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Nodal Network Generator for CAVE 3

Joseph V. Palmieri and Kenneth A. Rathjen

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ILLUSTRATIONS

ILLUSTRATIONS (Contd)

SUMMARY

Grumman, under contract NAS1-14643, developed the computer code CAVE3 ("A General Transient Heat Transfer Computer Code Utilizing Eigenvectors and Eigenvalues") that performed a specialized transient thermal analysis. Under the present funding a new extension of CAVE3 was developed which automates the creation of the input.

The new software:

- Utilizes Tektronix 4014 Graphic Scopes to display models
- Utilizes Tektronix Tablet Digitizers to generate model geometry
- Graphically displays the model geometry
- Creates a finite difference digital dataset with all conduction links computed ready for input to CAVE3.

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Section 1

INTRODUCTION

The Network Generator software created for Langley Research Center automates the creation of finite difference thermal models for input to the CAVE3 code provided Langley under contract NAS1-14643. The software makes use of the interactive capabilities of the INTERCOM CDC timesharing system on the Langley Research Center CDC 6600 computer. It utilizes the Tektronix 4014 Graphic Scope and digitizing interface and makes use of the appropriate Tektronix software resident in the Plot-10 package. The Network Generator utilizes the graphics hardware to expedite the transformation of geometric data to digital data and provides visual confirmation of geometric and nodal networks.

The Network Generator is broken into two distinct programs: geometric data input and model generation. The geometry data input software is labeled NNDIG and makes use of Tektronix digitizing hardware to create a data set containing the pertinent geometric information needed. This option provides the user with the capability to transfer geometric data from a scaled diagram displaying the model to be analyzed to the computer as a digital data set. This software does not have to be run if the user wants to generate the resultant geometry file by hand (if digitizing hardware were not available).

In either case, the geometry is fed to the model generation program (NNGEN). It is here that the actual finite difference model is created. NNGEN uses the geometry supplied to it with the specific properties of the materials to be analyzed and creates the digital data set that represents the finite difference model. Software establishes the numbering sequence, determines all geometric voids within the model, and bookkeeps all couplings. The software can generate two- or three-dimensional models and provides the user with the ability to have internal or boundary (surface) nodes.

Mr. James L. Hunt of the High Speed Aerodynamics Division, Langley Research Center, Virginia, served as the NASA technical monitor for the program.

At Grumman, the contract was administered by the Advanced Development office under Mr. Fred Berger, Manager of Advanced Development System Engineering, Dr. Kenneth A. Rathjen was Study Manager and Mr. Joseph V. Palmieri was Engineering Specialist, Software Development.

Section 2

NODAL NETWORK GENERATOR DESCRIPTION

The Nodal Network Generator package was created to automate the procedure of creating a digital math nodal to be used as input to the CAVE3 code (Reference 1). The package consists of two distinct programs; a Nodal Network Digitizing (NNDIG) program and a Nodal Network Generator (NNGEN) program. The package makes use of the Tektronix digitizing tablet and graphic scope (Model 4014) to transfer geometric nodal information directly to the computer and plot the resulting nodal network.

The program enables a user to create a math model by merely digitizing the vertices of homogeneous sectors and digitizing a grid increment that defines the nodal surface. The program will automatically compute the geometric centroid of the nodal areas and place the nodes there, then automatically compute all the nodes each node sees, the conductance between nodes, the capacitance of the node, and the radiation area of the node surfaces in the x, y, and z direction. The program will determine whether the body has voids within it and will establish boundary nodes to identify this condition.

The program has two nodal options that can be employed; nodes can be placed at the centroids for all nodes or placed at the surface for boundary nodes with the conductances adjusted for the distance from the surface to the centroid. The program also provides a three-dimensional feature which allows the user to create a three-dimensional regular model. The sections to follow will explain all of these features in detail.

Once the software has been accessed and executed, the Nodal Network Generator will create an input file capable of being run with CAVE3. The only change to the data that may have to be made would be to include the boundary conditions using the areas created by the program, include interface conductance effects if desired, and incorporate any radiation couplings.

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Section 3

PROBLEM SETUP & PROGRAM LIMITATIONS

The first step in the development of a thermal math model is the creation of the nodal model on paper. Here the user can superimpose a nodal grid on the physical boundaries of the object to be analyzed. The Nodal Network Generator needs this first step as the engineer did in establishing a digital math model. The graphic representation of the nodal network must meet certain criterion before it can be used in conjunction with NNDIG. Consider Figure 1, a structure made up of a number of different materials. Each block shown (I - VI) represents a sector. This will be explained later. The geometry should first be laid out in a convenient orientation relative to a righthand Cartesian coordinate system. Because the Nodal Network Generator only analyzes regular three-dimensional shapes, we need only be concerned with the top view of the structure.

The external boundaries of the object should then be drawn to scale (Figure 2). Once the perimeter has been established, the body itself should be broken down into sectors. Sectors are defined as homogeneous divisions of the body being analyzed and having isotropic properties within the sector bounds. The sector can have no more than 15 vertices and all angles must be convex, i.e., no internal angle can exceed 180°. The body itself can have no more than 20 sectors. The geometry displayed in Figure 2 was broken up into six sectors. All sectors have uniform thickness normal to the plane of the paper. Sectors I and II are made up of the same material (steel) and have identical properties as are sectors III and IV (aluminum). Sectors V (steel) and VI (aluminum) have unique properties of their own. Notice that although Sectors I and II or III and IV have identical properties and would have met the homogeneous and isotropic rule as one sector, they had to be broken up into two independent sectors because an internal angle exceeded 180°.

With the sectors and sector vertices identified, it is now necessary to establish a network grid. The Nodal Network Generator is designed to set up rectangular and/or triangular nodes. The node boundaries are established by the grid size and its interaction with the physical boundaries of the model. The network grid is a system of lines

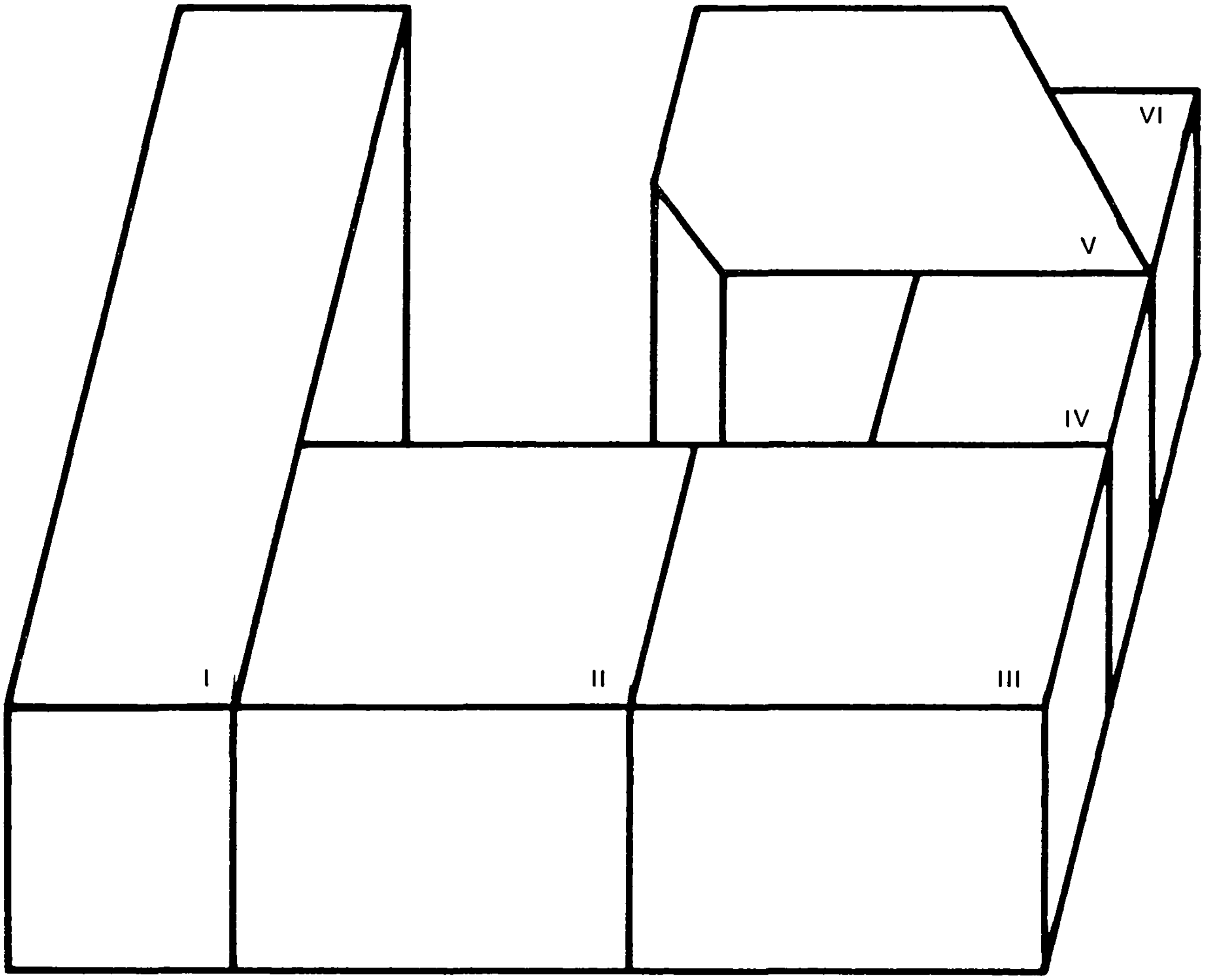

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FIG 1. STRUCTURE TO BE ANALYZED

parallel to the x and y axes that delineates the node boundaries of the body. The grid lines must be established running parallel to the x and y axis and will ultimately define the actual node size.

To establish a grid, the user must assure that:

- Each vertex will be intercepted by a grid line in both the x and y direction
- Each sector surface that is intercepted by a grid line must also be intercepted at that point by the orthogonal grid line. (This ensures that sloped boundaries of a sector are divided into triangular nodes and not trapezoidal nodes)

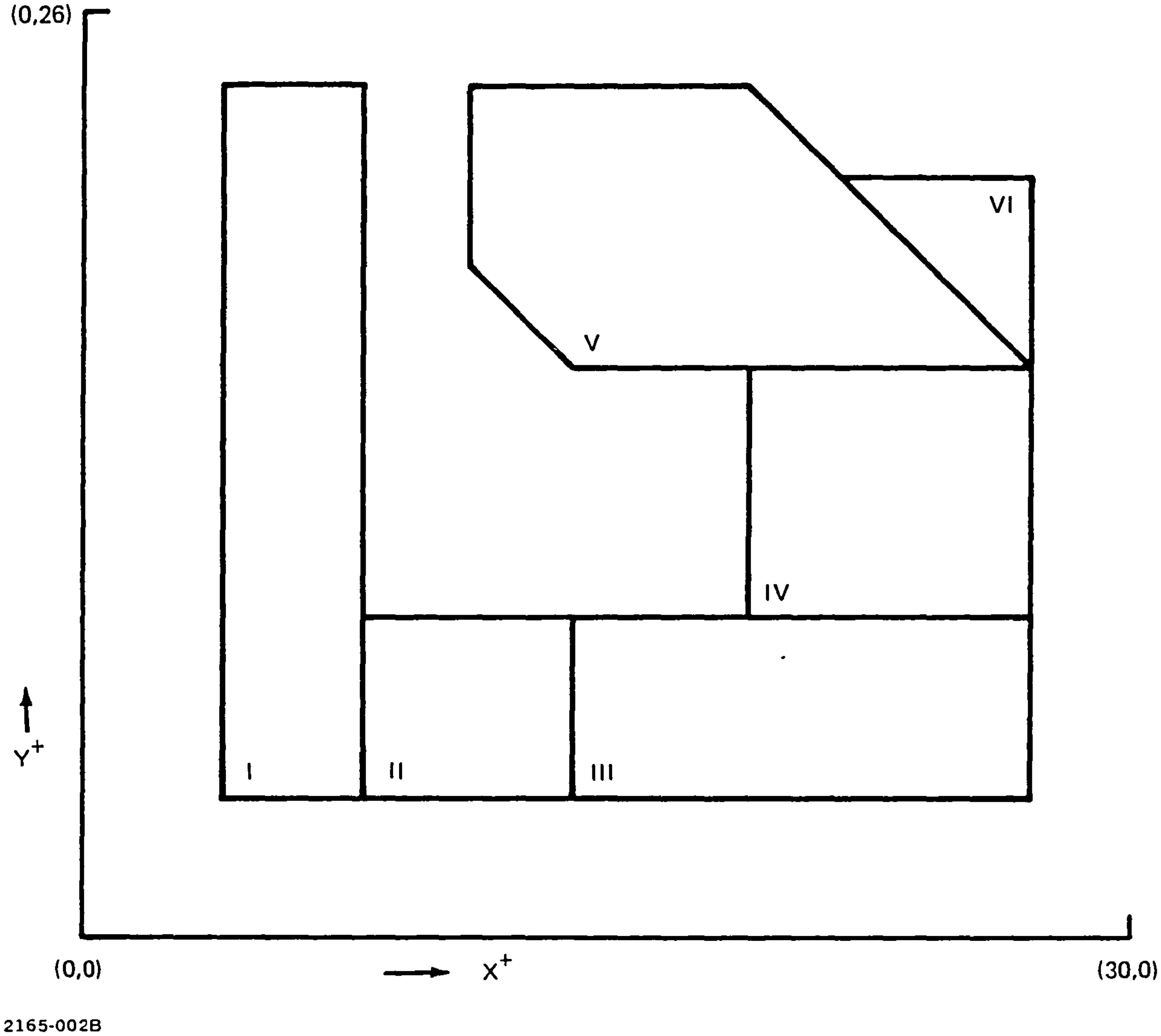


FIG. 2 MODEL LAYOUT

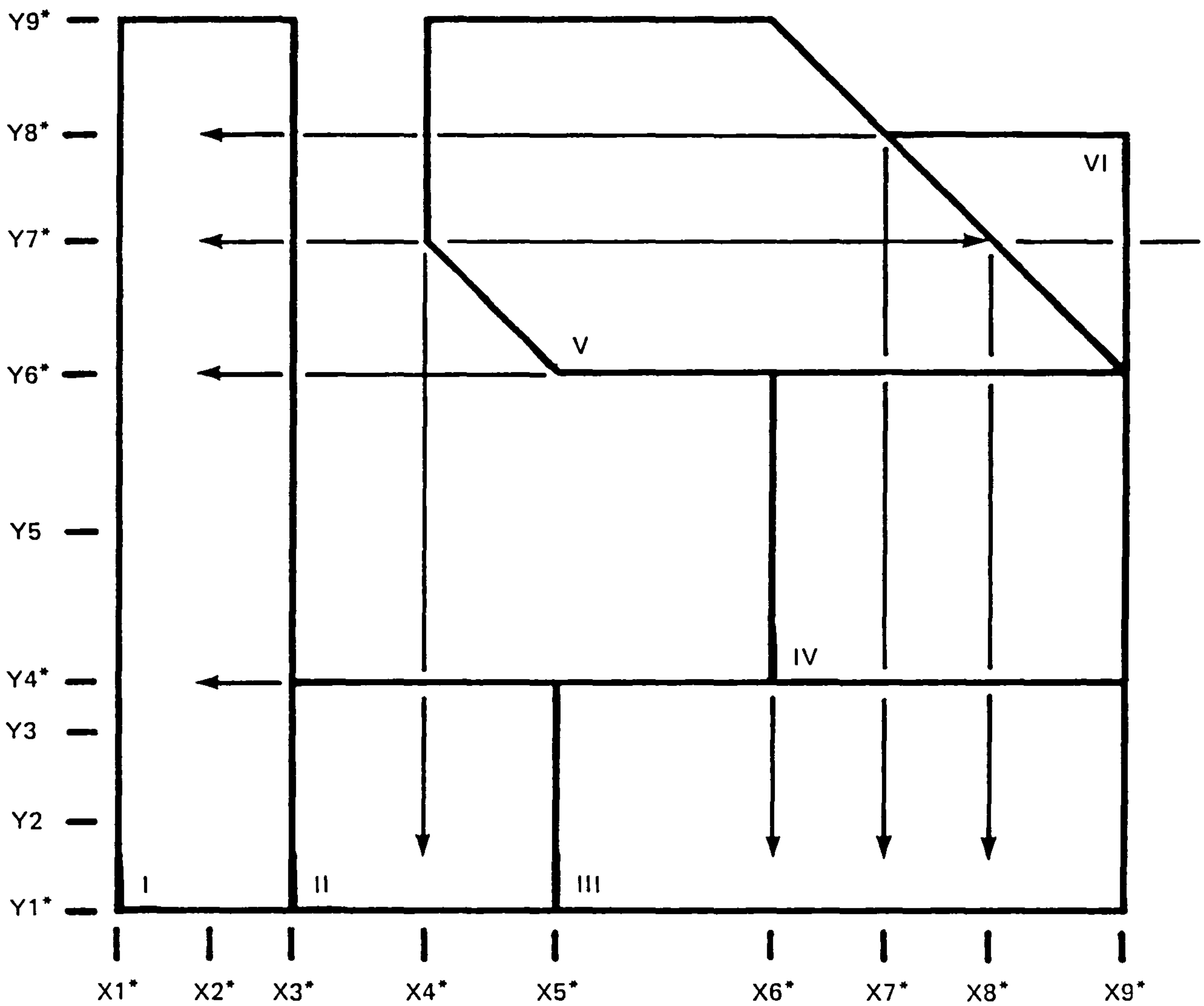
- When employing the boundary option (Section 5), each sector must be divided at least once by a grid line in the primary plane of the body (x-y plane in Figure 2). This allows the program to "decide" where the boundary is located and, thus, where to place boundary nodes. It is inconsistent with the boundary option to allow a node to "see" boundary condition on opposite sides of a node. (This does not apply to the direction normal to the primary plane of the body because a one-layer model can be used with either option).

Figure 3 displays the step-by-step development of a nodal network. Note the incremental steps defined by the grid line locations in the x and y direction. All grid lines shown that have an asterisk indicate a grid line position that must be in the model. All non-asterisk lines are optional and at discretion of the user. Because it was stated previously that each vertex of a sector must have a grid line pass through it in both the x and y direction, when establishing the grid the user should first project lines parallel to both axes emanating from each vertex as is demonstrated in Figure 3 by the arrows shown. Grid lines X1, X3, X4, X5, X6, X9, Y4, Y6, Y7, Y8, and Y9 were created this way. Note the Y7 projection crosses a skewed line of sectors V and VI, and, according to the rules previously stated, an orthogonal grid line must emanate from the intersection. This therefore established grid line X8. Lines Y2, Y3, and Y5 were put in to better define the analysis by the user. Note that the user included X2 to satisfy criterion from boundary option. As shown, depending on the shape of the model analyzed, the number of nodes created may be large just from required grid lines.

Once it has been established, the grid work (Figure 4) will represent the nodal boundaries of the model. Note by using this method all nodes are in line with one another, which is a necessary condition for the Nodel Network Generator.

Now that the model is established on paper, the user can access NNDIG and NNGEN to create an input data set to CAVE3 that contains all the network couplings and values of capacitance and conductance.

The Nodal Network software will provide the user with the option of placing nodes at the geometric centroid of the node or at a predescribed surface location. The program also provides the user with the ability to create a three-dimensional model, in which case the network developed will be mirrored down to a select number of layers (up to 10 layers). The nodes will be incremented and three-dimensional couplings will be established. All of these options will be described, but lead to another limitation. The program can currently create a model containing up to 500 nodes. Note the limitation on the amount of nodes created, maximum number of sectors, and maximum amount of vertices per sector are totally arbitrary and were limited only to reduce the amount of computer core needed to run the program. Any one or all of these limitations can be increased by simply re-dimensioning the program.



*GRID LINE POSITION THAT MUST BE IN THE NODAL

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FIG. 3 MODEL GRID CREATION

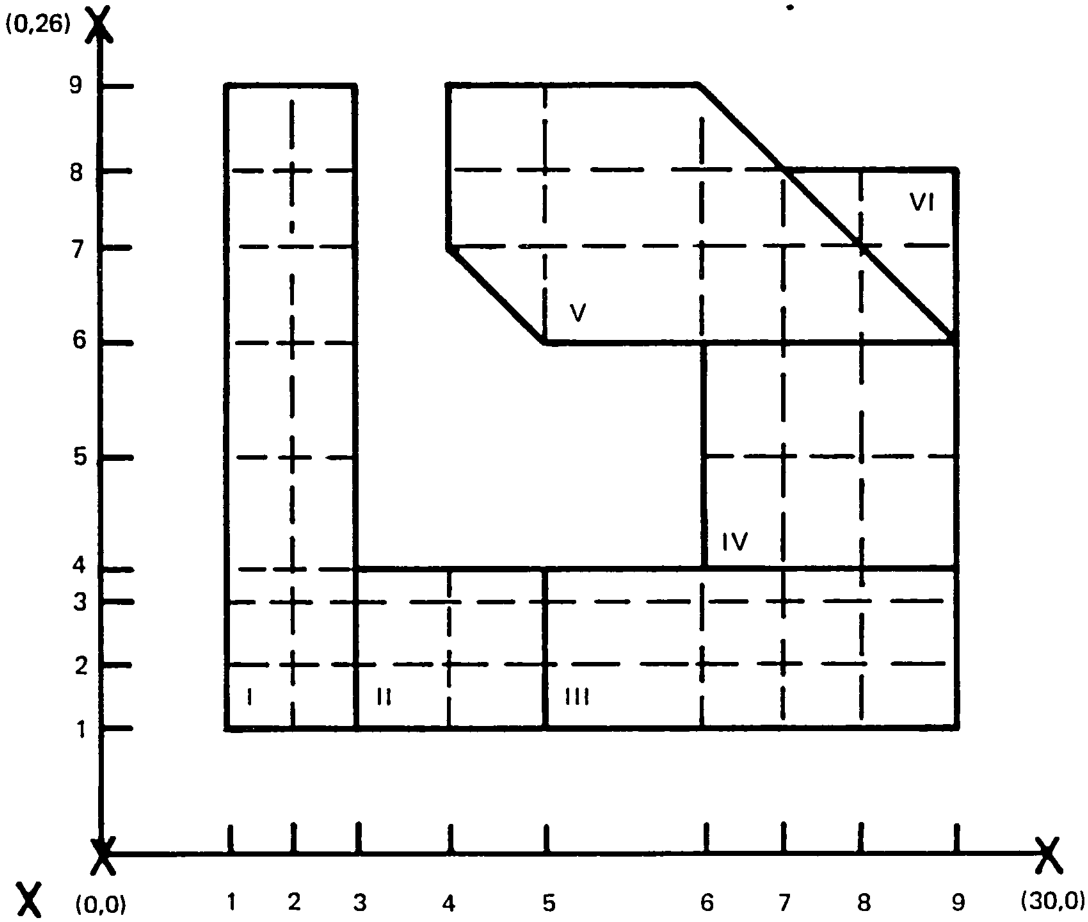

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FIG. 4 GRID LAYOUT

Section 4

INPUT DATA - MANUAL OR DIGITIZED (NNDIG) SETUP

The input needed to create the digital thermal model is basically the description of the physical geometry, i.e. the coordinates (x and y) of all sector vertices, and the x and y position of the grid lines and the material properties, conductivity, the specific heat, the density, and thickness of the material. The units inputted should be consistent, i.e., if the scaled drawing is measured in feet, make sure the thickness is also in feet and the conductivity contains the units of feet, etc. The program contains a feature to automatically create this data set using the Tektronix graphic scope and digitizing board. Although it is easy to use, this feature is not necessary. The user can manually create the data set needed as input.

Figure 4 displays a nodal breakdown of the network to be analyzed. Figure 5 displays the actual format of the data needed. Figure 6 represents a data set created manually. Note the program requires the number of sectors created within the model, in this case six (Figure 6). It also requires the number of layers and overall thickness of the model, which we input as 3 and 15., respectively, i.e., we chose to obtain three nodal cuts through the model and the overall depth of the model is 15 units. The next card is the respective thickness of each of the cuts, i.e., 3., 5., and 7 units. If the cuts have identical thicknesses, the user could have inputted a zero (0.) in which case the program would automatically compute the thickness by dividing the overall thickness by the number of layers. As shown, three unique values of thickness were supplied.

The program then needs the number of vertices for the first sector (5), the density (489), the specific heat (.1), and the conductivity (27). The next card should have the x and y coordinates of the first vertex, the next card the coordinates of the second vertex, etc, until the user has input the coordinates of each vertex on individual cards. It should be noted that the coordinates of the vertices must be entered in a continuous clockwise pattern. Once the vertices are entered for sector I, then the property card is repeated for sector II. The user must supply the number of

INPUT FORMAT	
1st Card – TITLE (64 characters)	16A4
2nd Card – ISECT, NLAY, THICK1	2I5, F10 4
3rd Card – THICK (1), THICK (2),– – – – – – – THICK (10)	10F7 2
The next group of cards is required for each sector (I = 1 to ISECT)	
1st sector card – IVERT (I), DENS (I), CP(I), AK(I)	I2, 3F10 4
The next group of sector cards define the vertices (J) for the sector (I)	
2nd sector card – XVERT (I, J), YVERT (I, J)	2F12 3
(IVERT + 1) sector card – XVERT (I, IVERT), YVERT	
The next group of card defines the coordinates of the grid lines	
X (1), 0	
X(K), 0	
0 , Y(1)	
0 , Y(L)	

DEFINITION OF VARIABLES		
ISECT	–	number of sectors
NLAY	–	number of layers
THICK1	–	overall thickness of model
THICK (K)	–	thickness of each layer where K = (1 NLAY)
IVERT (I)	–	number of vertices in sector I
DENS (I)	–	density of sector I
CP (I)	–	specific heat of sector I
AK (I)	–	conductivity of sector I
XVERT (I, J)	–	X vertex number J of sector I
YVERT (I, J)	–	Y vertex number J of sector I
X (K)	–	X coordinate of grid line where K = 1 to last X grid line
Y (K)	–	Y coordinate of grid line where K = 1 to last Y grid line

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FIG 5. INPUT DATA FORMAT & VARIABLE DESCRIPTIONS

```
3-D MODEL FOR REPORT
     6     3    15.0000
   3.00    5.00    7.00    0.0      0.0      0.0      0.0      0.0      0.0      0.0
 5  489.0000     0.1000   27.0000
       4.000       24.000
       8.000       24.000
       8.000        4.000
       4.000        4.000
       4.000       24.000
 5  489.0000     0.1000   27.0000
       8.000        9.000
      14.000        9.000
      14.000        4.000
       8.000        4.000
       8.000        9.000
 5  172.0000     0.2200  128.0000
      14.000        9.000
      27.000        9.000
      27.000        4.000
      14.000        4.000
      14.000        9.000
 5  172.0000     0.2200  128.0000
      19.000       16.000
      27.000       16.000
      27.000        9.000
      19.000        9.000
      19.000       16.000
 6  489.0000     0.1000   27.0000
      11.000       24.000
      19.000       24.000
      27.000       16.000
      14.000       16.000
      11.000       19.000
      11.000       24.000
 4  489.0000     0.1000   27.0000
      22.000       21.000
      27.000       21.000
      27.000       16.000
      22.000       21.000
     4.000      0.0
     6.000      0.0
     8.000      0.0
    11.000      0.0
    14.000      0.0
    19.000      0.0
    22.000      0.0
    24.000      0.0
    27.000      0.0
     0.0        4.000
     0.0        6.000
     0.0        8.000
     0.0        9.000
     0.0       12.000
     0.0       16.000
     0.0       19.000
     0.0       21.000
     0.0       24.000
```

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FIG. 6 SAMPLE INPUT TO NNGEN (MANUAL)

vertices contained in sector II, its density, specific heat, and conductivity. This card is followed by the coordinates of the vertices of sector III, and so on until you have inputted the material card and vertices for each sector of the model. Note when supplying the vertices, the user should repeat the first vertex of each sector as the last to close the body for plotting.

The input needed now is the x location of the first grid line followed by a zero. This is continued until all x grid locations are defined. The same procedure is used for the y grid location, except that 0. is input first followed by the y coordinate of the grid location. The data file (Figure 6) is now ready for execution with NNGEN.

The above data file could have been automatically created in a fraction of the time using the digitizing option of the program. Figure 4 will again be used but this time in conjunction with the digitizer. An axis had to be drawn on the figure with reference point clearly denoted, as shown. Notice the grid tick points are marked on the respective axis. In this case we have nine grid marks in each direction. Note the number of grid points in the x direction does not have to equal the number of grid points in the y direction. The user should then affix the drawing to the digitizing table and access the program by typing at the Tektronix terminal: NNDIG (Figure 7).

```
nndig

PLEASE ENTER A TITLE FOR THE DATA FILE (60 CHAR - MAX)
3-d model for report

ENTER THREE(3) REF. PTS. (XRF(I),YRF(I),XRF(I))
AS DECIMAL NUMBERS SEP. BY COMMA
POINT 1>0.,26.,0.,
POINT 2>0.,0.,0.,
POINT 3>30.,0.,0.,
DIGITIZE THESE THREE(3) REF. PTS.


DIGITIZE TWO(2) PTS. (LOWER-LEFT & UPPER RIGHT)
EACH HALF INCH AWAY FROM PICTURE FRAME
2165-046B
```

FIG. 7 SAMPLE TERMINAL SESSION NNDIG

The program then asks the user a number of prompts, the first being, "Enter a title for use as the first card in the data file." The program then calls for the reference points. As shown, the three points marked on Figure 4 were input at the terminal and then were digitized in the order they were input. The user merely placed the digitizing cursor to each point and recorded the data. He then placed the cursor on the remaining points and did the same. Once the three points were recorded, he pressed the carriage return to transmit them to the computer. This establishes the reference of the drawing, and any point recorded within these reference points will have a value based on these points. The user is then requested to digitize (same procedure as above) a point to the lower lefthand corner of the drawing outside the reference frame and the upper righthand corner. This is used to scale the drawing to the screen size and sample marks are denoted in Figure 4. Once accomplished the screen will be erased.

The program will then ask the user how many sectors are to be digitized, how many layers the model will have, and what is the overall thickness (depth in the plane of the paper) of the model. As shown in Figure 8 the model has six sectors and will be a three-dimensional model consisting of three distinct cuts with an overall thickness of 15 units. The program then asks the respective thickness of each layer. As shown, the layers will have unit thicknesses of 3., 5., and 7., respectively. If they all had the same thickness or there were only one layer, a carriage return would have been sufficient and the program would automatically establish the correct thicknesses. This data is now used by the program to create the second and third cards of the data file.

```
ENTER THE NUMBER OF HOMOGENOUS SECTORS TO BE DIGITIZED
AND NUMBER OF LAYERS AND OVERALL THICKNESS
>6,3,15.,
ENTER THICKNESS OF EACH LAYER (10F7.0)
:-- C.R. ALONE INDICATES UNIORM THICKNESS
>3.,5.,7.,
```

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FIG. 8 INPUT OF OVERALL PARAMETERS

The program then queries the user (Figure 9) for the density, specific heat, and conductivity of the sector to be digitized. Once recorded, the user can begin digitizing the vertices of the sector. The vertices must be recorded in a clockwise manner starting at any vertex. The user should (for plotting purposes) return to the vertex he started with to close the geometry, i.e., the first vertex will also be the last vertex recorded. Once it is digitized, the geometry should be transmitted (carriage return). If there are more than nine vertices, you should transmit (carriage return) at or before nine, then proceed to record the remainder, never exceeding groups of nine before transmitting. Once accomplished, the user should press a backspace once, the carriage return to indicate he is finished with this sector. This procedure is repeated until all sectors are digitized (Figures 9 through 14).

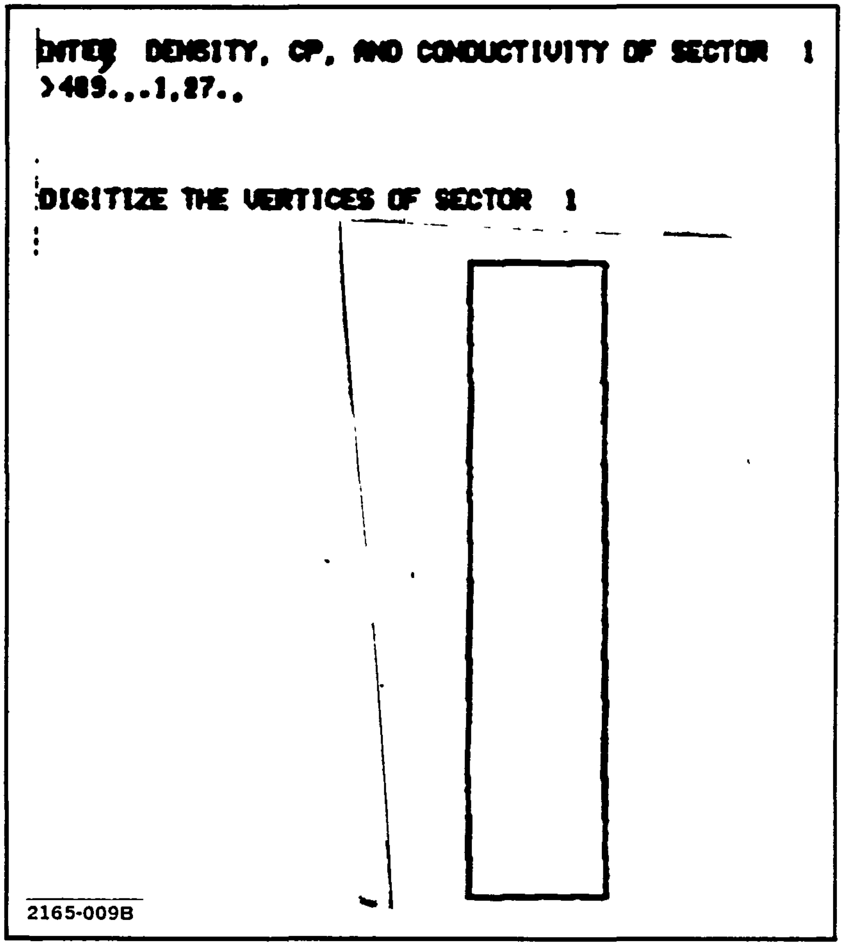

FIG. 9 DIGITIZE SECTOR I

The program will then ask the user to digitize the lines defining the subdivision along the x axis (Figure 15) that have been laid out on Figure 4. To do so as before, each point is recorded using the digitizing cursor and transmitted with the carriage return. Groups of up to nine recorded points may be stored before transmission is required (carriage return). Once complete, the user should press a backspace and carriage return to indicate this portion is finished. Figure 16 displays the same procedure for the y increments. Once completed (backspace then carriage return pressed), the screen will erase and a plot will be drawn of the sectors digitized (Figure 17). When the user is finished looking at the plot, a carriage return will erase the screen, and a data set will be established as shown in Figure 18.

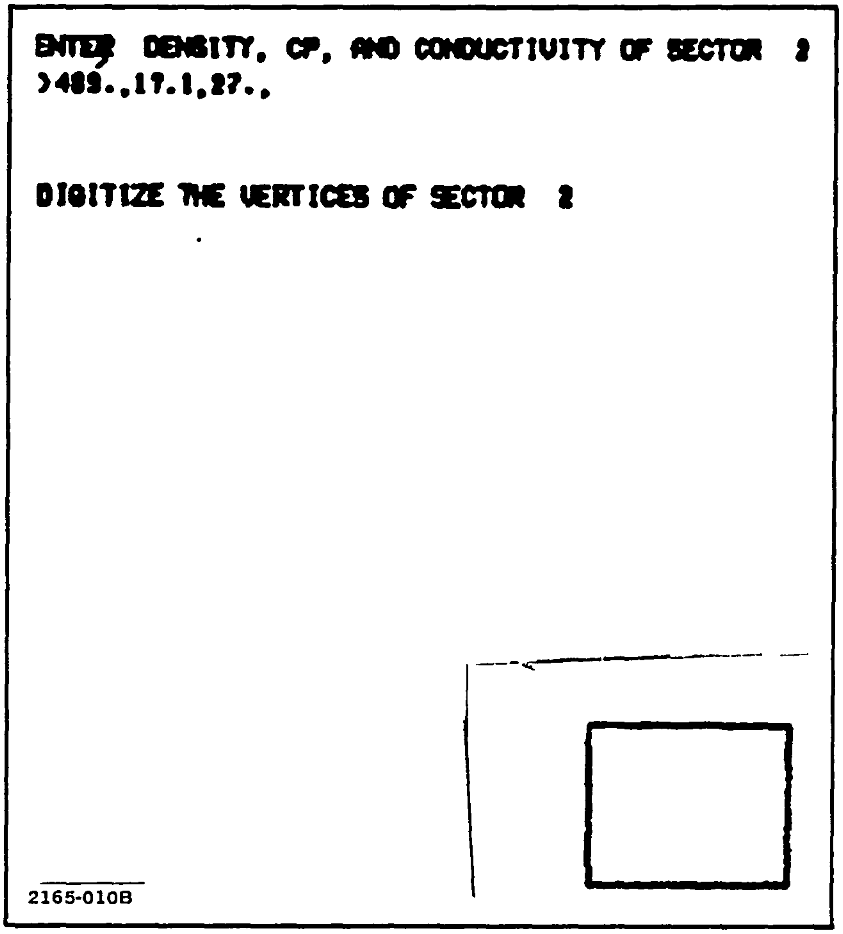

FIG. 10 DIGITIZE SECTOR II

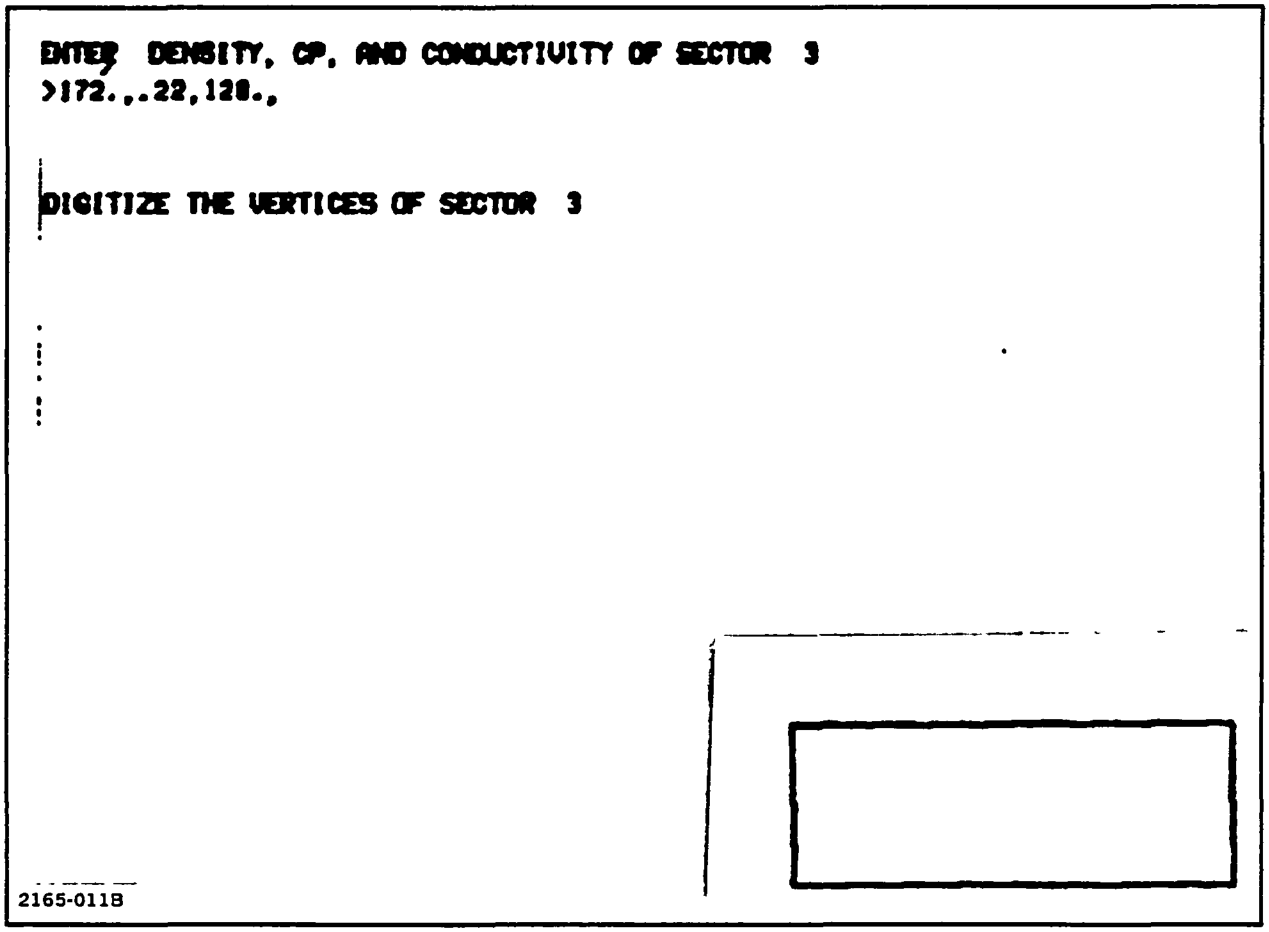

FIG. 11 DIGITIZE SECTOR III

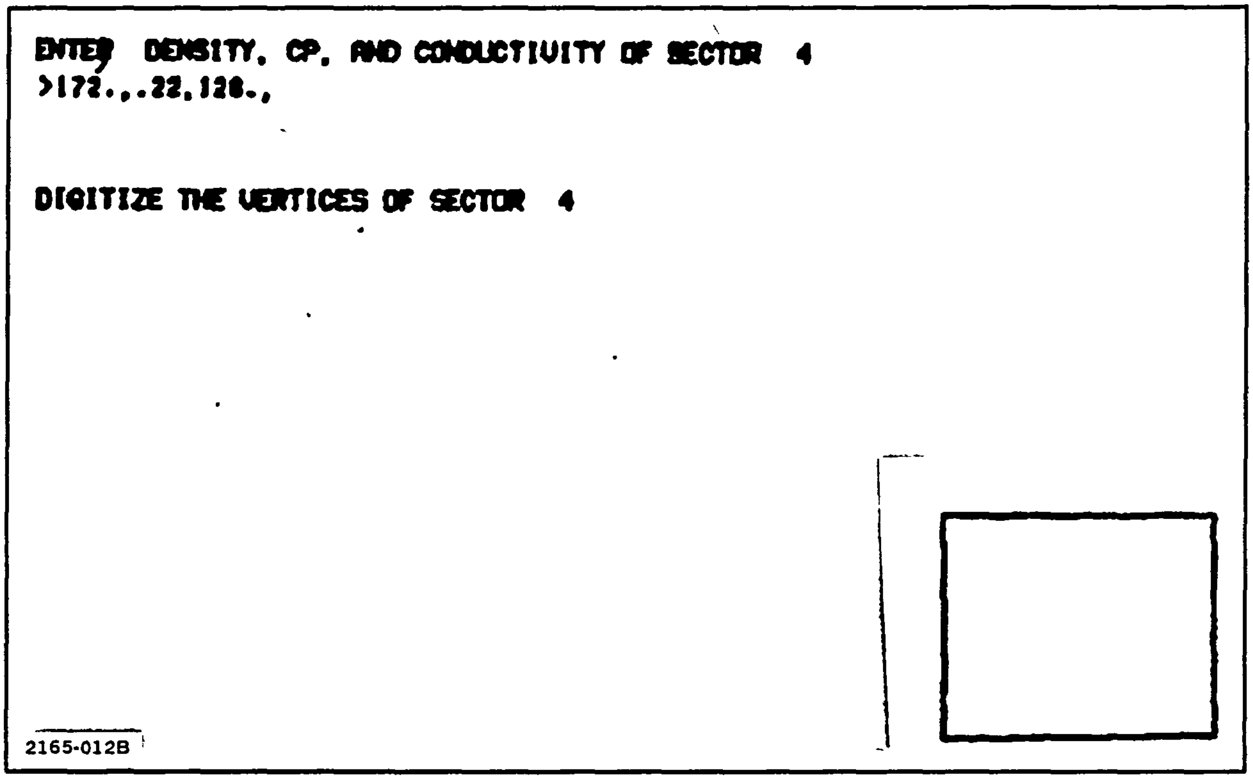

FIG. 12 DIGITIZE SECTOR IV

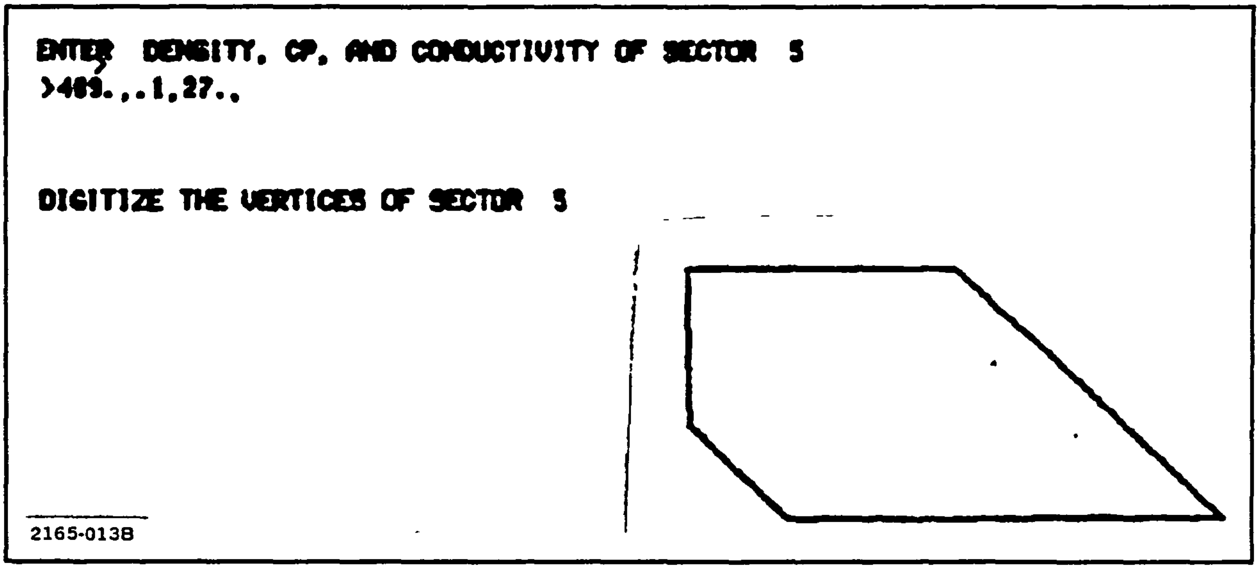

FIG. 13 DIGITIZE SECTOR V

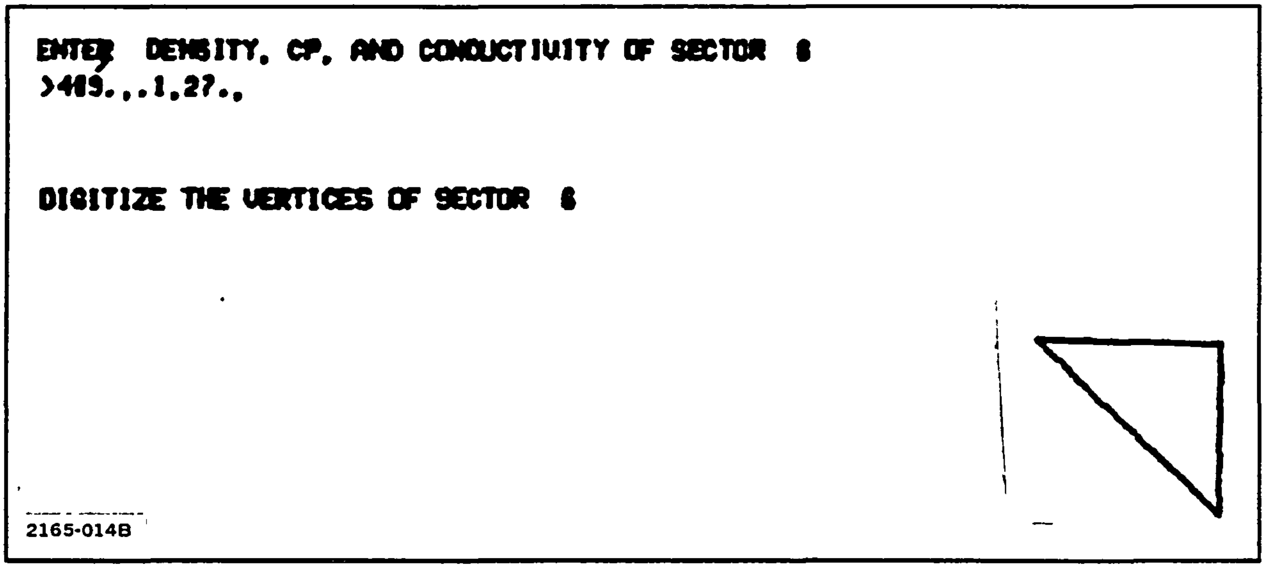

FIG. 14 DIGITIZE SECTOR VI

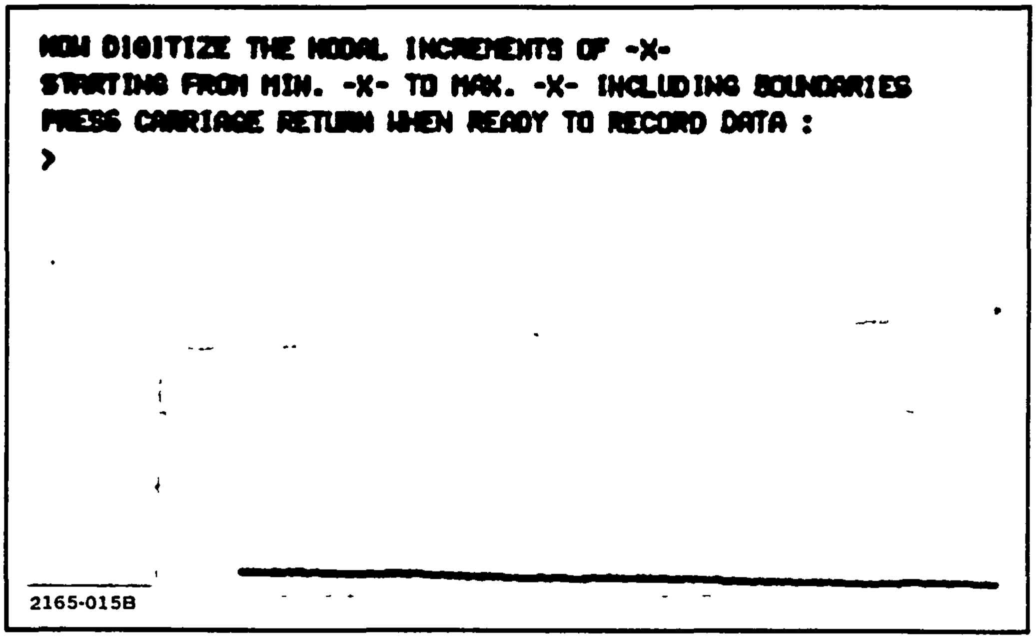

FIG. 15 DIGITIZE x GRID

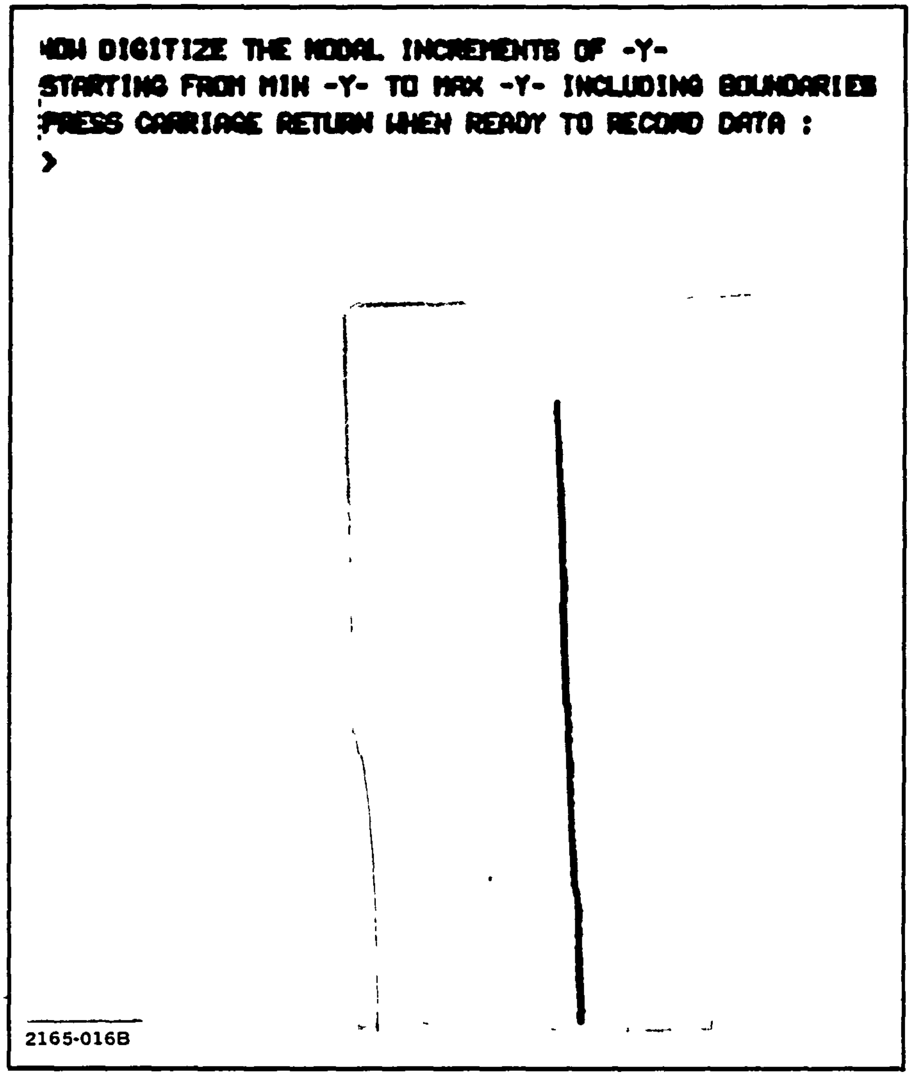

FIG. 16 DIGITIZE y GRID

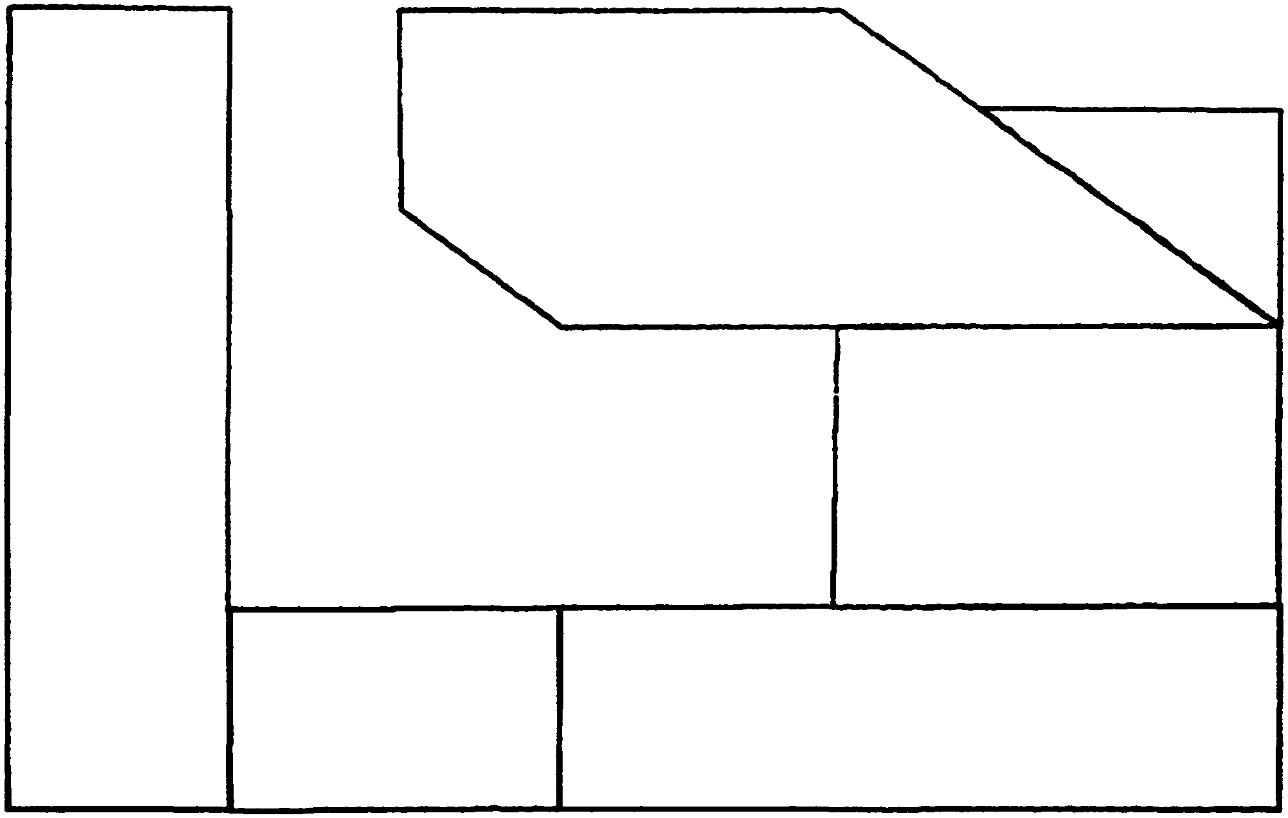

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FIG. 17 RESULTANT GEOMETRY PLOT

```
3-D MODEL FOR REPORT
    6     3    15.0000
   3.00    5.00    7.00    0.0      0.0      0.0      0.0      0.0      0.0      0.0
 5  489.0000     0.1000   27.0000
       3.967        24.029
       7.942        23.989
       7.968         3.905
       3.954         3.905
       3.967        24.029
 5  489.0000     0.1000   27.0000
       7.972         8.936
      13.917         8.977
      13.912         3.906
       7.967         3.864
       7.973         8.976
 5  172.0000     0.2200  128.0000
      13.957         8.976
      27.010         9.035
      26.964         3.925
      13.912         3.906
      13.957         8.976
 5  172.0000     0.2200  128.0000
      18.991        16.039
      26.983        16.039
      26.970         9.036
      18.897         8.997
      18.991        16.039
 6  489.0000     0.1000   27.0000
      10.994        23.968
      19.025        23.927
      26.982        15.999
      13.929        15.980
      11.031        18.976
      10.994        23.968
 4  489.0000     0.1000   27.0000
      21.534        21.461
      26.995        21.392
      26.982        15.999
      21.534        21.461
    3.912      0.0
    5.920      0.0
    7.928      0.0
   10.900      0.0
   13.912      0.0
   18.932      0.0
   21.422      0.0
   23.912      0.0
   26.964      0.0
    0.0        3.905
    0.0        5.917
    0.0        7.930
    0.0        9.057
    0.0       12.478
    0.0       16.019
    0.0       18.998
    0.0       21.452
    0.0       24.029
```

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FIG. 18 SAMPLE INPUT TO NNGEN (CREATED BY NNDIG)

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Section 5

MODEL GENERATOR (NNGEN)

Once it has been created, the geometry data file must be fed to the model generation portion of the program where the user has two options he might employ. The user can create a nodal network with the node centers located at the geometric centroid or the user can opt to have all boundary nodes moved to the surface in a predetermined fashion that will be described later. Each option will culminate in the creation of a data set capable of running with the CAVE3 code.

Using the geometry data file just created (Section 4), the user can create a thermal model by accessing the network generation program (NNGEN). As demonstrated in Figure 19, the program was accessed and it queried for an input of tolerance, a mechanism provided for in the software to allow for inaccuracies when digitizing.

```
nngen
INPUT TOLERANCE  E12.5
.1
ENTER NODE NO., COND NO., RAD NO., YOU WISH TO START WITH. IF 1 CR


DO YOU WISH TO SEE A PLOT OF THE INTERNAL NODE CONFIGURATION?
yes
2165-018B
```

FIG. 19 SAMPLE TERMINAL SESSION NNGEN

The routine establishes its bookkeeping scheme by looking for node centers that are in line with one another, i.e., common x or y coordinates. When digitizing, it is extremely difficult (and most unlikely) for the user to repeat a point exactly. An example is shown in Figure 18. The data set represented here is one that was produced by the digitizing portion of the program. Note any set of vertices of any sector. Most sectors will show repeat coordinates, i.e., a boundary that is parallel to either the x or y axis would create like x or y coordinates in two vertices. Note the first sector shows like x coordinates of 3.967 and 3.954; close but not exact. This error (0.013) was caused by the inability of the user to repeat exactly the x coordinate using the digitizing cursor. Although it is small, the error would have misaligned node centers causing the bookkeeping scheme to fail.

To overcome this, the program requires an input of tolerance which is used as a ± buffer on node center to determine allowable node alignment. The tolerance has been made an input because it depends upon the scale of the geometry and node size. In any case, it should always be less than half the distance of the smallest x or y nodal increment. Because the tolerance is only used to bookkeep the orientation of the nodes, it does not alter the actual value of the node centers and therefore does not vary the dimensional parameters.

A value of 0.1 was inputted for tolerance (any value up to approximately 1.0 could have been used in this case). The program then questions the user as to a starting node number, conductance number, and radiation number. This option was provided to allow the user to build a model in steps. In the terminal session provided, the user entered a carriage return indicating he wanted all numbering to start at 1. The routine then establishes the nodal arrangement of the geometry. Starting from the lower lefthand corner of the drawing, the routine establishes consecutive numbering of nodes and identifies any voids in the geometry, as demonstrated in Figure 20. The rectangular node centers are placed at the geometric centroid of the nodal area. In the case of triangular nodes, the node center is temporarily placed at the midpoint of the hypotenuse. This is only done for bookkeeping purposes for node alignment. At this point the software has established the bookkeeping of the model, i.e., it knows which nodes see which nodes, which nodes see void (boundary) for all three dimensions.

The program then asks the user whether he wants to see a plot of the internal node configuration, i.e., with all node centers located at the geometric centroid. Again note although it will pictorially be represented at the midpoint on the hypotenuse, the triangular node will actually be placed at its centroid for computations. As shown in Figure 19 the user responded YES, resulting in Figures 20 - 22. Note in Figure 20, the layer number is denoted. In this case, the user is creating a three-layer model. The numbering begins in the lower lefthand corner and increments to the right. The node centers are in line with one another and the node boundaries are identified. Note also the void in the model and that the software eliminated it from the sequencing.

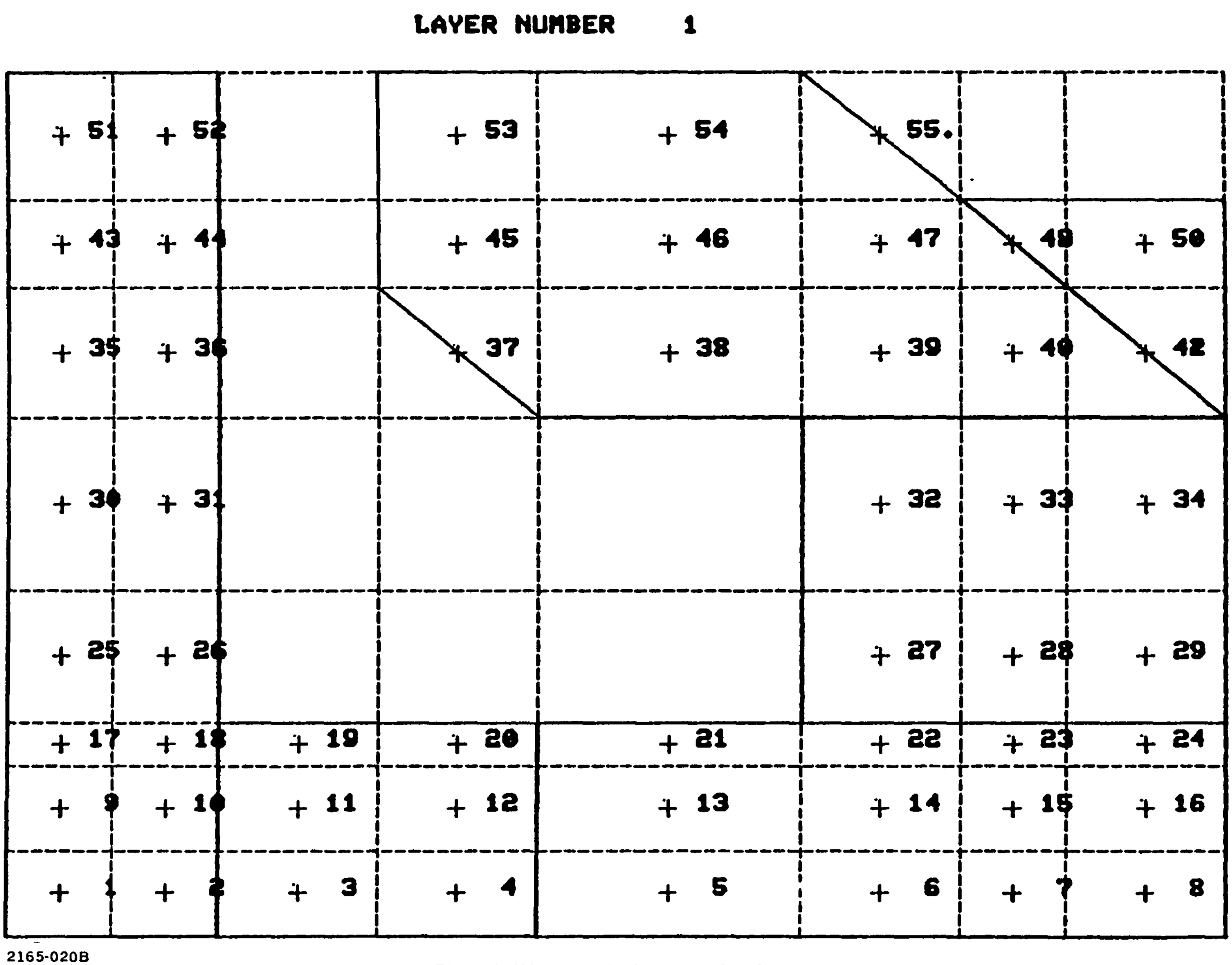
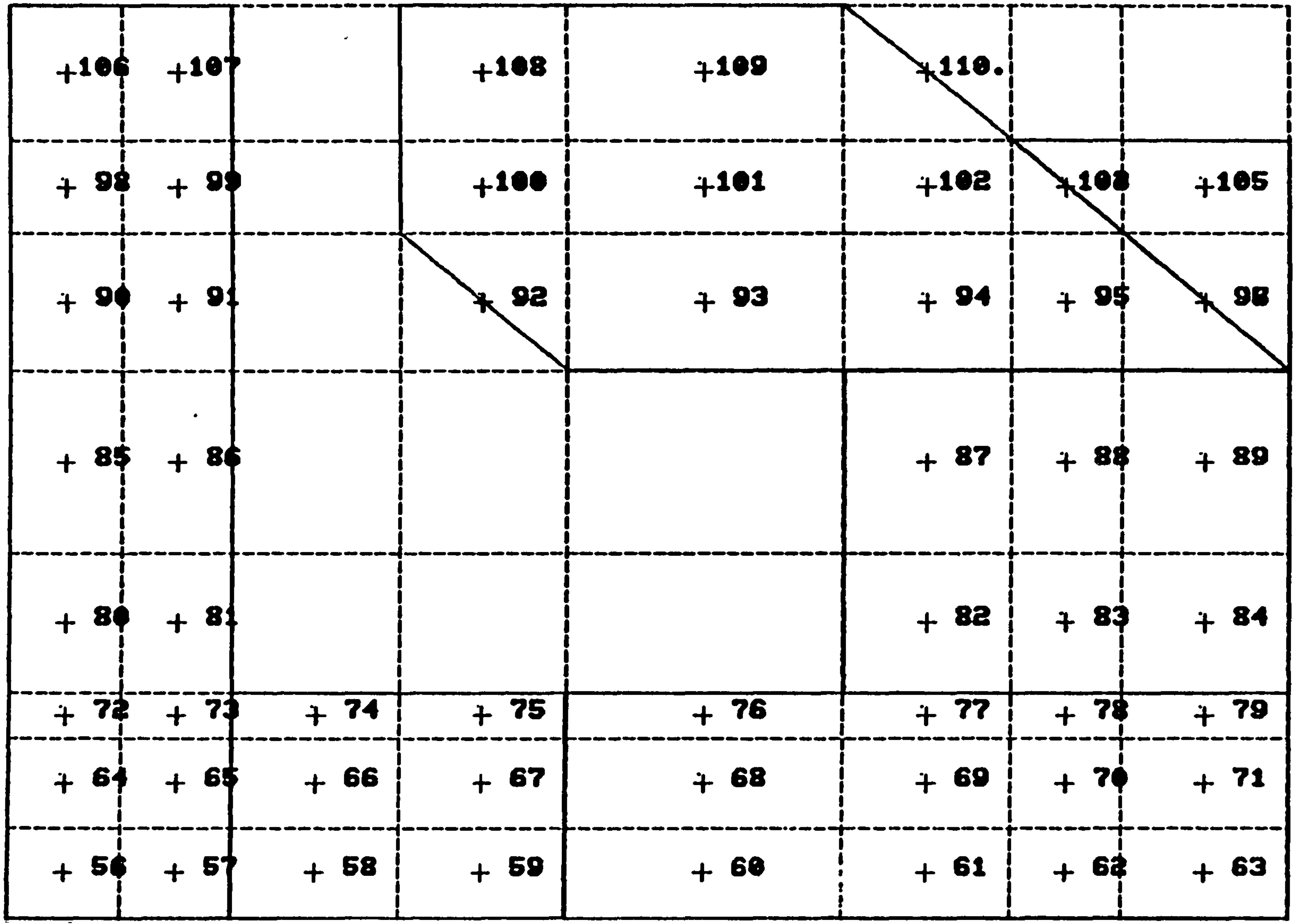


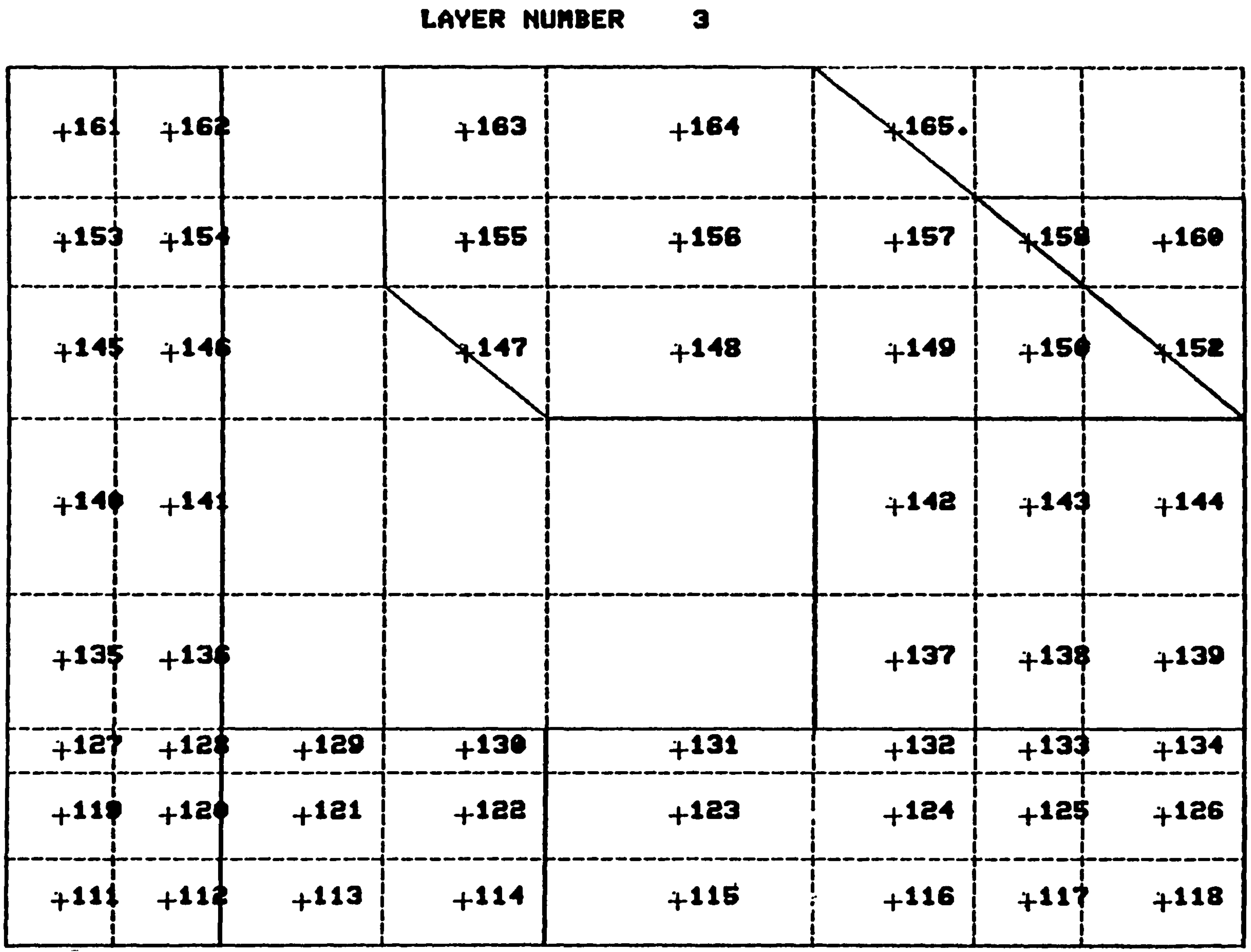
FIG. 20 INTERNAL NODES — LAYER 1

LAYER NUMBER 2



2165-021B

FIG. 21 INTERNAL NODES – LAYER 2



2165-022B

FIG. 22 INTERNAL NODES – LAYER 3

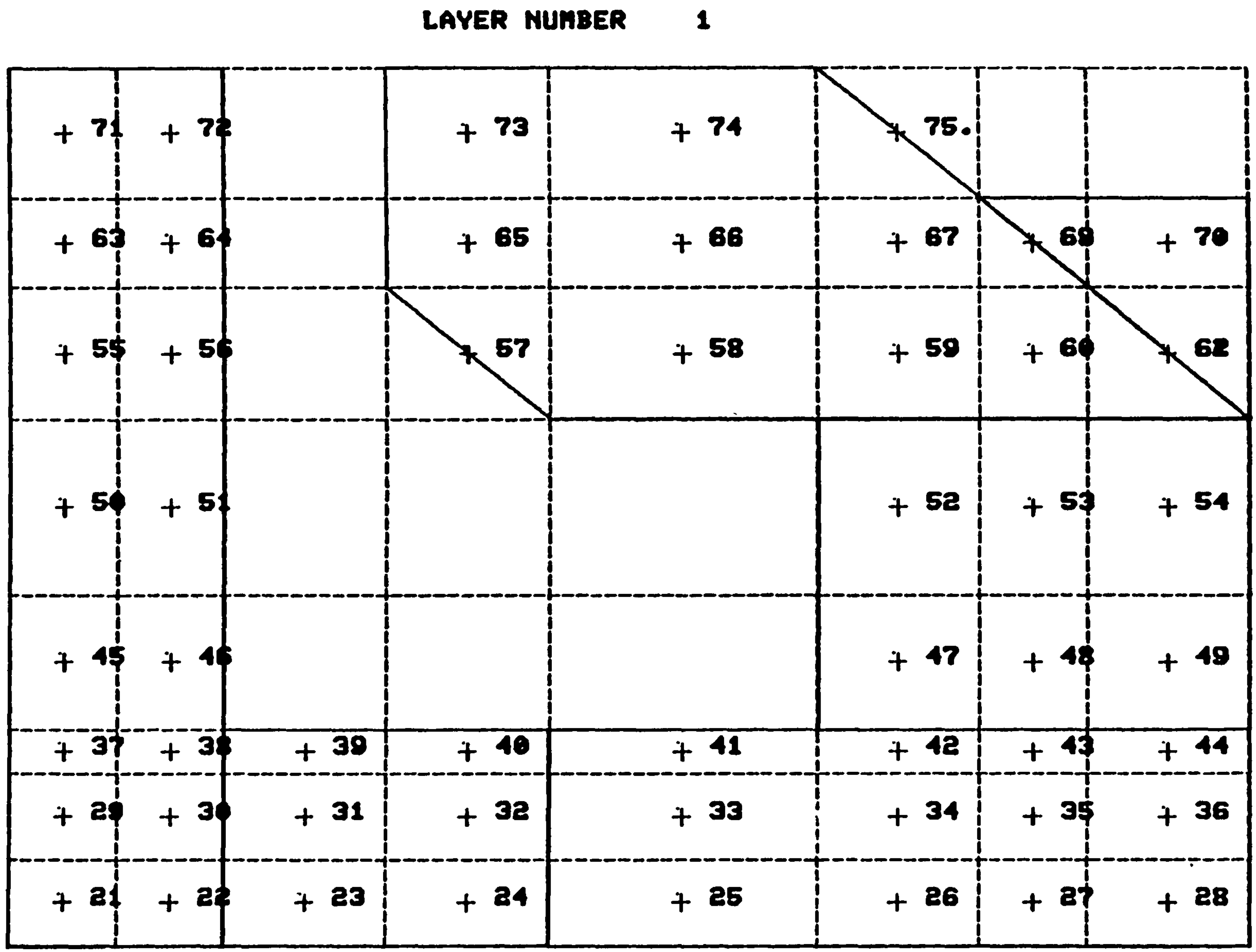
Also note nodes 41, 42 and 48, 49. Their positions are superimposed on one another again only for bookkeeping. Each node will go into its respective triangle at the geometric centroid. Once the plot is completed, the user must hit the carriage return to reactivate the routine, at which time the plot will be erased. In this case, once the first layer is completed and erased, the second layer is plotted (Figure 21). Note the first node plotted is 56, one greater than the last previous node plotted in layer one. The nodes are sequenced exactly as previously done and the plot is labeled LAYER 2. Hitting the carriage return plots the third and last layer (Figure 22), labeled as before, this time starting with node 111 and ending with 165.

Refer back to the option to set the starting node number, conductance, and radiation links for the demonstration included in Figures 23 - 25. Here the user chose to start numbering the nodes at 21, the conductance block at 45, and the radiation block at 37. As shown in Figure 24, the first node presented in numbered 21. In the data set created with the actual couplings (which will be discussed fully later), the first conductance number would be 45 and the first radiation number, 37. This is extremely useful when you are building a model in steps.

```
nngen

INPUT TOLERANCE  E12.5
.1

ENTER NODE NO., COND NO., RAD NO., YOU WISH TO START WITH. IF 1 CR
21,45,37,

DO YOU WISH TO SEE A PLOT OF THE INTERNAL NODE CONFIGURATION?
yes

2165-023B
```

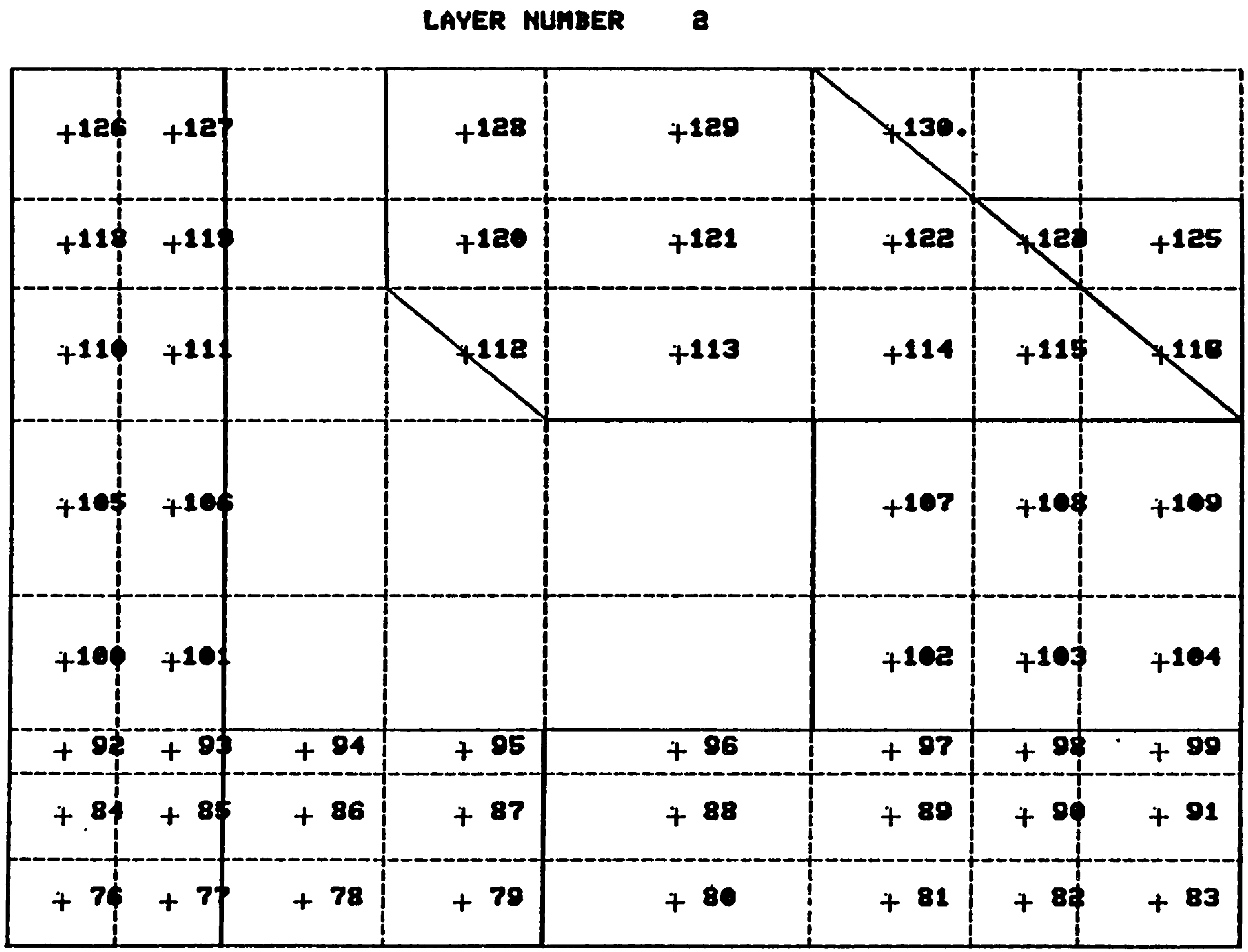
FIG. 23 INTERNAL NODES EXTENDED NUMBERING SCHEME

The program then provides a rotate option for the user which allows the user to see graphically an orthogonal view of the network. The program queries the user as to how many layers he or she wishes to see and the layer numbers - (starting from top to bottom). As shown, the user in this case chose three layers: 1, 4, and 7 (Figure 26). The results are shown in Figures 27 - 29. Compare Figure 27 with Figures 20, 21, and 22. Note the rotation that took place. Similarily with Figures 27 - 29 and the same figures. Note also that the layer numbering is from top to bottom.



2165-024B

FIG. 24 INTERNAL NODES EXTENDED NUMBERING SCHEME – LAYER 1



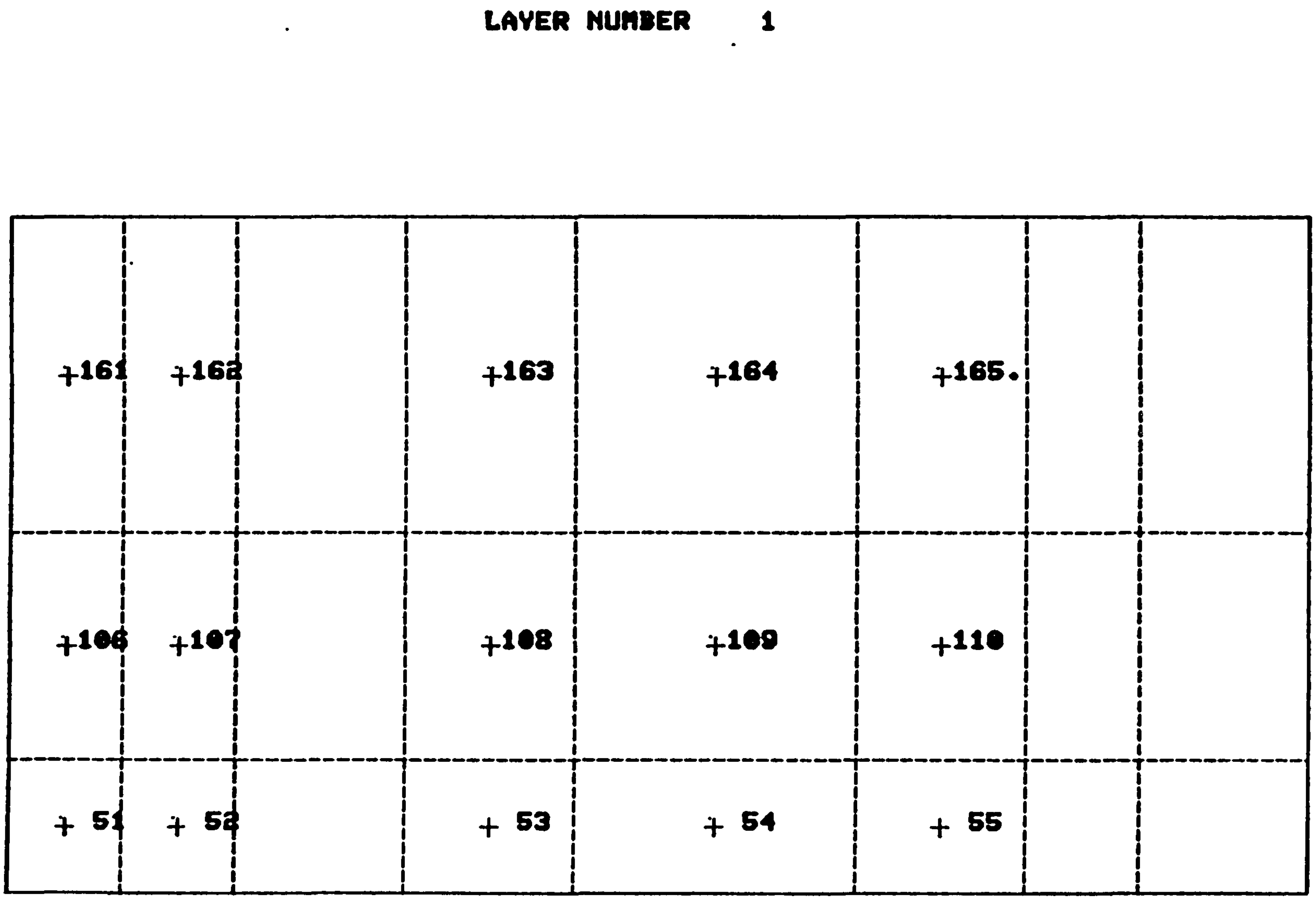
2165-025B

FIG. 25 INTERNAL NODES EXTENDED NUMBERING SCHEME – LAYER 2

```
     DO YOU WANT ROTATING LAYER OPTION
.yes
HOW MANY LAYERS DO YOU WANT
.3,
ENTER LAYER NUMBERS
.1,4,7,
```

2165-026B

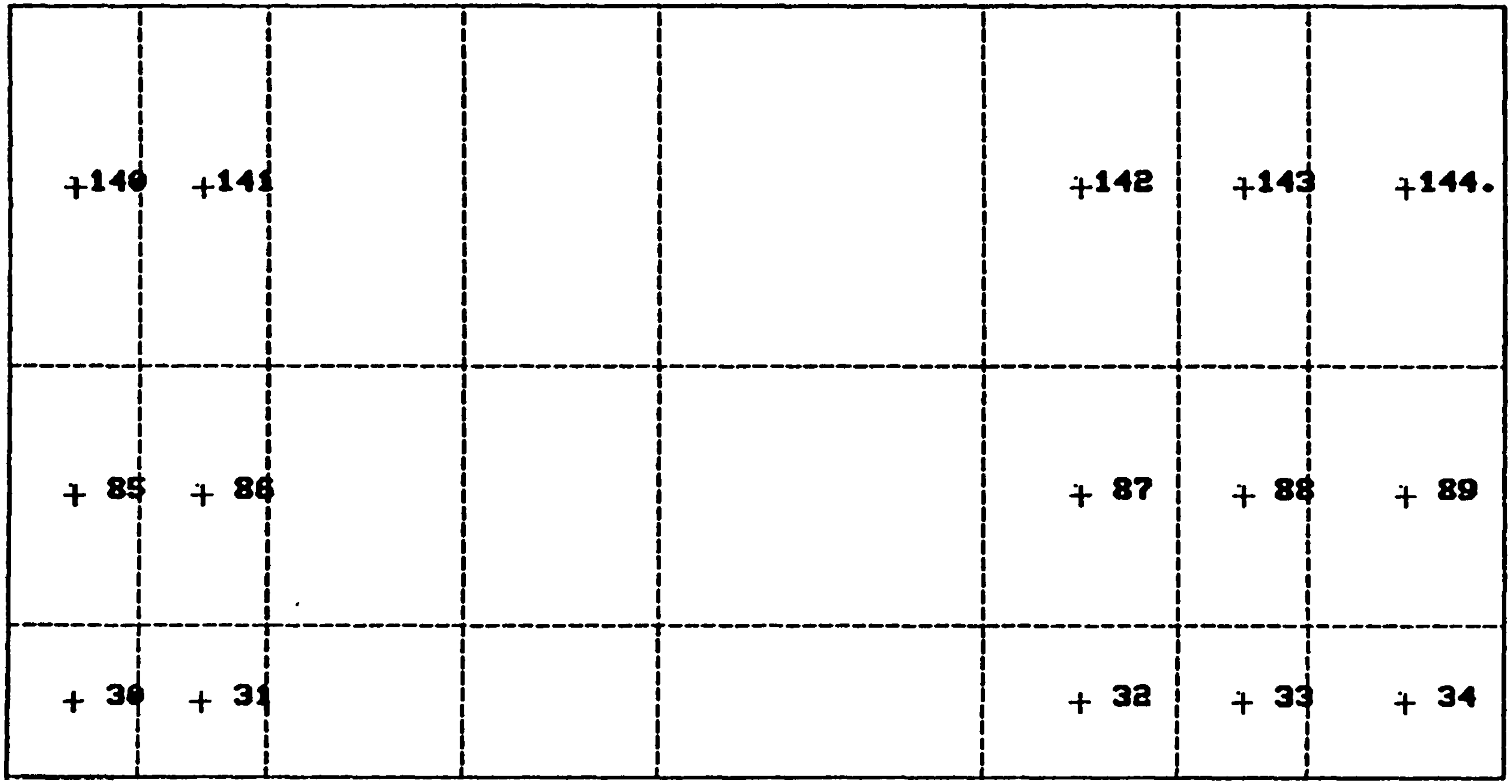
FIG. 26 ROTATE OPTION



2165-027B

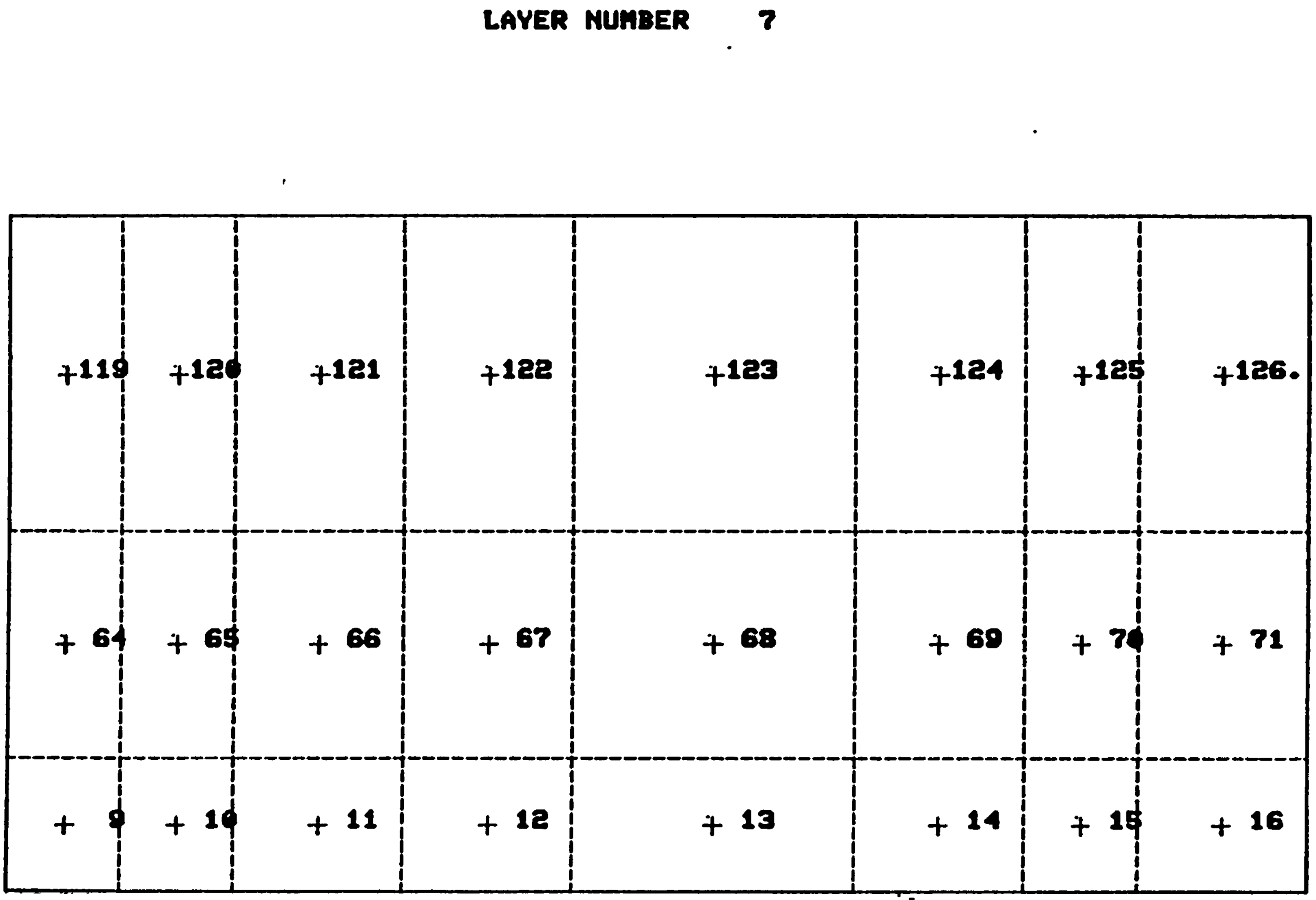
FIG. 27 ROTATE PLOT — LAYER 1

LAYER NUMBER 4



2165-028B

FIG. 28 ROTATE PLOT – LAYER 4



2165-029B

FIG. 29 ROTATE PLOT — LAYER 7

Upon hitting a carriage return the user will erase the screen and will be asked whether he wants to employ the boundary option (Figure 30). In this case, the user replied NO and was asked whether he wanted to create a CAVE3 input file. Once the user responds YES, the program has established the entire bookkeeping scheme of the model in all dimensions, i.e., it knows that node 20 (Figure 20) sees node 19 and 21 in the x direction and node 12 and a boundary in the y direction. It also knows that node 20 sees node 75 (Figure 21) and a boundary in the z direction. It has computed the conductance links to all nodes (other than boundary) using the distances referenced from the node centers. It has computed all capacitances and established radiation areas (all areas to boundary). See Section 6 for a description of coupling computation.

The program then asks the user for a control card and a series of title cards (up to four lines). If he has less than four, the user need only hit a carriage return for the next line to signal the program that the title entry is finished. The program then requests the START, DTIME, FINAL TIME, and SIGMA (Stephan Boltzman Constant) for execution and the initial temperature of iterated nodes.

The program then provides the user with the ability to create the convective boundary links. The user will be asked successively for the convective heat transfer coefficient for ± x direction ± y direction and ± z direction and the heat transfer coefficient for any diagonal boundary surfaces (hypotenuse). A carriage return indicates zero heat transfer. As demonstrated in Figure 30, the user indicated that a 100. BTU/hr ft^2 F coefficient was to be applied to any boundary surface facing the positive x direction (see Section 6). There should be a zero coupling to the negative x direction. For the y direction he chose a zero coupling to positive y and 200 BTU/hr ft^2 F to the negative y direction. The user also indicated a zero coupling in both z directions and any diagonal (carriage return with no response indicates zero couplings). In Section 6 the user can see a description of how the couplings are created. Briefly each direction +x, -y, etc., is given a specific boundary node number, i.e., positive x, 993, negative x, 994; positive y, 991; etc. In checking the couplings established in a partial output data set (Figure 31), note that there are no couplings to node 991 (+y), 994 (-x), 995 (hypotenuse), and 998 and 999 (±z).

```
DO YOU WISH TO USE THE BOUNDARY OPTION?
no
DO YOU WANT TO CREATE A CAVE3 INPUT FILE?
yes
ENTER THE CAVE3 CONTROL CARD (I5)
(NUMBND,NUMITR,NUMCON,NUMRAD,NUMNOD,NUMFLX,NSTR,NEVALU,IDIAG,IFLUX)
4,165,800,242,999,0,15000,5,0,0,
ENTER TITLE CARDS 4 MAX. AFTER LAST CARD HIT CAR. RET.
   test
       of
         nngen

ENTER START TIME,DTIME,FINAL TIME,SIGMA
0.,.1,1.,1.714e-8,
ENTER INITIAL TEMPERATURE OF ITERATED NODES
50.,
ENTER CONVECTING HEAT TRANSFER COEF FOR X DIRECTION,PLUS,MINUS
100.,0.,
ENTER CONVECTING HEAT TRANSFER COEF FOR Y DIRECTION,PLUS,MINUS
0.,200.,
ENTER CONVECTING HEAT TRANSFER COEF FOR Z DIRECTION,PLUS,MINUS

ENTER CONVECTING HEAT TRANSFER COEF FOR HYPOTENUSE
```

2165-030B

FIG. 30 CREATION OF INPUT FILE TO CAVE3

```
11100
22200                                              CONDUCTANCE BLOCK
    0     1     1     9  8.165E 01
    0     2     1     2  7.789E 01
    0     3     2    10  8.165E 01
    0     4     2     3  6.172E 01
    0     5     3    11  1.244E 02
    0     6     3     4  5.263E 01
    0     7     4    12  1.173E 02
    0     8     4     5  7.934E 01
    0     9     5    13  9.677E 02
    0    10     5     6  1.975E 02
    0    11     6    14  4.800E 02
    0    12     6     7  2.978E 02
    0    13     7    15  4.800E 02
    0    14     7     8  2.676E 02
    0    15     8    16  5.883E 02
    0    16     9    17  1.023E 02
    .     .     .     .     .
    .     .     .     .     .
    .     .     .     .     .
    .     .     .     .     .
    .     .     .     .     .
    0   356   107   161  5.819E 01
    0   357   108   162  1.443E 01
    0   358     1   992  1.205E 03
    0   359     2   992  1.205E 03
    0   360     3   992  1.836E 03
    0   361     4   992  1.730E 03
    0   362     5   992  3.012E 03
    0   363     6   992  1.494E 03
    0   364     7   992  1.494E 03
    0   365     8   992  1.831E 03
    0   366     8   993  5.793E 02
    0   367    16   993  6.159E 02
    0   368    24   993  3.381E 02
    0   369    26   993  1.026E 03
    0   370    29   993  1.026E 03
    0   371    31   993  1.063E 03
    0   372    34   993  1.063E 03
    0   373    36   993  9.054E 02
    0   374    38   992  3.012E 03
    0   375    42   993  9.054E 02
    0   376    44   993  7.245E 02
    0   377    49   993  7.245E 02
    .     .     .     .     .
    .     .     .     .     .
    .     .     .     .     .
2165-031B
```

FIG. 31 SAMPLE OUTPUT DISPLAYING BOUNDARY NODES (SHEET 1 OF 2)

```
       .     .     .     .       .

       .     .     .     .       .
       0   378    51   993 7.728E 02
       0   379    55   992 2.008E 03
       0   380    56   992 2.008E 03
       0   381    57   992 3.060E 03
       0   382    58   992 2.884E 03
       0   383    59   992 5.020E 03
       0   384    60   992 2.490E 03
       0   385    61   992 2.490E 03
       0   386    62   992 3.052E 03
       0   387    62   993 9.655E 02
       0   388    70   993 1.026E 03
       0   389    78   993 5.635E 02
       0   390    80   993 1.710E 03
       0   391    83   993 1.710E 03
       0   392    85   993 1.771E 03
       0   393    88   993 1.771E 03
       0   394    90   993 1.509E 03
       0   395    92   992 5.020E 03
       0   396    96   993 1.509E 03
       0   397    98   993 1.207E 03
       0   398   103   993 1.207E 03
       0   399   105   993 1.288E 03
       0   400   109   992 2.811E 03
       0   401   110   992 2.811E 03
       0   402   111   992 4.284E 03
       0   403   112   992 4.038E 03
       0   404   113   992 7.028E 03
       0   405   114   992 3.486E 03
       0   406   115   992 3.486E 03
       0   407   116   992 4.273E 03
       0   408   116   993 1.352E 03
       0   409   124   993 1.437E 03
       0   410   132   993 7.889E 02
       0   411   134   993 2.395E 03
       0   412   137   993 2.395E 03
       0   413   139   993 2.479E 03
       0   414   142   993 2.479E 03
       0   415   144   993 2.113E 03
       0   416   146   992 7.028E 03
       0   417   150   993 2.113E 03
       0   418   152   993 1.690E 03
       0   419   157   993 1.690E 03
       0   420   159   993 1.803E 03
   11100
   22200                                                RADIATION COUPLING BLOCK
       0     1     1   992 6.024E 00
       0     2     1   994 5.793E 00
       0     3     2   992 6.024E 00
       0     4     3   992 9.180E 00
       0     5     4   992 8.652E 00
       0     6     5   992 1.506E 01
       0     7     6   992 7.470E 00
       0     8     7   992 7.470E 00
       0     9     8   992 9.156E 00
       0    10     8   993 5.793E 00
```

2165-032B

FIG. 31 SAMPLE OUTPUT DISPLAYING BOUNDARY NODES (SHEET 2 OF 2)

Following the conduction block, the program supplies a radiation block which contains the link bookkeeping and the value of the node surface area exposed to the boundary. This block can be replaced with the actual radiation couplings when computed. A dummy block is supplied for Heat Sources where the user can supply the needed information. This block is followed by a Conductance Area Constant Block representing the $A/\Delta x$ term in computing the conductance link. This term is extremely useful when the user has a condition of changing properties. The data supplied is the conductance number, the constant values from the first and second nodes listed for that particular conductance number, and the sector number of each node. An example of the output is shown in Figure 32.

The final block of data is a dummy table to allow the user to supply one if needed. At this point the program will establish an output file on the system, and it will be in a format conductive to running CAVE3. The nodal arrangement will be that for all internal nodes. A segmented sample (because of its large size) is presented in Figure 33.

Figure 34 represents the second option provided, i.e., the boundary option. Had the user responded YES to the boundary option question, the program would have established all thermal parameters based on boundary node center locations. Figures 35 through 37 represent plots of the boundary option used on the model shown in Figure 3. A description of the boundary node conductance and orientation is described in Section 6. Figure 35 is identical to Figure 20 except any node exposed to a boundary is moved to the surface. The bookkeeping is identical but, when computing the conductance, a new conductive distance is used based upon its location relative to the node it sees (see Section 6). The program performs identically as before and establishes an output data file ready for input to the CAVE3 code.

```
     0  336  177  998 7.371E 00
     0  337  178  998 5.173E 00
     0  338  179  998 5.173E 00
     0  339  180  998 7.759E 00
     0  340  181  998 1.293E 01
     0  341  182  998 3.207E 00
 11100
 22200                                               HEAT SOURCE BLOCK
 11100
 22200                                                      COND--AREA/X--BLOCK
         45         6.23925        5.86849     3    4
         46         5.76992        5.76992     3    3
          .            .              .        .    .
          .            .              .        .    .
          .            .              .        .    .
          .            .              .        .    .
          .            .              .        .    .
        377         2.84492        2.03209     1    1
        378         2.84492        2.03209     1    1
        379         3.52783        2.51988     5    5
        380         3.52781        2.51986     5    5
        381         4.32406        3.08861     5    5
        382         2.42406        1.73147     5    5
        383         2.42406        1.73147     6    6
        384         1.81805        1.29860     1    1
        385         6.06014        4.32867     1    1
        386         3.00594        2.14710     0    0
        387         3.00592        2.14709     5    5
        388         1.84219        1.31585     5    5
        389         1.84219        1.31585     5    5
        390         1.93972        1.38552     0    0
        391         1.93972        1.38552     0    0
        392         2.90958        2.07827     0    0
        393         4.84930        3.46378     0    0
        394         2.40534        1.71810     0    0
        395         1.20266        0.85904     0    0
        396         2.94823        2.10588     0    0
        397         2.06905        1.47789     0    0
        398         2.06905        1.47789     0    0
        399         3.10357        2.21684     0    0
        400         5.17261        3.69472     0    0
        401         1.28285        0.91632     2    2
 11100
 22200                                           TABLE BLOCK
 11100
 11100
 11100
2165-033B
```

FIG. 32 SAMPLE OUTPUT DISPLAYING CONDUCTION CONSTANT

```
TEST CASE
        BOUNDARY NODE OPTION
                                USING T14DC001 DATA


   0     0    12     0
   00.0        0.6000E-020.1220E 020.1714E-08     1
22200                                        TEMPERATURE BLOCK FOR ITERATED NODES
   0     1    -100.00
   0     2    -100.00
   0     3    -100.00
   0     4    -100.00
   0     5    -100.00
   0     6    -100.00
   0     7    -100.00
   .     .       .

   .     .       .

   .     .       .

   .     .       .
   0   158    -100.00
   0   159    -100.00
   0   160    -100.00
   0   161    -100.00
   0   162    -100.00
   0   163    -100.00
   0   164    -100.00
   0   165    -100.00
11100
22200                                        TEMPERATURE BLOCK FOR BOUNDARY NODES
11100
22200                                        CAPACITANCE BLOCK
   0     1 5.688E 02
   0     2 5.688E 02
   0     3 8.668E 02
   0     4 8.170E 02
   0     5 1.100E 03
   0     6 5.724E 02
   0     7 5.193E 02
   0     8 6.690E 02
   0     9 6.048E 02
   0    10 6.048E 02
   0    11 9.216E 02
   0    12 8.656E 02
   0    13 1.170E 03
   0    14 6.085E 02
   0    15 5.521E 02
   .     .       .

   .     .       .
```

2165-034B

FIG. 33 SAMPLE OUTPUT FILE (SHEET 1 OF 3)

```
      0   154  1.600E 03
      0   155  2.384E 03
      0   156  4.150E 03
      0   157  2.158E 03
      0   158  9.792E 02
      0   159  9.792E 02
      0   160  2.523E 03
      0   161  1.771E 03
      0   162  1.771E 03
      0   163  2.543E 03
      0   164  4.426E 03
      0   165  1.151E 03
  11100
  22200                                              CONDUCTANCE BLOCK
      0     1      1      9 3.500E 01
      0     2      1      2 5.193E 01
      0     3      2     10 5.500E 01
      0     4      2      3 6.172E 01
      0     5      3     11 8.331E 01
      0     6      3      4 5.263E 01
      0     7      4     12 7.839E 01
      0     8      4      5 7.934E 01
      0     9      5     13 6.518E 02
      0    10      5      6 1.943E 02
      .     .      .      .      .
      .     .      .      .      .
      .     .      .      .      .
      0   537    164    998 3.879E 03
      0   538    165    998 1.009E 03
  11100
  22200                                              RADIATION COUPLING BLOCK
      0     1      1    992 6.024E 00
      0     2      1    994 5.793E 00
      0     3      2    992 6.024E 00
      0     4      3    992 9.180E 00
      0     5      4    992 8.652E 00
      0     6      5    992 1.506E 01
      0     7      6    992 7.933E 00
      0     8      7    992 7.107E 00
      0     9      8    992 9.156E 00
      0    10      8    993 5.793E 00
      0    11      9    994 6.159E 00
      .     .      .      .      .
      .     .      .      .      .
      .     .      .      .      .
2165-035B
```

FIG. 33 SAMPLE OUTPUT FILE (SHEET 2 OF 3)

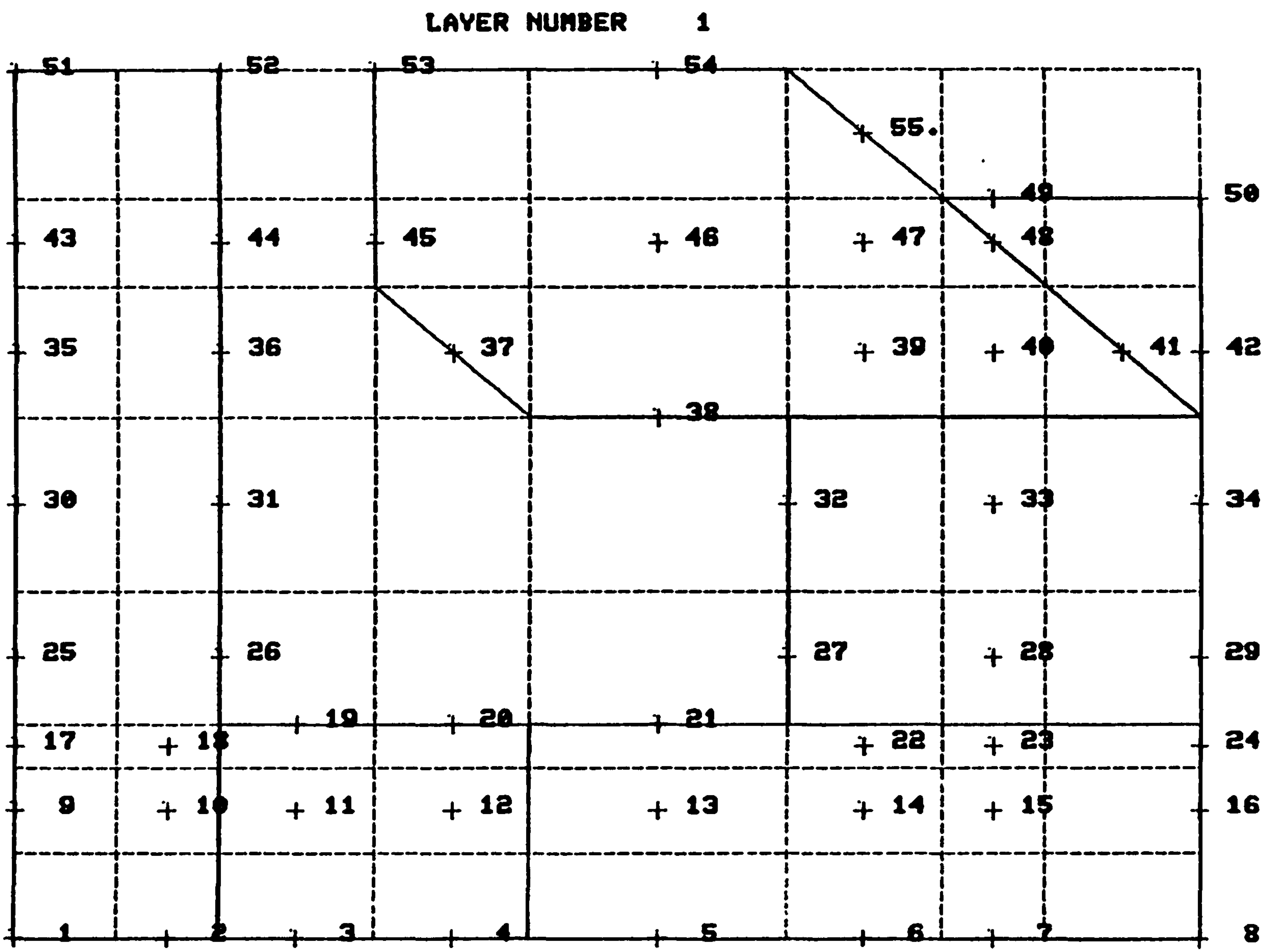
```
      0  235   158   998 2.861E 00
      0  236   159   998 2.861E 00
      0  237   160   998 7.371F 00
      0  238   161   998 5.173E 00
      0  239   162   998 5.173F 00
      0  240   163   998 7.429F 00
      0  241   164   998 1.293E 01
      0  242   165   998 3.363E 00
  11100
  22200                                             HEAT SOURCE BLOCK
  11100
  22200                                                                  CCND--APEA/X--BLOCK
          1          3.11963         5.86849     1     1
          2          2.38496         5.76992     1     1
          3          3.11963         5.86848     1     1
          4          5.76992         3.78627     1     2
          5          4.75401         8.94301     2     2
          6          3.78627         4.01734     2     2
          7          4.48053         8.42864     2     2
          8          4.01734         2.30797     2     3
          9          7.79905        14.67119     3     3
          .             .               .        .     .
          .             .               .        .     .
          .             .               .        .     .

        356          2.42465         1.73189     5     5
        357          1.26111         0.90080     5     5
        358          0.57211         0.40865     5     5
        359          0.57211         0.40865     6     6
        360          1.47411         1.05294     6     6
        361          1.03452         0.73335     1     1
        362          1.03452         0.73394     1     1
        363          1.48534         1.06131     5     5
        364          2.58630         1.84736     5     5
        365          0.67260         0.48043     5     5
  11100
  22200                                             TABLE BLOCK
  11100
  11100
  11100
2165-036B
```

FIG. 33 SAMPLE OUTPUT FILE (SHEET 3 OF 3)

```
DO YOU WISH TO USE THE BOUNDARY OPTION?
yes

DO YOU WISH TO SEE A PLOT OF THE BOUNDARY NODE CONFIGURATION?
yes
```

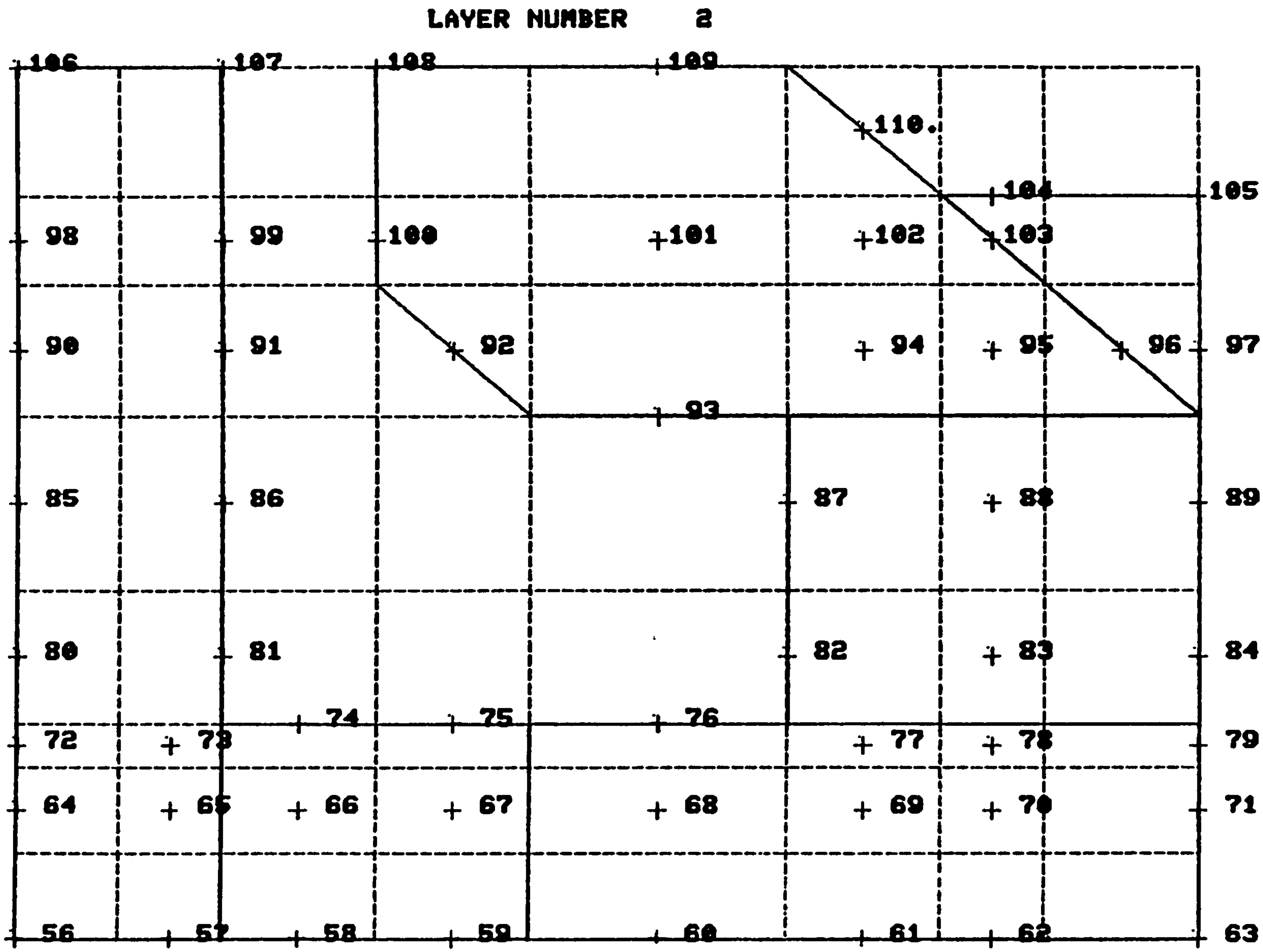
2165-037B

FIG. 34 BOUNDARY NODE OPTION



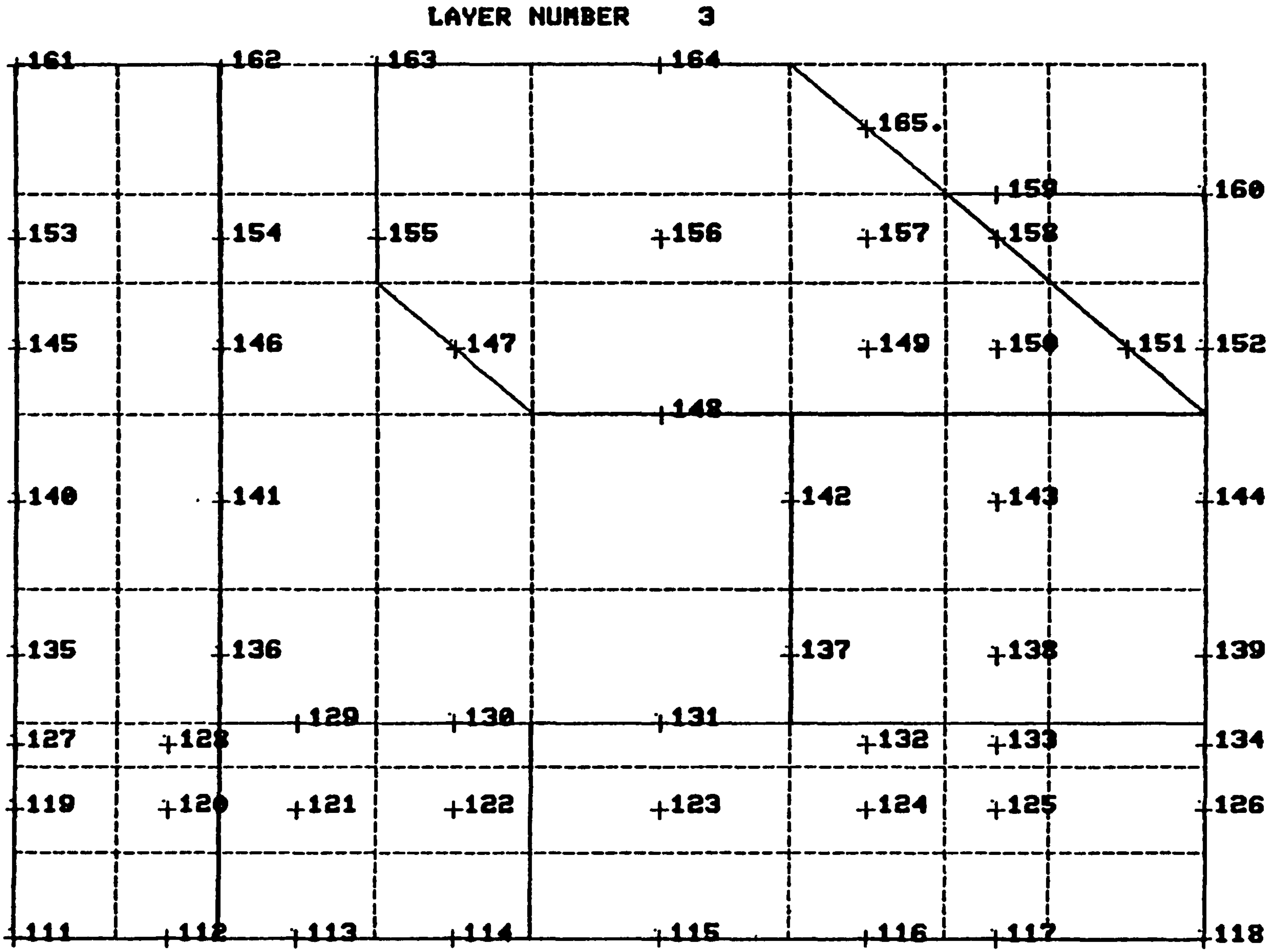
2165-038B

FIG. 35 BOUNDARY NODE OPTION – LAYER 1



2165-039B

FIG. 36 BOUNDARY NODE OPTION – LAYER 2



2165-040B

FIG. 37 BOUNDARY NODE OPTION – LAYER 3

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Section 6

DETERMINATION OF COUPLINGS

The units of length and area are based on the model dimensions in the input file. Consistency of units is the responsibility of the user. Both conductance couplings and radiating areas are calculated by the program.

6.1 CONDUCTANCE (K)

6.1.1 Rectangular Nodes

6.1.1.1 Internal - The determination of conductive couplings is calculated as $K = kA/L$ where A is the cross-sectional area between nodes, and L is the distance between centroids.

6.1.1.2 Boundary Option - The conductive coupling calculation is the same as that for internal nodes except that the additional length out to the boundary of surface nodes is taken into account. This approach is applied in all three dimensions.

6.1.2 Triangular Nodes

6.1.2.1 Internal - The node center is assumed to be at the centroid of the triangle. The determination of conductance is illustrated in Figure 38.

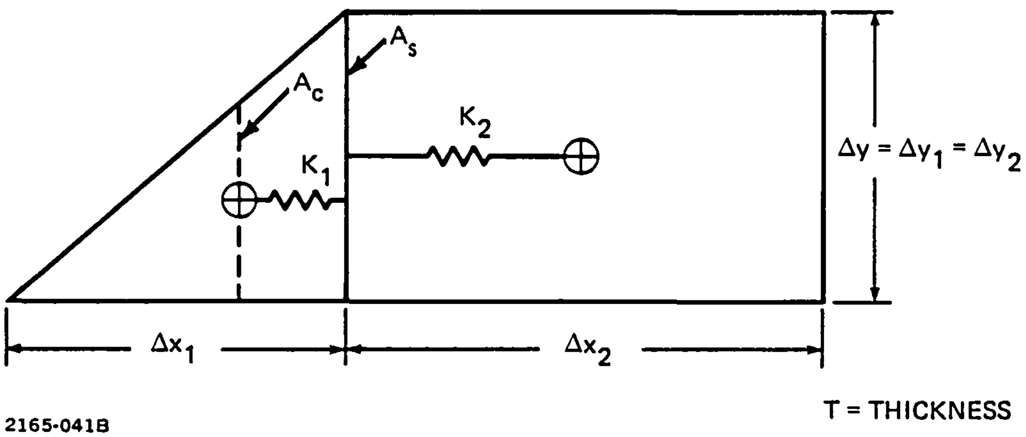

FIG. 38 DETERMINATION OF CONDUCTANCE LINKS – TRIANGLE TO RECTANGLE

For triangular nodes, the cross-sectional area is the average of the area at the node surface and that at the centroid parallel to the node surface.

s = surface
c = centroid

$$A_{avg} = \frac{A_c + A_s}{2} = 5/6\ A_s$$

$$K_1 = \frac{kA}{L} = \frac{k_1\ (5/6\ (\Delta Y)\ t)}{\Delta X_1/3} = 5/2\ k_1\ \frac{\Delta Yt}{\Delta X}$$

$$K_2 = \frac{kA}{L} = \frac{k_2\ \Delta Yt}{\Delta X_2/2} = \frac{2k_2\ \Delta Yt}{\Delta X}$$

$$K_{12} = \frac{K_1\ K_2{}^*}{K_1 + K_2}$$

Another internal triangular node configuration is illustrated in Figure 39. In this case the average cross-sectional area between the centroid and the sloped boundary is:

$$A = 5/6\ \left(\sqrt{(\Delta X)^2 + (\Delta Y)^2}\right) t$$

and

$$L_{1\text{-interface}} = 1/2\ \left(1/3\ \sqrt{(\Delta X)^2 + (\Delta Y)^2}\right) = 1/6\ \sqrt{(\Delta X)^2 + (\Delta Y)^2}$$

thus

$$K_1 = \frac{k_1 A}{L} = \frac{k(5/6\sqrt{})\ t}{1/6\sqrt{}} = 5\ kt$$

and as before

$$K_{12} = \frac{K_1 K_2}{K_1 + K_2}$$

*Note that the displacement between nodes in the y-direction has been neglected.

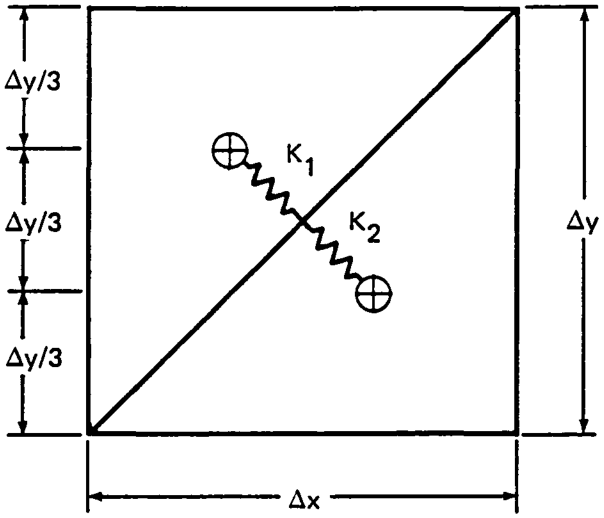

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FIG. 39 DETERMINATION OF CONDUCTANCE LINKS – TRIANGLE TO TRIANGLE

It should be noted that this representation is accurate for isosceles triangular nodes. For triangular nodes with a large aspect ratio (e. g., greater than 2:1) this representation may not give adequate results so that a more nearly square grid in desireable when using triangular nodes.

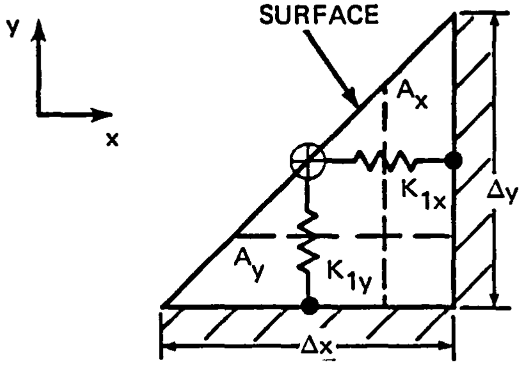
6.1.2.2 Boundary Option - the conductive coupling calculation is the same as for internal nodes except that the additional length out to the surface or corner of the node is taken into account. In each case the average cross-sectional area taken over the length L is used. Figure 40 illustrates the calculation details for the possible configurations.

6.2 RADIATION

As an aid to the user, exposed surface areas of the nodes are set up in the radiation coupling block. These areas can either be modified or deleted. Seven fictitious boundary node designations have been used to allow rapid identification of node surfaces. These boundary nodes are set up as the second node number in the radiation coupling format. The boundary nodes are defined in the following table:

CONFIGURATION

EQUATIONS



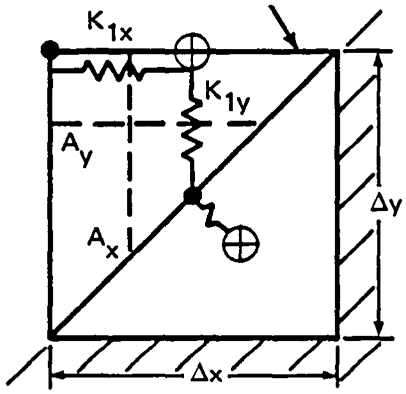
Avg x-direction area = A_x

$A_x = 3/4\ \Delta y * t$

t = layer thickness

$$K_{1x} = k \frac{[A_x]}{\Delta x/2} = 1.5\,k \frac{\Delta y * t}{\Delta x}$$

also $$K_{1y} = k \frac{A_y}{\Delta y/2} = 1.5\,k \frac{\Delta x * t}{\Delta y}$$

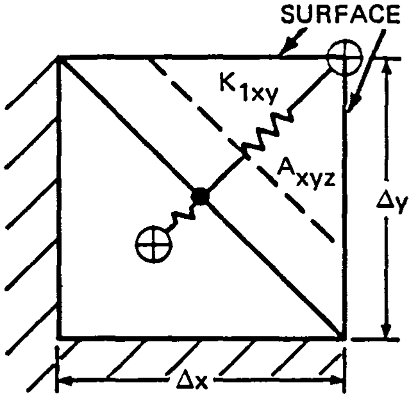


$A_x = 3/4\ y * t$

$A_y = 3/4\ x * t$

$$K_{1x} = 1.5\,k \frac{\Delta y * t}{\Delta x}$$

$$K_{1y} = 1.5\,k \frac{\Delta x * t}{\Delta y}$$



$$A_{xyz}\ \text{avg} = \left[1/2\ \sqrt{(\Delta x)^2 + (\Delta y)^2}\right] t$$

$$L = 1/2\ \sqrt{(\Delta x)^2 + (\Delta y)^2}$$

$$K_{1xy} = \frac{k\, A_{xyz\ avg}}{L} = kt$$

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FIG. 40 DETERMINATION OF CONDUCTANCE LINKS – BOUNDARY NODES

BOUNDARY NODE DESIGNATION	DIRECTION	PLANAR AREA
991	+ y side	xz
992	- y side	xz
993	+ x side	yz
994	- x side	yz
995	x - y (hypotenuse)	xyz
998	- z side	xy
999	+ z side	xy

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Section 7

BOUNDARY NODE ORIENTATION

When the boundary option is employed, the internal node configuration is altered to a prescribed surface configuration. The actual location of the surface node depends on the boundary orientation with respect to the node in question. Figure 41 displays the movement of the internal node to the surface. The figure is broken down into 6 (A - F) representative surface nodes. "A" represents an internal node surrounded on all sides but one. The node is then placed at the midpoint of the surface exposed to boundary when the boundary option is activated. Although only one orientation of "A" is shown, the movement could have been in any direction, i.e., the boundary could have been on the bottom (in which case the node would have been placed there), etc.

"B" represents a node surrounded on two adjacent sides and the node is placed at the corner. "C" represents a triangular node the hypotenuse of which sees boundary. The node is placed at the midpoint of the hypotenuse. "D" displays a triangular node bases of which are exposed to boundary, in which case the node is placed at the corner. "E" and "F" represent triangular nodes where only one base is exposed to boundary, in which the node is placed at the midpoint of that base.

Figure 42 displays improperly designed nodes that cannot employ the boundary option. When any of these arrangements are encountered, the program will leave the internal node unaltered and write a message in the output file warning the user that the node was not altered.

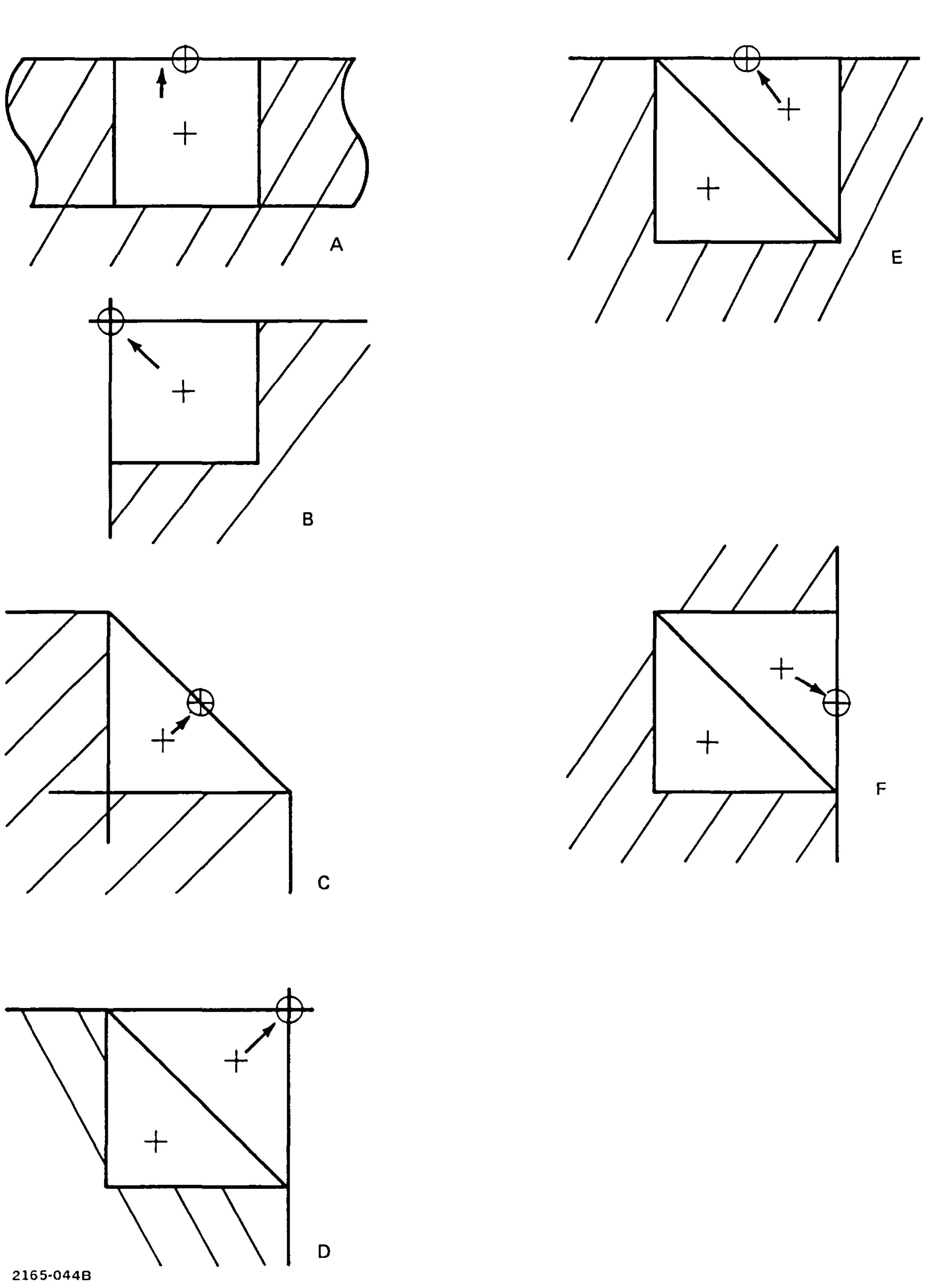

FIG 41 BOUNDARY NODE PLACEMENT

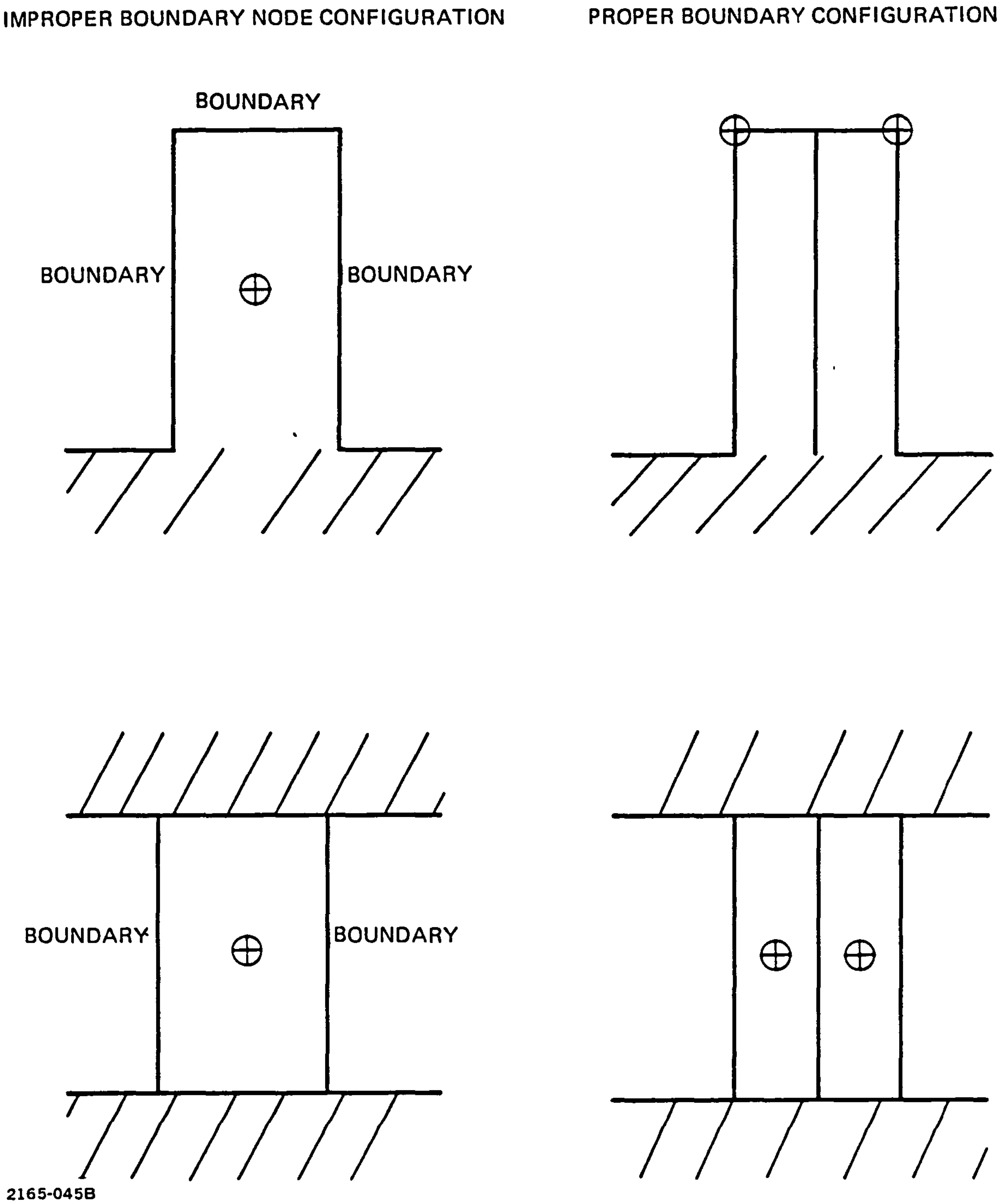

FIG. 42 IMPROPER NODE ORIENTATION

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Section 8

REFERENCES

1. J. Palmieri and K. Rathjen, "CAVE3: A General Transient Heat Transfer Computer Code Utilizing Eigenvectors and Eigenvalues," NASA CR145290, Feburary 1978.

1. Report No	2. Government Accession No	3. Recipient's Catalog No
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	6. Performing Organization Code
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Langley Technical Monitor: James L. Hunt

16. Abstract

Under contract NASA-14643, Grumman developed the computer code CAVE3 ("A General Transient Heat Transfer Computer Code Utilizing Eigenvectors and Eigenvalues") which performed a specialized transient thermal analysis.

Under the present funding, a new extension of CAVE3 code was developed that automates the creation of a finite difference math model in digital form ready for input to the CAVE3 code. The new software, Nodal Network Generator, is broken into two segments. One segment generates the model geometry using a Tektronix Tablet Digitizer and the other generates the actual finite difference model and allows for graphic verification using Tektronix 4014 Graphic Scope.

This report describes how to use the Nodal Network Generator.

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