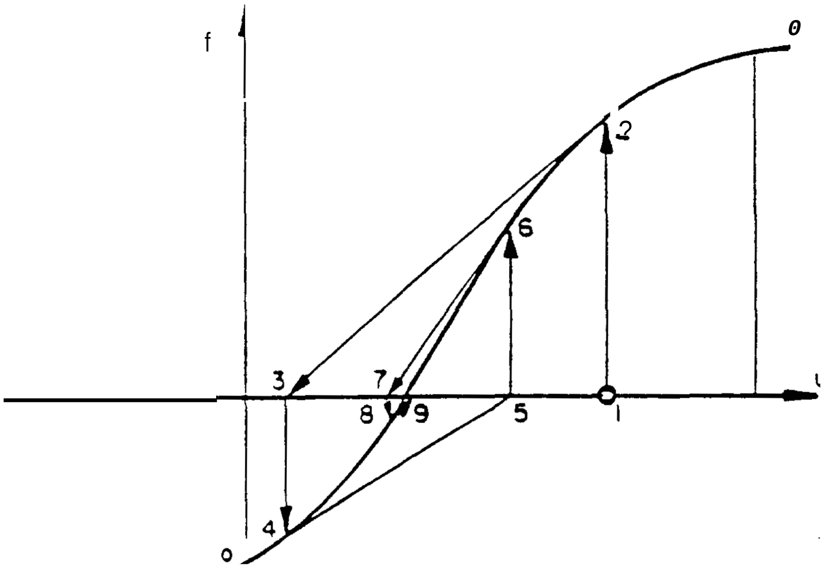


FIGURE *8-8*

NEWTON-RAPHSON ITERATIVE CONVERGENCE·
ONE DIMENSIONAL FUNCTION

Note that in a multi degree of freedom system there are n values for f and each f has n slopes. The solution process must therefore adjust all n values of f simultaneously by variation of the n variables.

APPENDIX C

NUMERICAL TESTING AND EXAMPLE PROBLEMS

C.1 INTRODUCTION AND DESCRIPTION OF PROBLEMS

To demonstrate the operation of GEODYN, the results from three test problems are reproduced in the following paragraphs. Please note that all inputs and outputs in these problems are given in English units, the units in which GEODYN was originally developed.

In summary, the test problems are as follows:

Test Problem No. 1

The first test problem simulates the freezing of a soil which is initially at 36.0°F by application of a 14.0°F boundary condition at the soil surface. This problem is fully described in Jumikis (1977). The anaytical solution for the temperature versus depth profile after 168.0 hours and the rate of movement of the freeze front are provided in the reference. .

Test Problem No. 2

Problem Number 2 is a solution to the transient heat conduction problem in cylindrical coordinates including the effects of phase change. This is a slightly revised version of the problem described on page 295 of Carslaw and Jaeger, and its solution has been reported by several other investigators. This problem is designed to simulate the rise in temperature in an initially frozen soil by introduction of a specified heat flux at the origin of the system,

Test Problem No. 3

The final example problem documents the operation of GEODYN when simulating a phase change problem with an active convective field. The test problem is that of a cold pipe in a relatively large soil mass. This problem is thought to be representative of what could be found where a cold pipeline crosses a stream.

Details of these three problems are presented in the following paragraphs; please note that the description of each problem begins on a separate page of text.

C.2 RESULTS FROM EXAMPLE PROBLEMS

C.2.1 Test Problem No. 1

The first test problem simulates the freezing of a soil which is initially at 36.0°F by application of a 14.0°F boundary condition at the soil surface. This problem is fully described in Jumikis (1977), and is schematically represented in Figure C-1. The analytical solution for the temperature versus depth profile after 168.0 hours and the rate of movement of the freeze front are provided in the reference.

To simulate this problem the network shown in Figure C-2 was prepared with the network generation option of a network preprocessor program **(GEOGRD)**. This network has 18 elements, 93 node points and one type of soil; the network is twelve feet long and two feet wide. The relevant material properties were specified as:

$K_x = K_y =$ 1.34 (frozen conductivity) BTU/ft-hr-°F

$K_x = K_y =$ 1.07 (unfrozen conductivity) BTU/ft-hr°F

$\beta_1 =$ 29.30 (frozen heat capacity) BTU/ft^3 · °F

$\beta_1 =$ 42.70 (unfrozen heat capacity) BTU/ft^3 · °F

$\lambda =$ 2966.4 (latent heat) BTU/ft^3

The problem was run for ten constant time steps of 1.75 days (42 hours) using $\varepsilon = 9.10$. A comparison between the analytic and numeric solution for the soil temperature profile after 7 days (168 hours) is shown graphically in Figure C-3, and in a tabular form in Table C-1. A comparison between the analytic and numeric predictions of the position of the freeze front is provided in Figure C-4 and summarized in Table C-2.

Review of Figures C-3 and C-4 and Tables C-1 and C-2 indicate a high degree of agreement between GEODYN's and Neumann's analytical solution for the problem. After 168.0 hours of elapsed time, both the position of freeze front and the overall temperature profile are nearly identical between the two solutions. At longer times there are larger, but still small, deviations between the two methods as shown in Figure C-4. It is believed that these small discrepancies can be attributed to the minimum spatial resolution available in the finite element network (approximately 0.15 feet) and to the way isothermal phase change is approximated. The encouraging aspect of Figure C-4 is that there is no tendency for the two solutions to diverge, and that the overall solution was smooth and convergent.

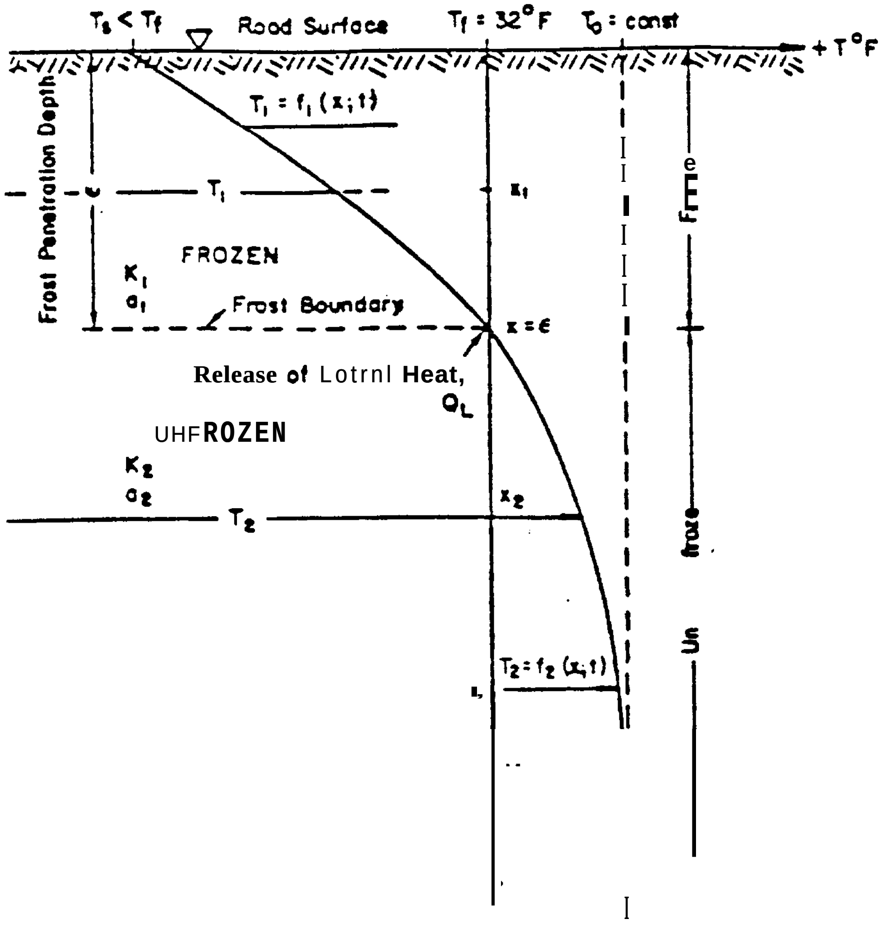


FIGURE C-1

SCHEMATIC DEFINITION OF THE CONDITIONS FOR TEST PROBLEM NO. 1

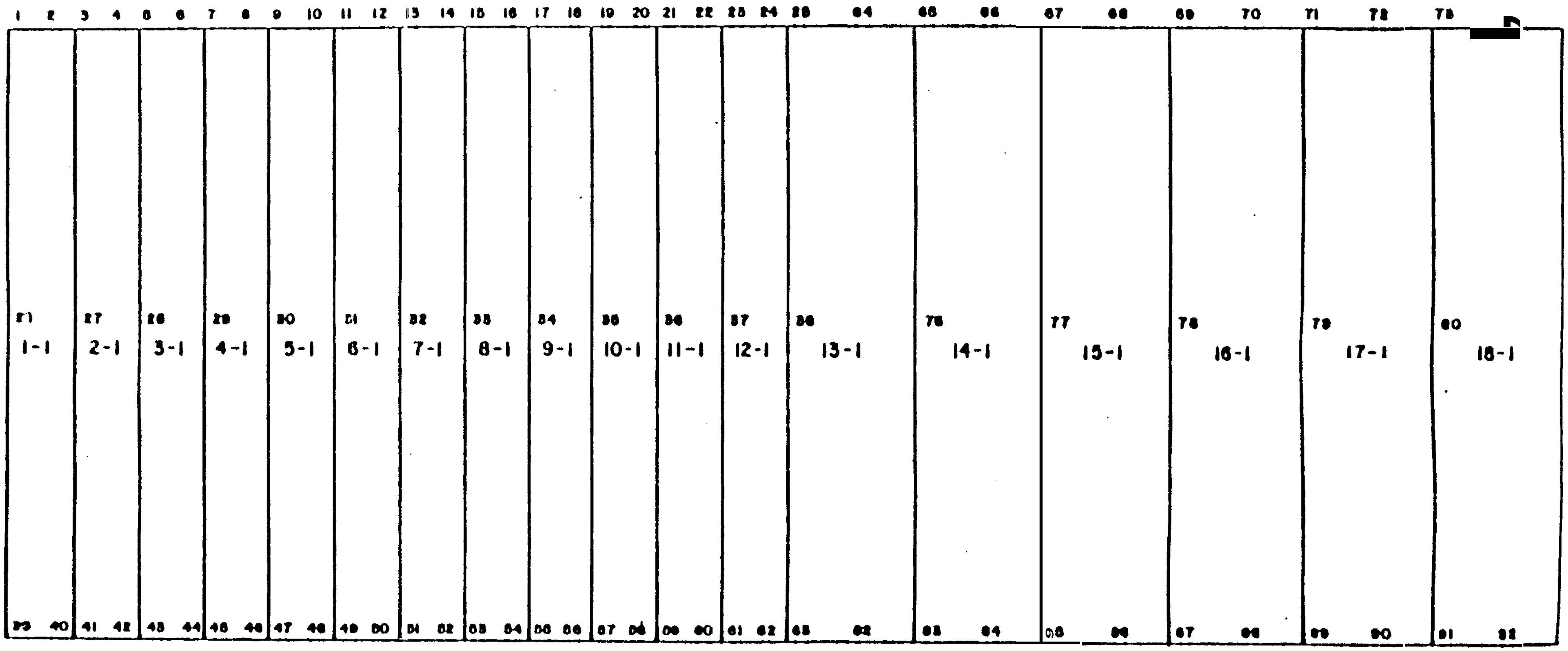


FIGURE C-2

FINITE ELEMENT NETWORK USED FOR TEST PROBLEM NO 1
(length = 12.0 feet, height = 2.0 feet)

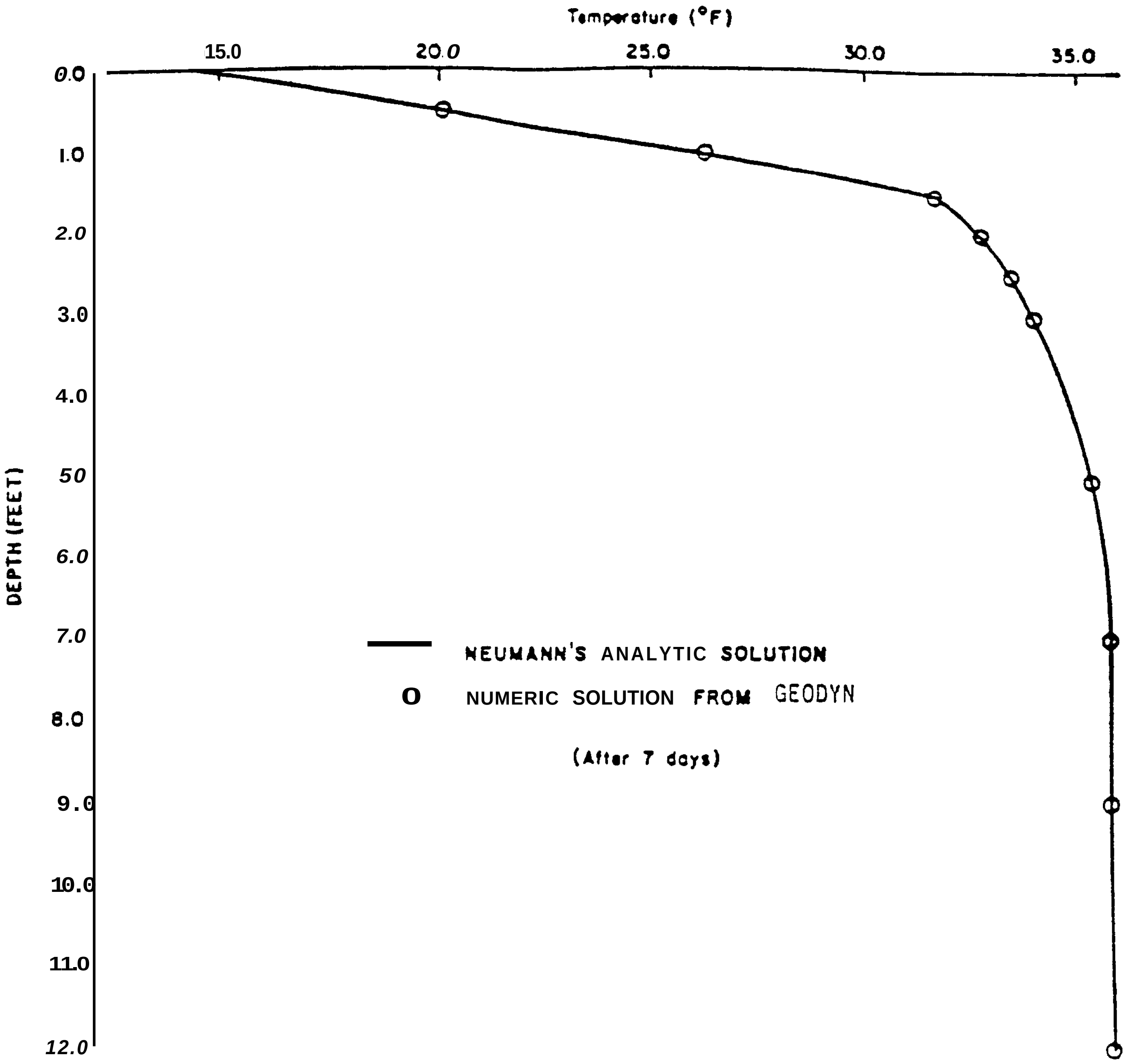


FIGURE C-3

COMPARISON OF ANALYTIC AND NUMERIC
SOLUTIONS FOR TEST PROBLEM NO. 1

TABLE C-1

COMPARISON OF ANALYTIC AND NUMERIC SOLUTIONS FOR TEST PROBLEM NO. 1 (after 7 days)

DEPTH (feet)	ANALYTIC SOLUTION (°F)	NUMERIC SOLUTION (°F)
8.00	14.000	14.000
0.50	20.190	20.172
1.00	26.000	26.296
1.50	31.800	31.818
1.52	32.000	---
1.57	---	32.000
2.00	32.800	32.688
3.00	34.000	33.393
4.00	34.900	34.914
5.00	35,400	35.463
8.00	35.900	35.965
10.00	35.997	35.933

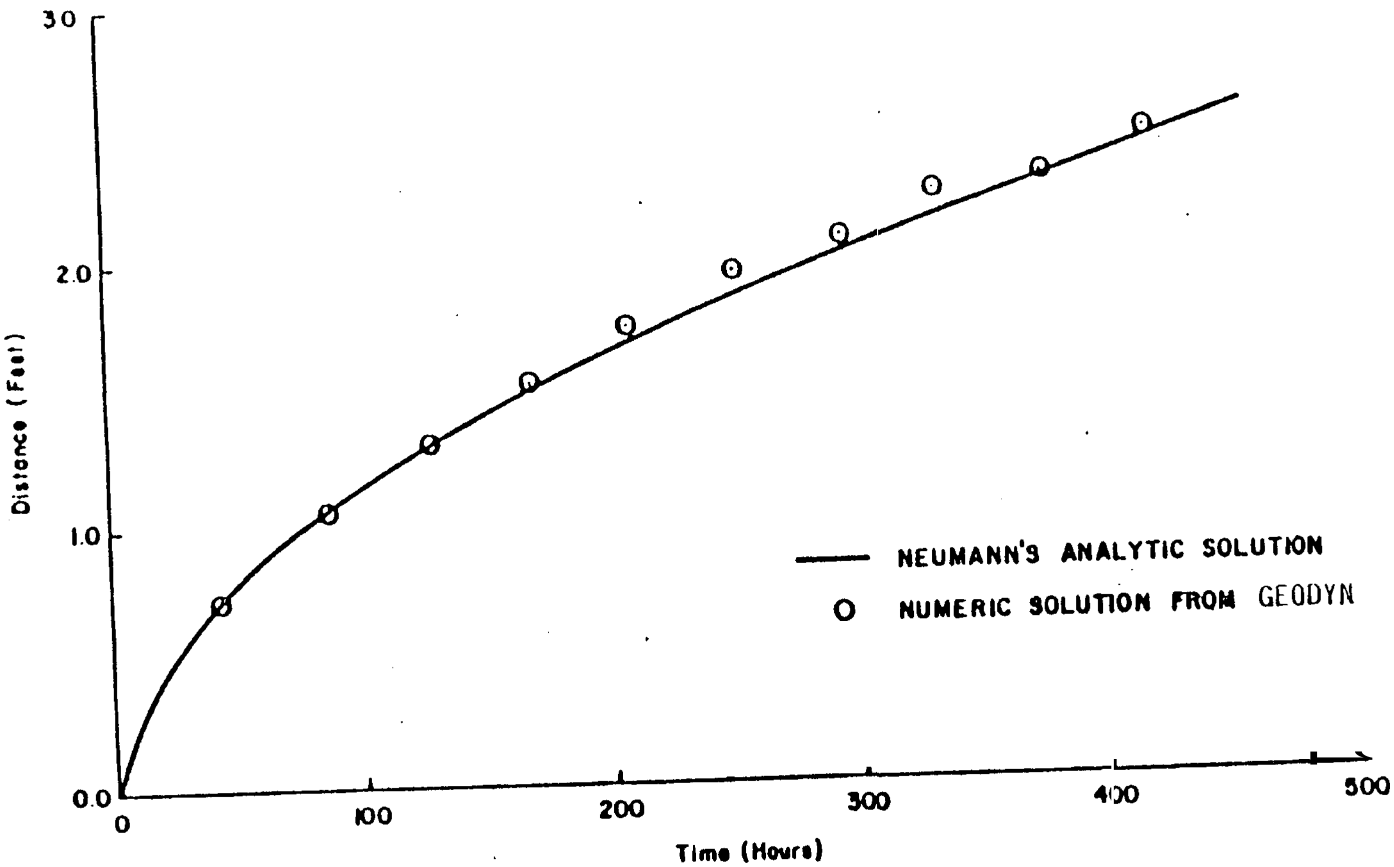


FIGURE C-4

COMPARISON OF ANALYTIC AND NUMERIC POSITIONS
OF THE FREEZE FRONT FOR TEST PROBLEM NO. 1

TABLE C-2

COMPARISON OF ANALYTIC AND NUMERIC POSITIONS OF THE FREEZE FRONT FOR TEST PROBLEM NO. 1

TIME (hours)	ANALYTIC DISTANCE (feet)	NUMERIC DISTANCE (feet)
42.0	0.76	0.75
84.0	1.08	1.07
126.0	1.32	1.34
168.0	1.52	1.57
252.0	1.86	1.35
294.0	2.01	2.07
336.0	2.15	2.25
378.0	2.28	2.27
420.0	2.41	2.45

C.2.2 Test Problem No. 2

Problem Number 2 is a solution to the transient heat conduction problem in Cylindrical coordinates including the effects of phase change. This is a slightly revised version of the problem described on page 295 of Carslaw and Jaeger, and its solution has been reported by other investigators.

This problem is designed to simulate the rise in temperature in an initially frozen soil by introduction of a specified heat flux at the origin of the system. The parameters used in this problem were:

K_f = 1.5 BTU/ft-hr-°F (frozen conductivity)
K_t = 1.0 BTU/ft-hr-°F (thawed conductivity)
C_f = 40 BTU/ft^3-°F (frozen heat capacity)
C_t = 50 BTU/ft^3/°F (thawed heat capacity)
L = 3003 BTU/ft^3 (latent heat)
t_f = 32.0°F (temperature at phase change)
Q = 7000 BTU/day (input heat flux)

According to Carslaw and Jaeger, the location of the melt front is given by the expression:

$$(tK_t/C_t)^{1/2}$$

where R = the location of the melt front (feet)

t = time (hrs)

λ = a coefficient depending on the physical properties problem which has been found to have a value of 0.4218 for the values indicated

To simulate this problem, a cylindrical network was constructed for input to the model. This network extended from r = 0.2 feet to r = 33.2 feet, and had unit height. The elements had a nominal r dimension of one foot to r = 18.2 and a dimension of 4.0 feet from 18.2 to 38.2 feet.

The input flux of 7000 BTU/day was specified over a finite area at r = 0.2 feet, and 99 percent of the latent heat was assumed to be exhausted over a temperature range of 0.1°F. The problem was simulated for a total of 500 days with gradually increasing tine steps which varied from 2.0 to 12.0 days in length.

The results of the simulation are presented graphically in Figures C-5. and C-6. Figure C-5 provides a comparison of the numeric and analytic calculations of the position of the melt front, while Figure C-6 indicates the numeric and analytic temperature profiles at times of 196.0 and 500.0 days. The analytic calculations of the temperature and profiles were computed from the equations presented on page 295 of Carslaw and Jaeger.

In both Figures C-5 and C-6, the numeric and analytic solutions are seen to be quite comparable. The position of the melt front is well within the limits of resolution of the finite elenent network (approximately 0.15 feet), and shows no sign of oscillation or any other undesirable or unexpected behavior. The temperature profiles are also in good agreement in shape and magnitude and would seem to confirm tne operation of the program. The results from this problem confirm the operation of GEODYN in cylindrical coordinates for problems with phase change.

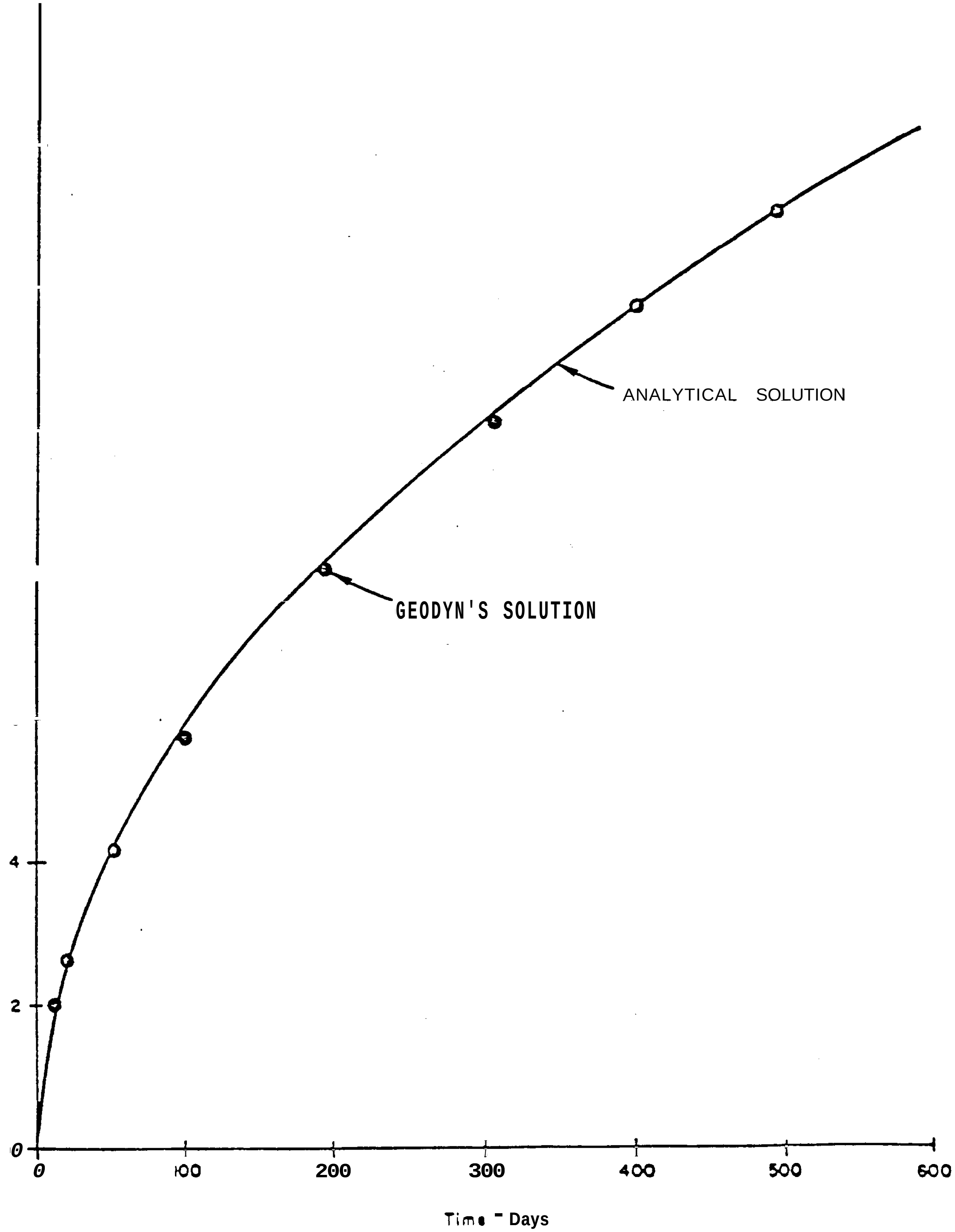


FIGURE C-5

POSITION OF THE 32° ISOTHERM
FOR PROBLEM NO. 2

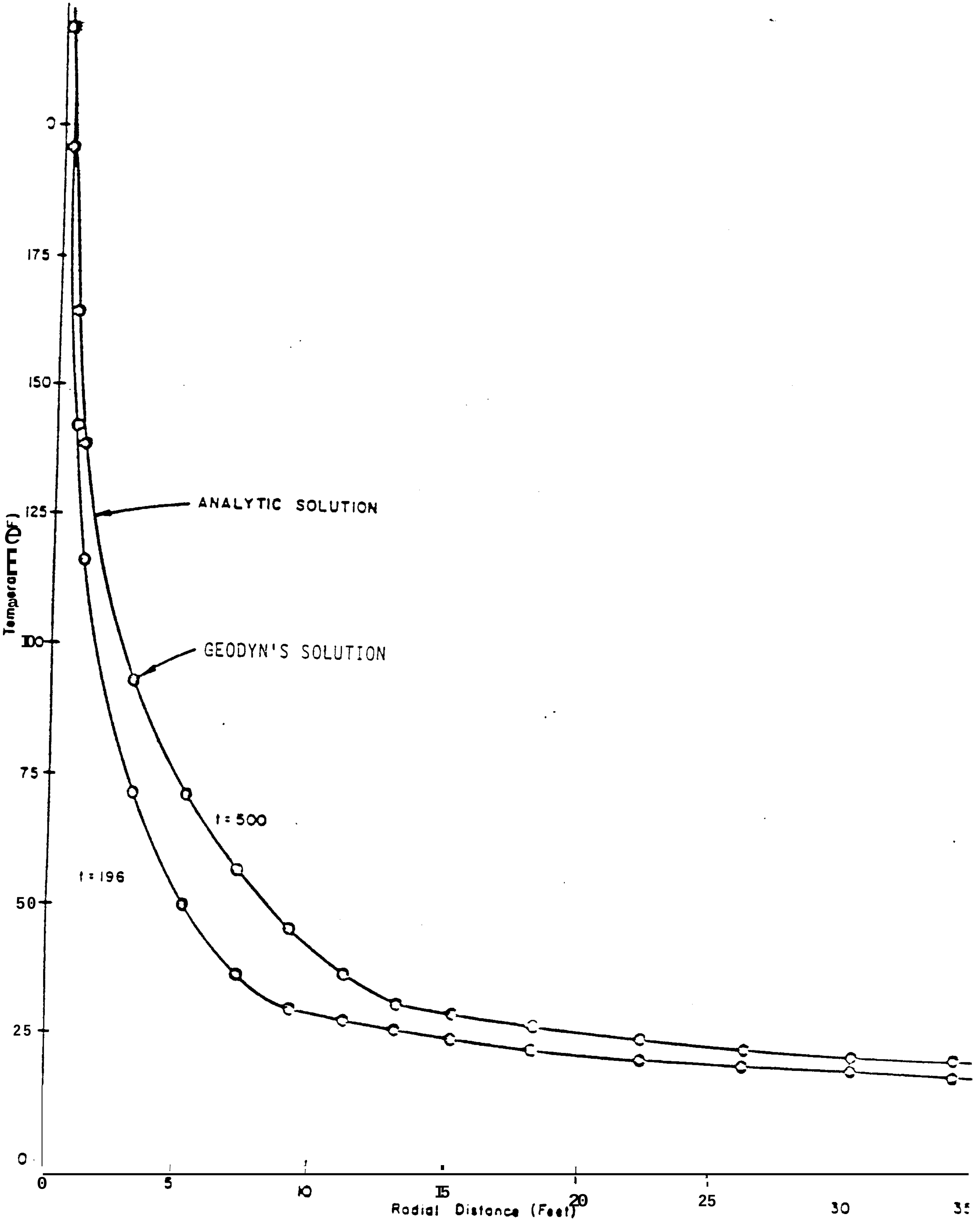


FIGURE C-6

COMPARISON OF ANALYTIC AND NUMERIC SOLUTIONS FOR PROBLEM NO. 2

C.2.3 Test Problem No. 3

The intent of this problem is to provide documentation on GEODYN when simulating a phase change problem with an active convective field. It should be understood that the user must specify the convective velocities as the model is not yet capable of simulating the physical movement of groundwater. The model accepts the input velocities and makes no further calculations on tne convective field except to set the velocities to zero if the local temperature falls below the freezing temperature. The reader should be aware that as moisture freezes in particular parts of a given system there will be local violations of flow continuity. This effect will undoubtedly cause some errors in the temperature predictions, but such effects are judged to be small for the examples presented.

The test problem is that of a cold pipe in a relatively large soil mass. This problem is thought to be representative of what could be found where a natural gas pipeline crosses a stream.

The test problem was set up using the finite element network shown in Figure C-7 with the following specifications:

- An overall network size of 34 feet horizontally and 30 feet vertically
- Pipe diameter of 4.0 fest
- Top surface at a constant temperature of 33°F
- Left face at a constant temperature of 32.1°F
- Right face and bottom surface at zero gradient
- For active convection, a constant flow velocity from left to right

The physical parameters used for the problem are the following:

- Pipe properties (shaded area in Figure C-7)

Frozen $K = 0.137$ BTU/hr/ft/°F
Thawed $K = 0.137$ BTU/hr/ft/°F
Frozen $C = 0.1$ BTU ft^3
Thawed $C = 0.1$ BTU ft^3
$\alpha = 1.0$
$\lambda = 1.0$
$\varepsilon = 0.1$

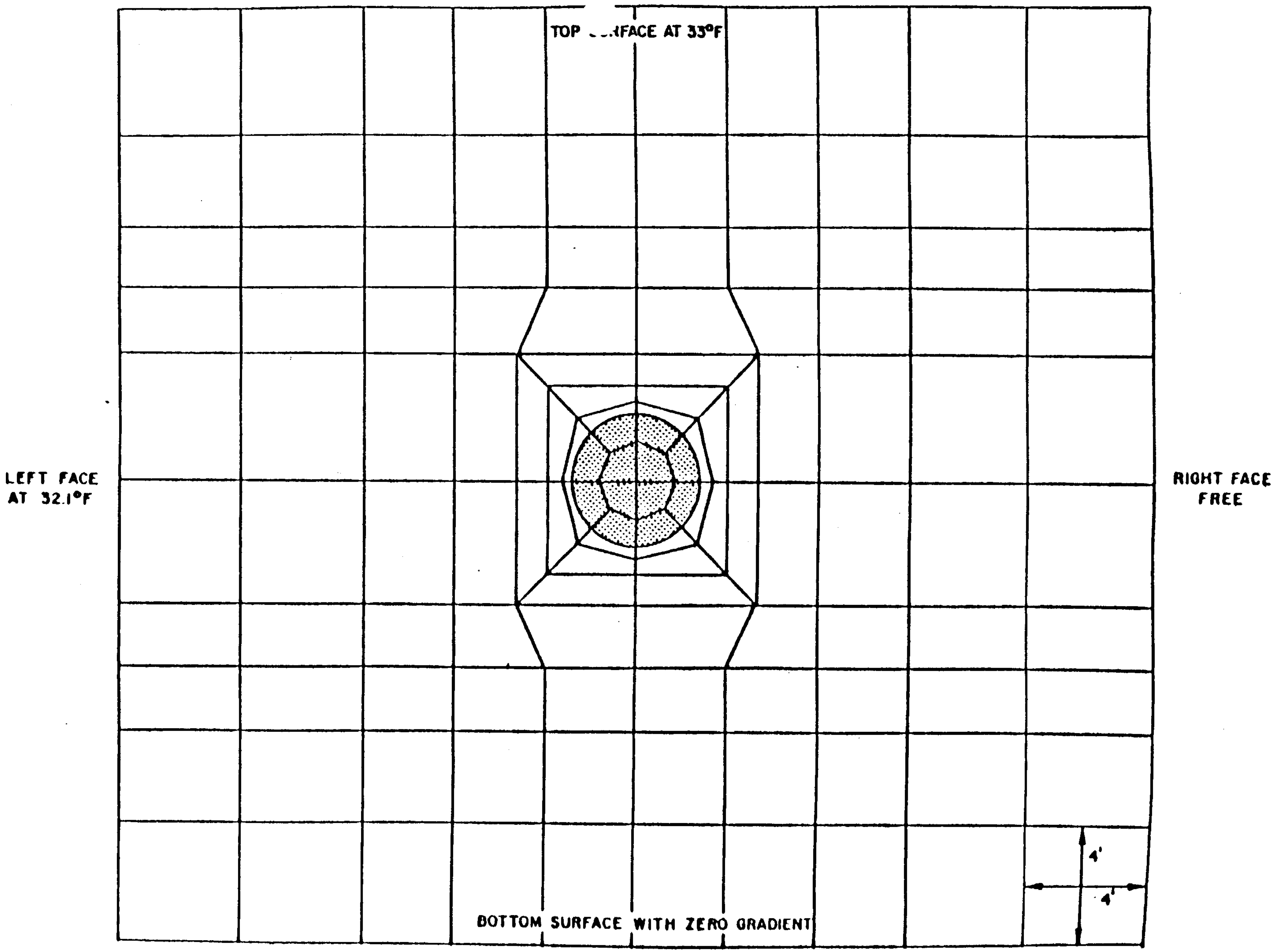


FIGURE C-7

FINITE ELEMENT NETWORK FOR CONVECTIVE PROBLEMS

- ***Soil*** properties (all unshaded area in Figure 2-14)

Frozen K = 0.62 BTU/hr/ft/°F
Thawed K = 0.62 BTU/hr/ft/°F
Frozen C = 28 BTU ft^3
Thawed C = 28 BTU ft^3
$\alpha = 1.0$
$\lambda = 1.0$
$\varepsilon = 0.1$
porosity = 0.4
net g.w. velocity = 0.25 ft/day horizontally; vertical velocity zero in all **cases**

To demonstrate the operation *of* GEODYN with and without convective effects, two simulations were carried with the above parameters. In each case the simulations were run dynamically for a total of 180 days in 20 time steps which varied in length from 2 to 14 days. Both simulations were carried out using pipe temperatures *of* 31°F, with and without an active convective field.

The results from the two simulations is presented in graphical format in Figures C-8 to C-9. The results are presented as contour plots of temperature after 180 days *of* simulation and were prepared with RMA's post-processor, program **GEOPLT**. Please note that on each plot the temperature at five node points has been plotted in numerical format for reference purposes.

Since no analytic solutions are available for this test problem, **it** is not possible to comment on the accuracy of these sinulations. Several other comments are considered appropriate, however, and are provided below:

- In the simulations shown, GEODYN was quite stable and convergent. This is considered a good sign, and provides a great deal of confidence that the coupled problem of heat and moisture transport with phase change can be undertaken with existing algorithms.
- Comparisons between the no convection and with convection problems for the same pipe temperature all show the expected differences even though the differences are small. The effects of convective field increase as the pipe temperature increases, as would be expected.
- In order to show dramatic effects of convection, **it** would be required to increase the flow velocities by a substantial amount (say an order of magnitude). This can be done if

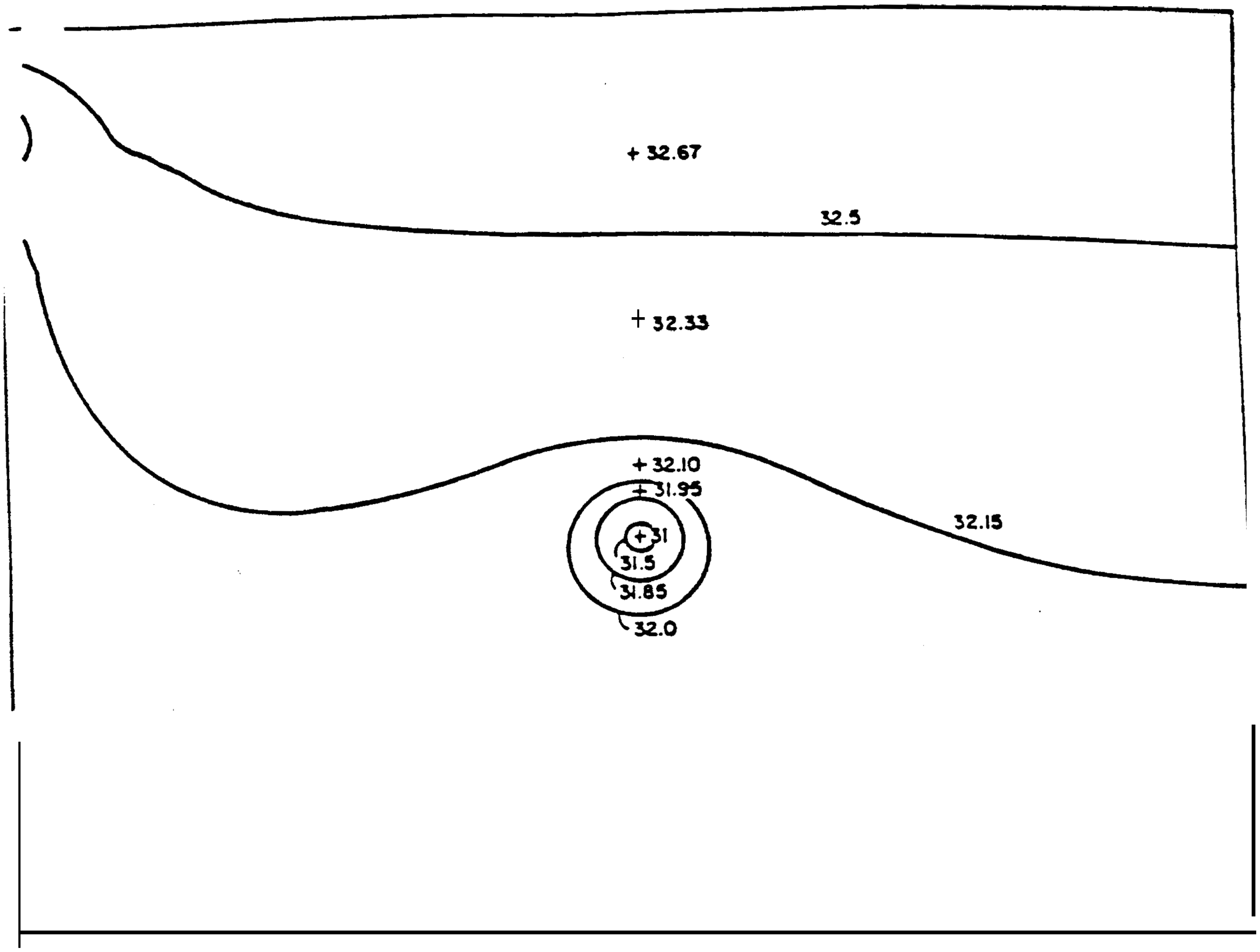


FIGURE C-8

31°F PIPE - NO CONVECTIVE FLOW

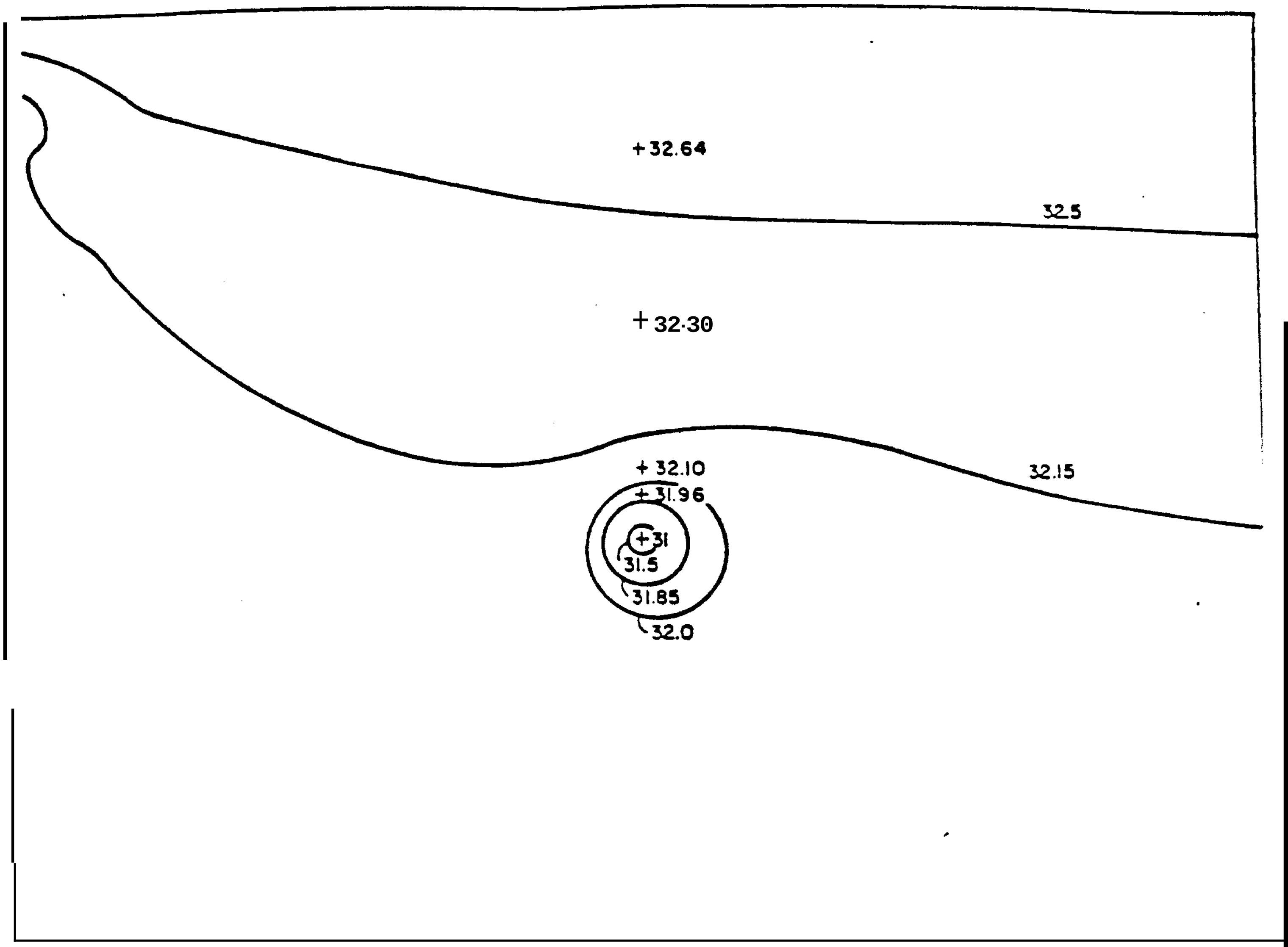


FIGURE C-9

31°F PIPE WITH CONVECTIVE FLOW

desired, although the results herein are sufficient to document the operation of the convective terms.

In the process of developing Problem Number 3, it was found that GEODYN (and, presumably, other models) was sensitive to how accurately the geometry of the pipe was specified. In other words, if the geometry of the pipe was not specified to a reasonable degree of accuracy, the resulting freeze front contours for the no convection cases would not be circular. This problem was resolved in GEODYN by careful specification of the pipe coordinates. In models which employ a nonisoparametric formulation this could be a substantial limitation near the pipe. This should be kept in mind when simulating exacting thermal problems.

APPENDIX H

GEOPLT

Operating Instructions

OPERATING INSTRUCTIONS FOR THE
COMPUTER PROGRAM GEOPLT

A Program for Contouring Temperature Fields
Produced by the GEODYN Program

by

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LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The purpose of the GEOPLT program is to produce contour plots of the temperature- fields generated by the geothermal simulation program, GEODYN. GEOPLT is not a simulation program, but rather a postprocessor in RMA's geothermal modeling system.

The current capabilities of GEOPLT are the following:

- Input and interpret the geometric layout (network) used by the GEODYN program,
- Plot the outside boundary of the network.
- Plot user-defined contour values within the area of interest (which may be smaller than the entire network).
- Produce multiple contour plots in a single computer run.

GEOPLT works by superimposing a finite difference grid over the finite element grid, and then producing the contours on the finite difference grid. This system has both advantages and disadvantages, but seems to be well suited to the needs of the geothermal program.

CHAPTER 2

PROGRAM ORGANIZATION AND DESCRIPTION

GEOPLT cansists of one main routine and several callable subroutines as shown in Figure 2-1. Contour plots are produced by calls to standard Calcomp plotting routines in the various subroutines. Brief descriptions of each of the program routines are provided below in alphabetical order after a description of the main routine. The only exception to this is for the routine called CONTOR. This routine is actually a library of routines which produces a contour plot from a rectangular grid of values. While RMA has successfully adapted them for contouring purposes, they were not written by RMA and have not been documented herein.

MAIN ROUTINE

GEOPLT's execution begins by reading and echo printing (on logical unit 6) the user-specified run control information. These data include the number of plots to compute, the records to use from the GEODYN save file, and the resolution desired in the rectangular grid overlay,

Next, the program inputs the first file record from GEODYN plot file, which contains the geometric information, and checks to see if a subsection of the network is to be contoured. Following this, GEOPLT scales the plot to the user input dimensions and then calls subroutine LOCATE to determine the finite element which contains each rectangular grid point. After returning from LOCATE, the program enters the plotting loop. Within this loop the program reads the GEODYN file and checks to see if a plot is desired. If no plot is desired, the program continues to loop. If a plot is desired, a call is made to subroutine POINTS to place the temperature values on the rectangular grid and then to subroutine BNOIT to draw the network outline. Next, a call is made to VIEWER to complete the contour plot and then to NOTES to annotate the plot. This process is continued until all plot requests have been filled and/or the end-of-file condition is encountered on the GEOOYN input file. In either case the plot file is closed and program execution is terminated.

Subroutine BNDIT

If the user so requests, subroutine BNOIT will plot the outside boundary of the network. This option is used mainly to provide a framework for the plot and to check to see that no internal regions have been omitted from the network. A specified list of node numbers may also be read and plotted.

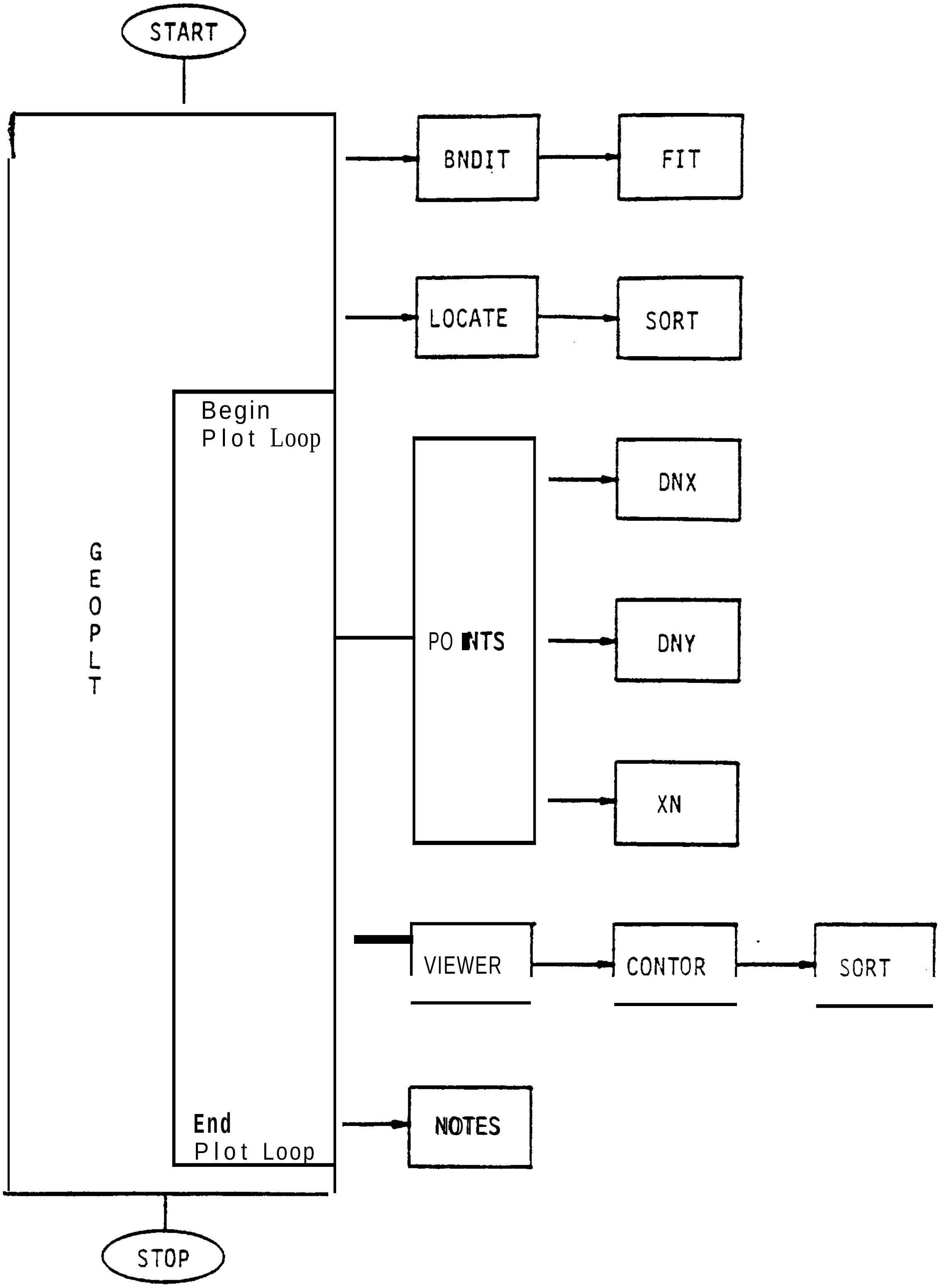

FIGURE 2-1

PROGRAM ORGANIZATION
GEOPLT PROGRAM

Subroutine BNOIT is called from the main program and makes a call to subroutine FIT.

Subroutine CONTOR

Subroutine CONTOR is actually a library of routines which produces a fairly sophisticated contour plot from a given rectangular grid of values. The rectangular grid is supplied to CONTOR in the COMMON block OPTION in the array TF. CONTOR reads the user-defined contour values and plots the contour lines a segment at a time via standard CALCOMP calls.

CONTOR was not written by RMA and is not fully documented herein. A list of the routines which comprise the plotting library is provided below for reference purposes:

CENTER
CONTOR
FINI
FOLLOW
GERBAR
GUIDE
.PIECES
START
TRACER
NUMBR

Subroutine (function) DNX

Subroutine DNX will calculate the value of a particular shape function x-direction derivative at a given location (in local coordinates) for either triangular or quadrilateral finite elements. ONX is called from subroutine POINTS and makes no further calls.

Subroutine (function) DNY

Subroutine DNY will calculate the value of a particular shape function y-direction derivative at a given location (in local coordinates) for either triangular or quadrilateral finite elements. DNY is called from subroutine POINTS and makes no further calls.

Subroutine FIT

When a plot of the network outline is requested, the calling routine generates a list of the nodes which define an element side and the x and y coordinates of these three nodes are passed to FIT. This enables FIT to pass a finite element shape function through the points and to plot, in a piecewise linear fashion, the exact shape of both curved and straight element sides.

Subroutine LOCATE

GEOPLT works by placing a rectangular grid over the user-defined finite element grid. In order to complete this process it is necessary to locate the particular finite element in which any given grid point resides. It is the function of subroutine LOCATE to make this determination —

Computationally, LOCATE begins by entering a loop on all system elements. It then calculates the x and y bounds for the elements and enters a loop on the grid points which may be enclosed by the element. Within this loop, LOCATE solves for the intersection of element side and rectangular grid lines to establish the "in" or "out" condition. If the grid point is "out," a skip is made to the end of the loop. If a point is "in," the condition is recorded in the array IGRID, and computation continues.

Subroutine LOCATE is called from the main routine once in each program execution and makes a further call to subroutine SORT.

Subroutine NOTES

After the basic contour plot and its outline have been completed, subroutine NOTES is called to annotate the plot. Its function is to output to 'the plot the maximum and minimum values found on the rectangular grid, the user specified contours, the time for the plot (from the GEODYN file) and the user provided coment. Subroutine NOTES makes no further calls.

Subroutine POINTS

GEOPLT produces a plot by overlaying a rectangular grid on the finite element grid and contouring from the rectangular grid. In this process it is necessary to find the element in which a rectangular grid point resides (the function of subroutine LOCATE) and to calculate the temperature at the grid point from the finite element shape functions. It is the function of subroutine POINTS to evaluate the temperature at each rectangular grid point from the finite element shape functions and node point temperatures.

To complete this operation, POINTS loops on each grid point in the rectangular network, It has a cross reference for the element in which the grid point resides (array IGRID), and iterates to find the exact local coordinate of the grid point. Once the coordinates are found, the value of the function is found by matrix multiplication of the shape functions.

Subroutine POINTS calls functions DNX and DNY to aid in the location process and function XN to evaluate the temperature. It is called once from the main program for each plot requested.

Subroutine SORT

Subroutine SORT is a Shell type sorting routine that sorts a vector inta ascending order in its own length. The sorting procedure is short, efficient and somewhat abstract, and the reader is referred to standard references for the theory of the Shell sort.

Subroutine SORT is called from subroutine LOCATE in the element definition process and from the CONTOR routines to order the input list of contours. Subroutine SORT makes no further calls.

Subroutine VIEWER

After the values to be plotted have been placed in the working array by subroutine POINTS, subroutine VIEWER is called to copy the values into the appropriate array for contouring. Subroutine VIEWER also initializes certain values neeaed by the contouring routines, and calls the contour routines. VIEWER acts as a contour interface and makes no calculations of its own.

Subroutine VIEWER is called once for each plot, and makes a further call to the contouring routines, CONTOR.

Subroutine (function) XN

Subroutine XN will calculate the value of a particular shape function at a given location (in local coordinates) for either triangular or quadrilateral finite elements. XN is called from subroutine POINTS and makes no further calls.

CHAPTER 3

EXAMPLE PROBLEM

To provide an example of GEOPLT's operation, a test problem has been run and the results are reproduced in the following paragraphs. This test problem is an extension of the test problem which is also presented in the GEOGRO and GEOOYN program documentation reports.

The objective of this example is to make two contour plots from the output file generated by GEODYN. Five contour values will be plotted, and the plot is to be done on a reduced section of the network to increase resolution; file records 4 and 6 from the GEODYN file are to be plotted. An annotated reproduction of the card image input file to **GEOPLT** for this problem is reproduced as Figure 3-1.

The output from GEOPLT for this example problem is reproduced in Figures 3-2 to 3-5, with Figures 3-2 and 3-3 showing the output that went to the line printer (logical unit 6) and 3-4 and 3-5 the two contour plots.

In Figure 3-2, the program produces an echo print of all the input data, including the file and plot specifications, the rectangular grid data, and the network subsection limits, if any. Following this, the list of file records to be plotted from the **GEOOYN** file is read and printed. The program then outputs the results of some internal checks, and prints several messages which are useful in confirming that the proper problem is being run.

Figure 3-3 shows the output that the program produces as the GEODYN files are read and the plots are produced. In this case file record 4 and 6 were to be plotted, and a message is output for each sequential **GEOOYN** file as it is read. When a plot file is reached the program outputs a message and the maximum and minimum grid values calculated in the rectangular overlay plus an echo of the contour specifications. This process is simply repeated until all plot requests have been satisfied or the end-of-file is reached on the input file.

The contour plots produced in this run are shown in Figures 3-4 and 3-5. Each plot shows the requested contours in the upper right corner, and the time from the GEODYN file (in hours) and the user coment in the left corner. The plots are straightforward except for some minor anomalies in some of the contours. This is a manifestation of the grid overlay procedure and sometimes happens when thermal gradients are very small. Note that the outline of the pipe has been plotted in Figure

3-5. The pipe outline demonstrates the line trace option described in Chapter 4 (Card Type E).

```
 1 TEST RUN FOR GEOPLT DOCUMENTATION
 2    64.     2.     1.     55.     55.     1.64.     1.64.     0.     190.     0.     323
 3.    4.     6
 4     0
 5.GEODYN FILE 4
 6      5.      -1..      -0 05.     0.0.     0 05.     0 03
 7.   17
 8      7.  16.  26.  35.  45.  47.  50.  52.  55.  57.  60  62.  63.  56.  27.  17.   8
 9:GEODYN FILE 6
10.     5.      -1..      -0.05.     0.0.     0 05.     0 03
```

```
A. Job Title
B. Job Controls
C. File Record Numbers
D. Plot Outline Control
F. Plot Title
G  Contour Specification
D. Plot Outline Control
E. Specified Line Definition
F. Plot Title
G. Contour Specification
```

FIGURE 3-1

CARD IMAGE INPUT FILE FOR
GEOPLT EXAMPLE PROBLEM

```
                    PROGRAM CEOCRD
          A GEOTHERMAL CONTOURING PROGRAM
                    DEVELOPED BY
          RESOURCE MANAGEMENTS ASSOCIATES
         LAFAYETTE, CALIF -- NOVEMBER 1982


     TEST RUN FOR GEOPLT DOCUMENTATION.. INPUT FILE FROM CEOPYN DOCUMENTATION

 INPUT CEOPYN FILE(LUG)                 64
NUMBER OF PLOTS(LUV)                     2
PLOT OUTLINE OPTION(IBPP)                1
X GRID LINES(NX)                        55
Y GRID LINES(NY)                        55
X CORD SCALE(XSCALE)                   1.6
Y CORD SCALE(YSCALE)                   1.6
MIN X NODE NUM(NXPMIN)                   0
MAX X NODE NUM(NXPMAX)                 190
MIN Y NODE NUM(NYPMIN)                   0
MAX Y NODE NUM(NYPMAX)                 323


     THE FOLLOUINC    2 FILES WILL BE PLOTTED

         4     6


     XMIN =          0.00
     XMAX =          5 18
     YMIN =          0.00
     YMAX =          4 61


NE,NP    100    329
```

FIGURE 3-2

GEOPLT ECHO PRINT OF INPUT **DATA**

```
                    PROCRAM CEOCRD
           A GEOTHERMAL CONTOURING PROCRAM
                    DEVELOPED BY
           RESOURCE MANAGEMENTS ASSOCIATES
          LAFAYETTE, CALIF -- NOVEMBER 1982


 TEST RUN FOR GEOPLT DOCUMENTATION.  INPUT FILE FROM CEODYN DOCUMENTATION

  FILE,TIME,NODES =    1     182.4      417

  FILE,TIME,NODES =    2     364 8      417

  FILE,TIME,NODES =    3     729 6      417

  FILE,TIME,NODES =    4    1094 4      417

 GRID VALUES FOR PLOT   I   FROB FILE    4

 MAX VALUE =      0.055
 MIN VALUE =     -8.310

 CEODYN FILE 4

 CONTOUR INPUT SPECS
5     -1.000    -0 050     0.000     0 030     0.050

  FILE,TIME,NODES =    5    1459 2      417

  FILE,TIME,NODES =    6    1814 0      417

 BOUNDARY NODE POINTS
7    16   26   35   45   47   SO   52   55   S7   60   62   63   36   27   17
a

 GRID VALUES FOR PLOT   2  FROM FILE    6

 MAX VALUE =      0 054
 MIN VALUE =     -8 314

 CEOPYN FILE 6

 CONTOUR INPUT SPECS
5     -1 000    -0 050     0 000     3 030     0 050
```

FIGURE 3-3

GEOPLT OUTPUT **FROM FILE READING**
AND **PLOT GENERATION**

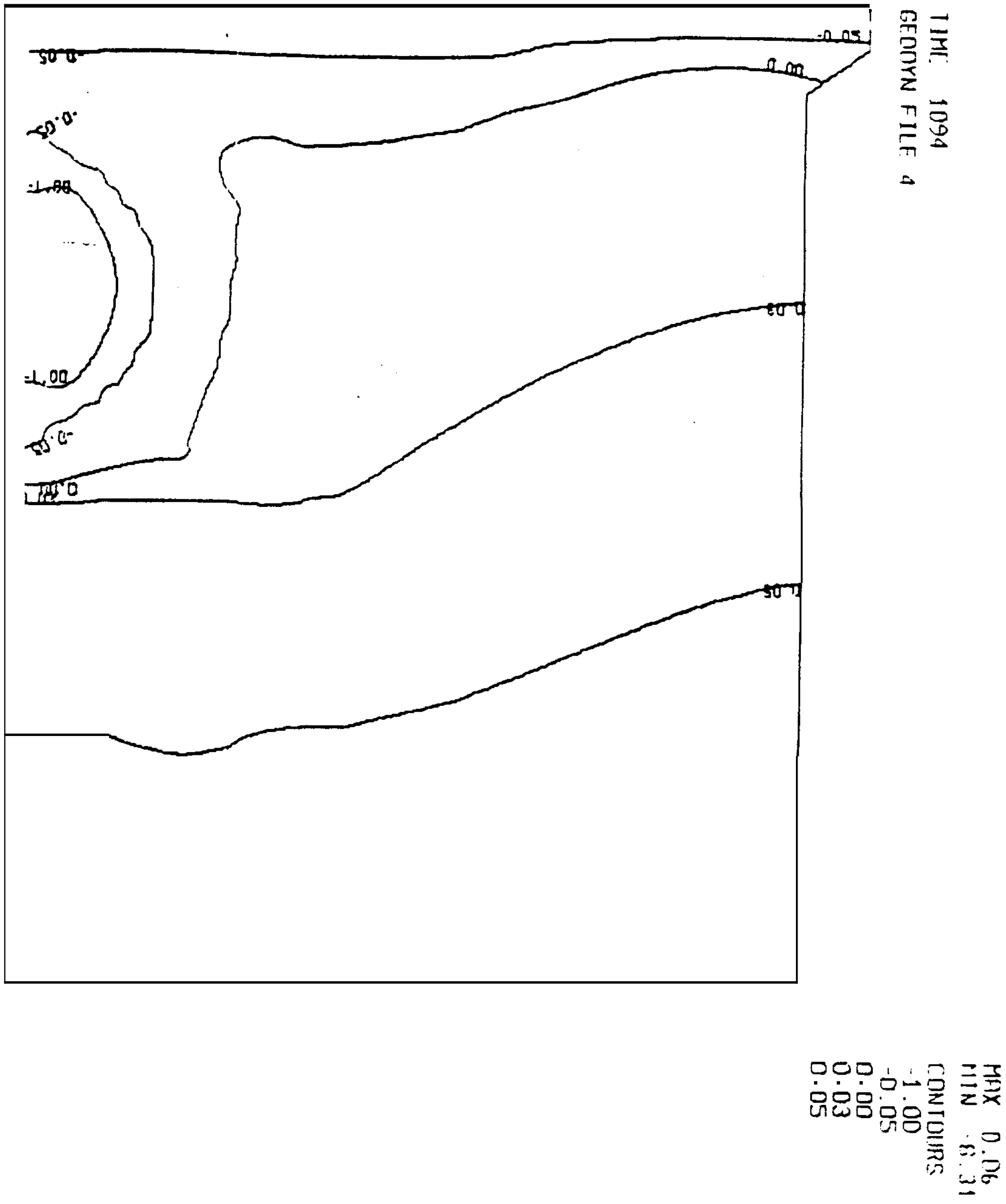

FIGURE 3-4

EXAMPLE CONTOUR PLOT FROM
GEODYN FILE 4

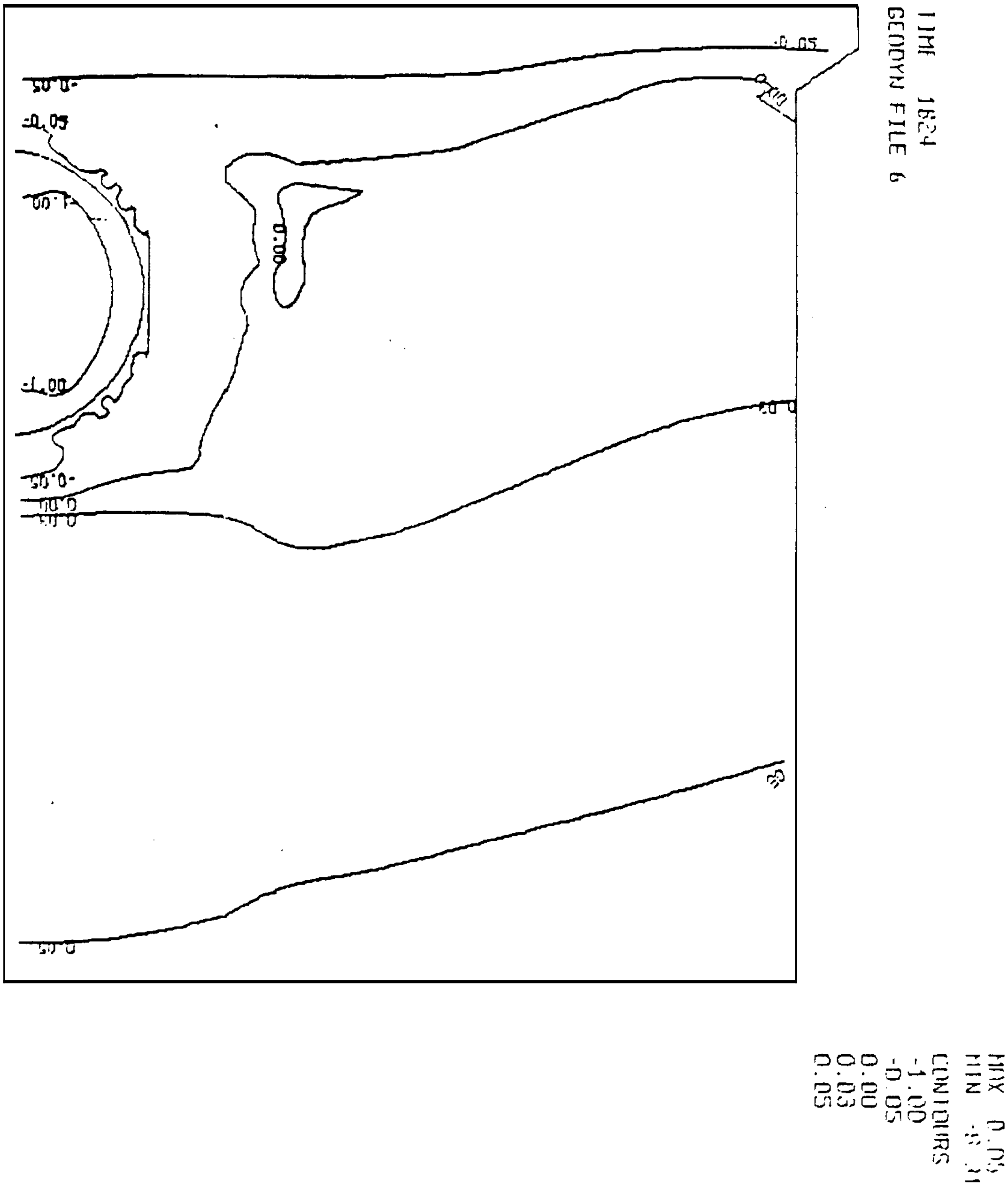

FIGURE 3-5

CONTOUR PLOT **FROM**
GEODYN FILE 6

CHAPTER 4

PROGRAM INPUT INSTRUCTIONS

The input data for GEOPLT are read from the card reader (logical unit 5) and output to the line printer (logical unit 6) and the plotter. The program can be run by using a combination of card image inputs and the output file from program GEODYN. A schematic description of the file units which are required by GEOPLT is shown in Figure 4-1.

DATA INPUT FORMATS

The following paragraphs sumnarize the exact card formats expected by GEOPLT. The user should follow this sequence exactly, and input the data in the same order as it is described. In all cases the program will expect to input this information on FORTRAN logical unit 5 unless otherwise noted. Finally, the reader is urged to review the input and output from the example problem if questions arise.

Please' note that all inputs to GEOPLT are in free field format. This means that all data on a specified card image must be supplied, with individual values separated by blanks or commas. A slash (/) at the end of a line indicates the end of record and may be used to advantage in some cases. If less than the proper number of items are input on a given card image, the program will look at the next card to complete its list. This is a common error in free field input, and must be checked carefully by the user.

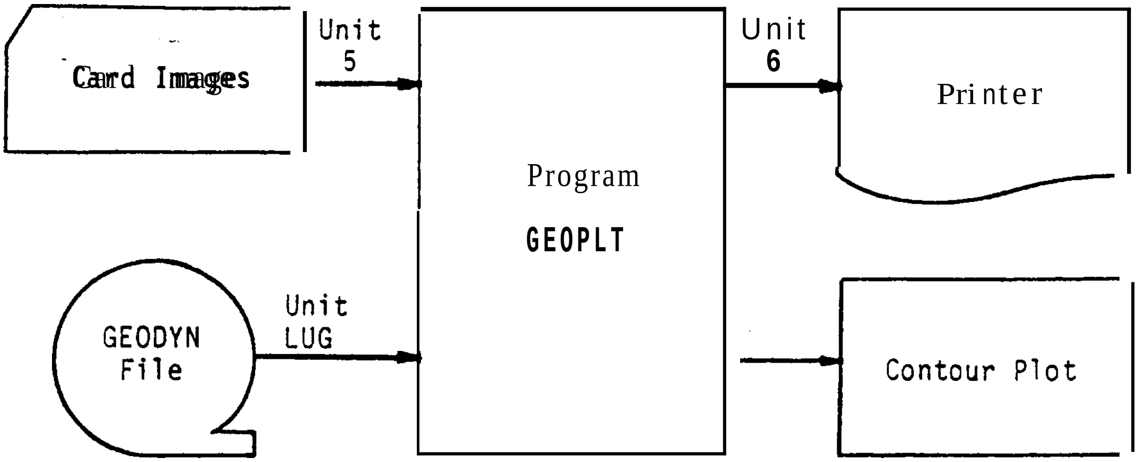

FIGURE 4-1

FILE ORGANIZATION
GEOPLT PROGRAM

CARD TYPE	INPUT SEQUENCE	VARIABLE NAME	DESCRIPTION
A.	Job Title		
	1	TITLE	Any alphanumeric information to be used for run identification. This appears on the printed output only.
B.	Job Controls		
	1	LUG	The FORTRAN logical unit number containing the output file from program GEODYN.
	2	LUV	The number of plots to be made from the GEGDYN output file.
	3	IBPP	Enter 1 if the outer boundary of the network is to be plotted; otherwise enter zero.
	4	NX	Enter the number of X grid lines to be used in the contour generation ($\leq$ 65); if zero, NX is set to 35.
	5	NY	Enter the number of Y grid lines to be used in the contour generation ($\leq$ 65); if zero, NY is set to 35.
	6	XSCALE	A scale factor which multiplies the X coordinate inputs before plotting.
	7	YSCALE	A scale factor which multiplies the Y coordinate inputs before plotting.
	8	NXPMIN	Node number of minimum X location in a partial network plot. If zero, taken as network minimum.
	9	NPXMAX	Node number of maximum X location in a partial network plot. If zero, taken as network maximum.
	10	NPYMIN	Node number of minimum Y location in a partial network plot. If zero, taken as network minimum.
	11	NYPMAX	Node number of a maximum Y location in a partial plot. If zero, taken as network maximum.
C.	File Record Numbers		
	1-100	LIST	A list of the file record numbers (i.e., time step number) to be plotted from the GEODYN file. The number of elements in this 'list is LUV (Card B.2), and they need not be in sequentiel order. Up to 100 values may be input.

CARD TYPE	INPUT SEQUENCE	VARIABLE NAME	DESCRIPTION
D.	Plot **Outline** Control - omit if IBPP (Card B.3) is zero.		
	1	NPTS	If IBPP is greater than zero, there are two options. If NPTS=0, only the network bounday will be plotted. If NPTS≠0, NPTS values will be read and plotted for Card Type E. If NPTS>0, the outline will also be plotted; if NPTS<0 only the input points will be plotted.
E.	Specified Line Definition - omit if NPTS (Card D.1) or IBPP (Card 5.3) is zero		
	1-400	NPB	A list of up to 400 node numbers (following element sides) which describe a line to be placed on the contour plot. This card *is* read only if NPTS≠0. NPTS values will be read.
F.	Plot Title		
	1	LITL	Any 80 column comment which is to appear on the plotted output.
G.	Contour Specification		
	1	NUMV	The number of contours to be attempted for this file. Up to 20 values may be specified.
	2-21		The contour values to be plotted.

NOTE: Card Types D through G are required for each contour plot. A total of LUV (Card 8.2) sets are required.