NASA CR-145069

OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

Technical Report 76-M6

(NASA-CR-145069) TAP 1: A FINITE ELEMENT PROGRAM FOR STEADY-STATE THERMAL ANALYSIS OF CONVECTIVELY COOLED STRUCTURES Interim Report, 1 Sep. 1975 - 30 Sep. 1976 (Old Dominion Univ. Research Foundation) 135 p G3/34
N77-13367
HC A07
MF A01
Unclas
57936

TAP 1: A FINITE ELEMENT PROGRAM FOR STEADY-STATE THERMAL ANALYSIS OF CONVECTIVELY COOLED STRUCTURES

By

Earl A. Thornton

Interim Report

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Under
Research Grant NSG 1237
September 1, 1975 - September 30, 1976
Allan R. Wieting, Technical Monitor
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TAP 1: A FINITE ELEMENT PROGRAM FOR STEADY-STATE THERMAL ANALYSIS OF CONVECTIVELY COOLED STRUCTURES

By Earl A. Thornton[1]

SUMMARY

A finite element computer program (TAP 1) for steady-state thermal analysis of convectively cooled structures is presented. The program has a finite element library of six elements: two conduction/convection elements to model heat transfer in a solid, two convection elements to model heat transfer in a fluid, and two integrated conduction/convection elements to represent combined heat transfer in tubular and plate/fin fluid passages. Nonlinear thermal analysis due to temperature dependent thermal parameters is performed using the Newton-Raphson iteration method. Program output includes nodal temperatures and element heat fluxes. Pressure drops in fluid passages may be computed as an option. A companion plotting program (TAPPLT) for displaying the finite element model and predicted temperature distributions is presented. User instructions and sample problems are presented in appendixes.

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INTRODUCTION

TAP 1 (Thermal Analysis Program) was written in the course of research aimed toward the development of finite element methodology for the thermal analysis of convectively cooled structures. The finite element methodology and applications to several convectively cooled structures are presented in reference 1.

The main body of this report presents: (1) the salient features of the finite element theory, (2) the computer program organization, (3) the finite element library, (4) the nonlinear solution algorithm, and (5) a companion computer graphics program TAPPLT. General directions for use of the programs are presented in Appendices A-C. Program input data and output are illustrated with sample problems in Appendix D.

FINITE ELEMENT FORMULATION

Thermal analysis of convectively cooled structures includes coupled conduction and convective heat transfer in a region consisting of a solid structure and a moving fluid. The problem may be mathematically formulated in terms of the energy equations of the solid and fluid assuming incompressible flow (ref. 2). For steady-state heat transfer, neglecting viscous energy dissipation in the fluid, the temperature $T\ (x, y, z)$ satisfies:

$$\vec{\nabla} \cdot (\underline{\underline{K}}_S \cdot \vec{\nabla} T) = 0 \tag{1}$$

for the solid region and

$$\rho C_p \vec{V} \cdot \vec{\nabla} T - \vec{\nabla} \cdot (\underline{\underline{K}}_F \cdot \vec{\nabla} T) = 0 \tag{2}$$

for the fluid region where $\underline{\underline{K}}_S$ and $\underline{\underline{K}}_F$ denote the conductivity tensors of the solid and fluid, respectively; ρ is the fluid mass density; and C_p is the fluid specific heat. The thermal properties of the solid ($\underline{\underline{K}}_S$) and fluid ($\underline{\underline{K}}_F$ and C_p) are temperature dependent. The velocity vector $\vec{V}$ (eq. 2) specifies the fluid motion as a function of the spatial coordinates and, in general, is unknown. Equations (1) and (2) must be solved subject to specified boundary conditions on the external surfaces of the region and appropriate continuity conditions at the solid/fluid interface.

In the most general approach to thermal analysis of convectively cooled structures the steady-state velocity distribution of the fluid must first be determined by solving the momentum and continuity equations of fluid flow. With the fluid velocity distribution known, equations (1) and (2) may then be solved simultaneously for the temperature distribution in the solid/fluid region.

In TAP 1 a simplified finite element solution procedure is employed using a number of assumptions customarily used in practical heat transfer analysis (ref. 1). The thrust of the assumptions is the elimination of the computation of the fluid velocity distribution.

The solid region of the convectively cooled structure is represented by standard conduction/convection elements. Two conduction/convection elements, a rod and a quadrilateral, are available in the program. The fluid region of a convectively cooled structure is modeled by elements which represent convective heat transfer in the coolant passages. Basic convective finite elements were developed for the fluid to represent each of the terms in equation (2). The first term is represented by a mass transport convection element, and the second term is represented by surface convection elements with unknown fluid temperatures. Special integrated conduction/convection finite elements were also developed: (1) a tube/fluid element, and (2) a plate-fin/fluid element. The basic convection elements and the integrated conduction/convection elements may be combined with the standard conduction elements for analysis of a variety of convectively cooled structures. Any of the elements may also be used independently.

PROGRAM ORGANIZATION

The organization of TAP 1 is based on the SAP family of structural analysis programs (refs. 3, 4). A flow chart of the TAP 1 main program is presented in figure 1. The main program consists of eight subroutines which are sequentially called in a normal program execution. These subroutines

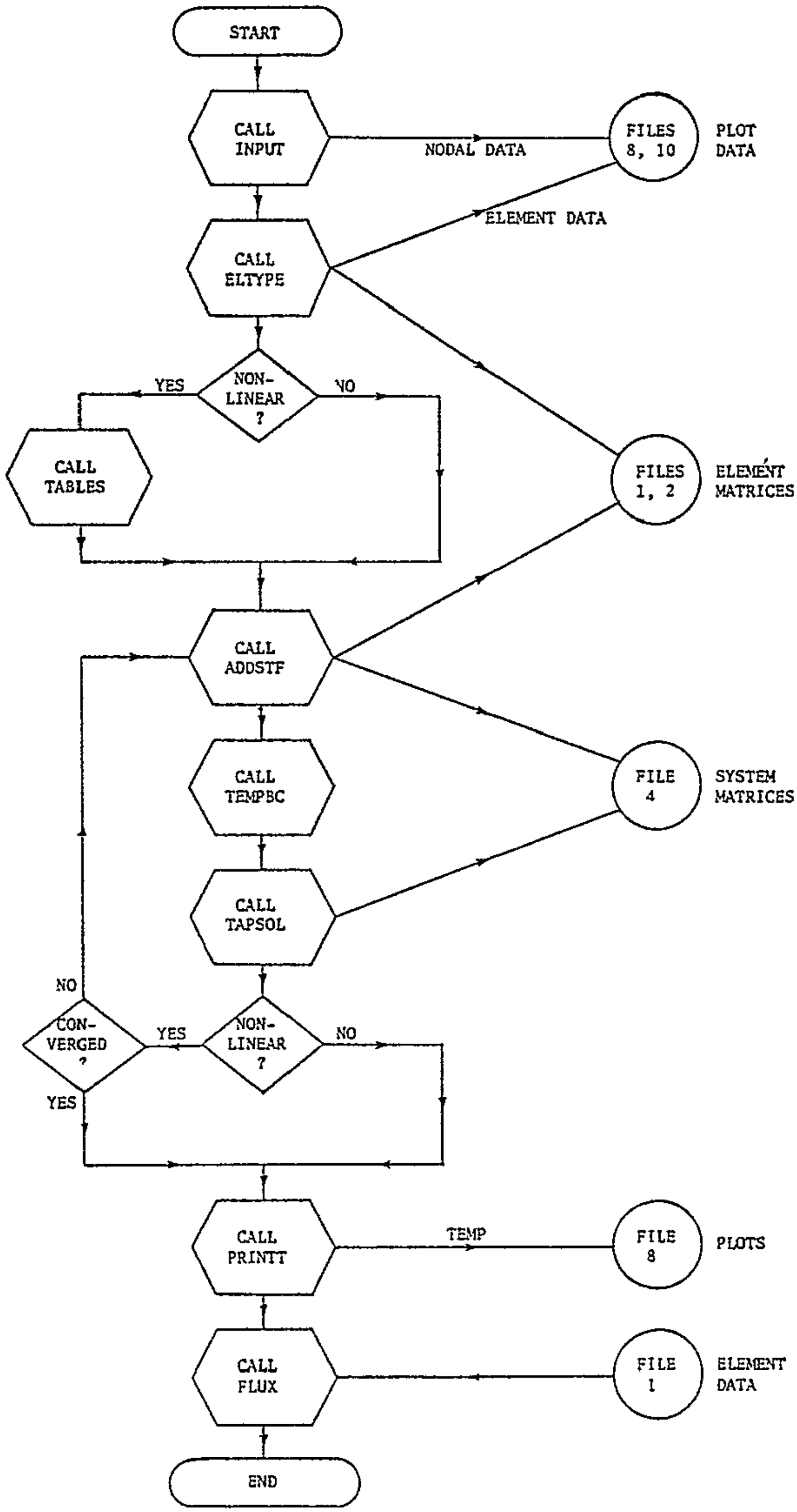


Figure 1. Flow chart of program TAP 1.

process input data, generate plot files, assemble and solve the equations, print nodal temperatures, and perform heat flux calculations. Dynamic storage allocation is used to store all input data and large arrays in a blank common designated in the main program as A. At execution, the amount of blank common storage available is calculated in the main program from the JOB card field length. The amount of blank common is the only restriction on the amount of input data, i.e., there are no other limitations on number of nodes, elements and thermal parameters.

Nodes (INPUT)

The thermal system is described by a set of nodal points with unknown temperatures. A nodal point is described by a data card containing the node number, a boundary condition code (zero or one), the nodal coordinates, a generation parameter, and a specified nodal temperature if required. Nodal points which may be entered in rectangular Cartesian coordinates (x, y, z) or cylindrical coordinates (R, Y, Θ). Input data for regular nodal patterns may be reduced by utilization of a nodal generation capability based on linear interpolation. All nodal point data are retained in core during the assembly of the element conductance matrices. Nodal point data are also saved on an auxiliary storage file if plots are requested.

A boundary condition code of zero indicates an unknown nodal temperature. A boundary condition code of one indicates a specified nodal temperature which will be held constant during the solution. Heat loads and convective boundary conditions are specified as a part of the element input data.

Elements (ELTYPE)

Elements are entered into the program in groups which consist of a number of sequentially numbered elements of the same type. There may be more than one group of the same element type. Data generation schemes are provided for all elements to reduce input data for regular finite element meshes.

The input data for all elements follows the same general scheme: (1) a control card for each element group, (2) a set of thermal parameter cards, and (3) a set of element cards. For a linear analysis thermal parameters are entered as constants; for a nonlinear analysis table numbers are entered. Each element may have different thermal parameters.

Element conductance matrices, heat load vectors and heat flux matrices are computed as the element data cards are read. These matrices are stored sequentially on files for later use in assembly of the system equations and in heat flux computations. For elements with more than one thermal parameter, the element conductance matrices are resolved into components, one for each thermal parameter. For a linear analysis the conductance matrices are formed for the thermal parameters entered; for a nonlinear analysis the conductance matrices are formed initially for unit thermal parameters. Element connectivity data are saved on an auxiliary storage file if plots are requested.

As element data are processed the system bandwidth is computed. Bandwidth is defined herein as the maximum difference between two connected node numbers plus one to account for the diagonal. The bandwidth is used later in the program to determine storage requirements for the system conductance matrix. For optimum program storage requirements and execution times the bandwidth should be a minimum. Bandwidth is determined by the user's nodal numbering scheme (see ref. 5).

After all element data have been processed, the nodal coordinates are no longer needed, and the corresponding core storage area is used for other variables. The nodal boundary conditions are, however, retained in core since they are required later in the solution process.

Thermal Parameter Tables (TABLES)

For a nonlinear analysis thermal parameter tables are required. The input data consists of a control card for each table and a set of cards containing temperature and thermal parameter data points. The thermal parameter data are retained in core during the balance of the solution process. Ordinarily, the amount of core storage required for the tables is small in comparison to storage required for the system matrices. In the solution process, linear interpolation and extrapolation are used in looking up thermal parameters.

Assembly of System Matrices (ADDSTF)

The system conductance matrix and heat load vector are formed in blocks as shown in figure 2. Because of mass transport convection and the Newton-Raphson iteration process, the system conductance matrix may, in general, be asymmetrical. Hence, advantage of matrix symmetry could not be taken as in structural analysis. The number of equations in a block depends on the amount of blank common storage available and is computed in the program from the equation:

$$NEQB = (MTOT - 2*NUMNP - 2*NUMTB - NENT)/(4*MBAND) \tag{3}$$

where

NEQB - number of equations in a block;

MTOT - amount of blank common storage;

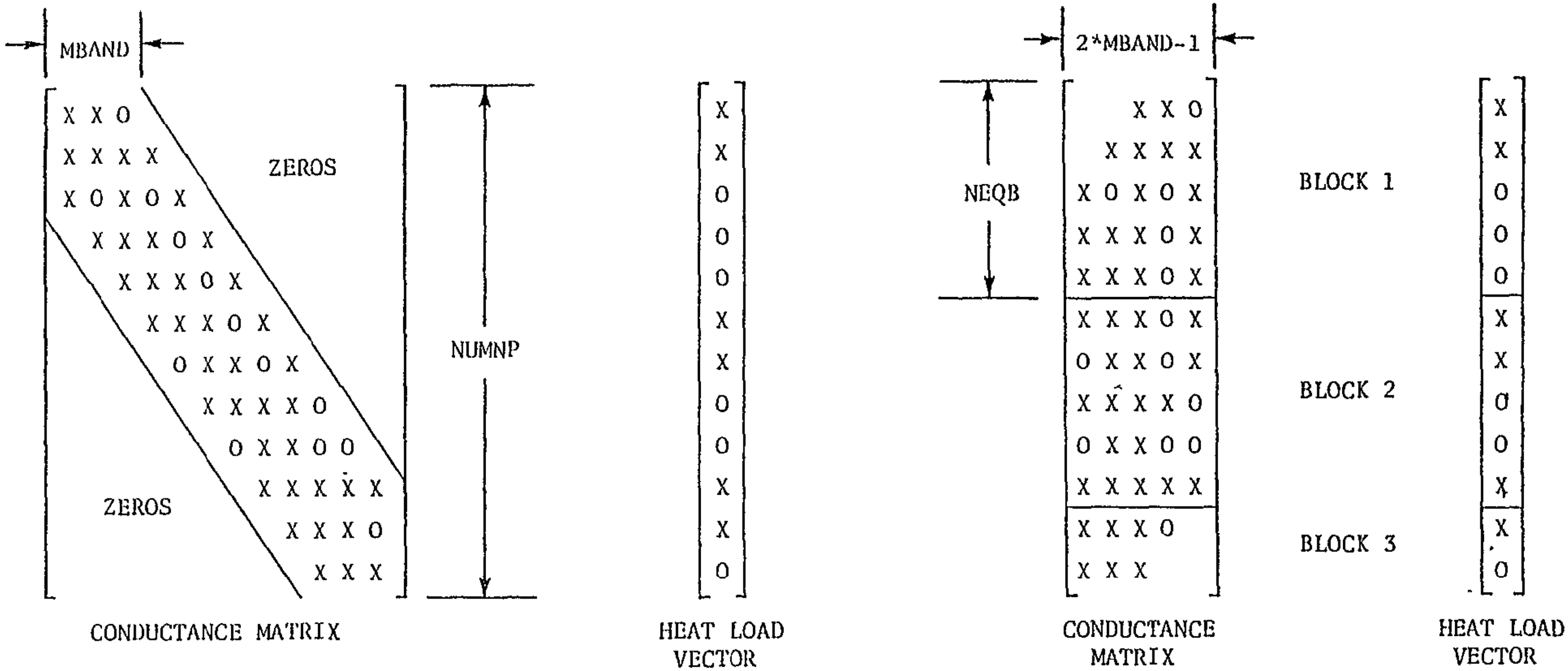
NUMNP - number of nodal points;

NUMTB - number of tables;

NENT - number of table entries;

MBAND - bandwidth of conductance matrix.

With the number of equations per block known, the thermal conductance matrix and heat load vector are assembled two blocks at a time by direct addition of the element matrices. During a nonlinear analysis the Newton-Raphson correction to the element matrices is performed as part of the assembly operation. In the assembly operation it is necessary to pass through the element matrices which are stored on a file. In order to minimize file reading (ref. 4), element matrices which pertain to the next several blocks are written on another file. This method, for large problems, significantly reduces the amount of file reading in the formation of the equation blocks.



(a) Actual System Matrices.

(b) Block Storage of System Matrices.

Figure 2. Program storage of system matrices.

In a linear analysis the equation blocks are assembled only once; in a nonlinear analysis the equation blocks are reassembled for each iteration (see fig. 1).

Boundary Conditions (TEMPBC)

In finite element thermal analysis with TAP 1 the only nodal boundary conditions required are specified temperatures (i.e., temperature gradients can not be specified). Specified nodal temperature data are entered into the program with the nodal input data. Heat fluxes and convective boundary conditions are entered with the element data and are incorporated by the program into the system heat load vector. For a boundary with zero heat flux, no boundary condition need to specified; the heat load terms corresponding to zero heat fluxes are automatically taken as zero.

The program handles the temperature boundary conditions using the method described in reference 6. Basically, this method consists of modifying the conductance matrix and heat load vector such that the size of the matrices is unchanged. The advantage of this approach is the ease of indexing the equations, i.e., the node numbers and equation numbers are the same. A disadvantage is that extra equations are carried in the solution process. For TAP 1 thermal analysis temperature is the only degree of freedom per node, hence the penality is not very large since usually only a small percentage of the equations have specified temperatures.

Solution for Temperatures (TAPSOL)

The general, banded, simultaneous equations are solved by Gauss elmination. The subroutine is based upon the banded out-of-core symmetric equation solver, BANSOL, presented in reference 7. Operations with zero coefficients are skipped. Matrix data is transferred into core two blocks at a time. If a sufficient amount of blank common is available to store the equations in two blocks or less, an in-core solution is performed. The basic limitation on the equation solver for a given field length is that the number of equations in a block must be greater than the bandwidth. Normally, this restriction poses no problem and may be overcome by increasing the field length or renumbering the nodes to reduce the bandwidth. Block size is automatically determined at execution.

For some assemblies (e.g., in series) of mass transport convection elements it is possible to obtain zero coefficients on the diagonal of the conductance matrix. Dependent on the boundary conditions, such a problem may cause the equation solver to stop with an error message to avoid a zero divisor in the Gauss elimination process. This difficulty can normally be overcome by renumbering the nodes so that a zero diagonal coefficient is filled in during the elimination process. A zero diagonal coefficient will not arise in the integrated thermal/fluid elements for a nonzero convection coefficient.

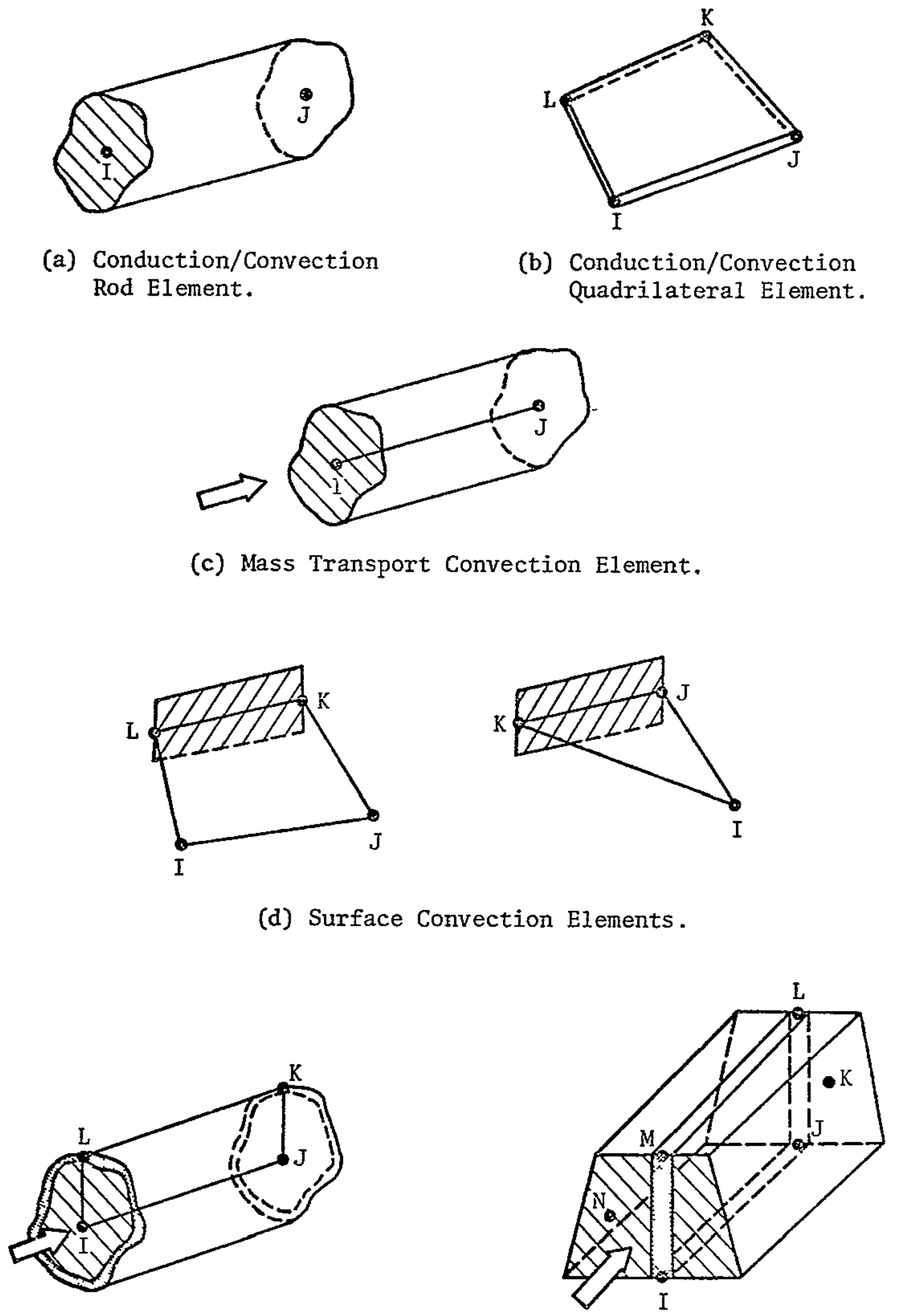
Heat Flux Calculations (FLUX)

After the nodal temperatures are computed, element heat fluxes are calculated using element matrices previously stored on a file. Typical element fluxes calculated include, e.g., for the quadrilateral conduction/ convection element, conduction heat flux components at the element centroid and convection heat fluxes on the top and bottom surfaces and four edges. In general, conduction heat flux components are positive in directions of the local element axes, and surface convection fluxes are positive into a surface.

For the integrated thermal/fluid elements pressure drops are computed as a user option in the heat flux computations. Pressure drop computations include flow-friction and flow-acceleration effects (see ref. 8). Pressure drops are computed for three user options: (1) constant density, (2) variable density using a density-temperature table, or (3) an ideal gas.

THE ELEMENT LIBRARY

The library consists of six elements (fig. 3) for either linear or nonlinear thermal analysis.



(a) Conduction/Convection Rod Element.

(b) Conduction/Convection Quadrilateral Element.

(c) Mass Transport Convection Element.

(d) Surface Convection Elements.

(e) Tube/Fluid Element.

(f) Plate-fin/Fluid Element.

Figure 3. Element library of TAP 1.

Conduction/Convection Rod Element

The rod element is based on the same assumptions as the NASTRAN rod element (ref. 9). A linear temperature variation is assumed between nodes. The element permits heat loading due to internal heat generation, prescribed surface heat flux or surface convection. The convection heat transfer coefficient and fluid medium temperature may be different at each node.

Conduction/Convection Quadrilateral Element

The quadrilateral element is based upon an isoparametric formulation similar to the approach described for structural elements in reference 5. The term isoparametric means the same interpolation functions define the element shape and the element temperature distribution. The temperature within the element is given by

$$T\ (\xi,\ \eta) = \sum_{i=1}^{4} N_i\ T_i \tag{4}$$

where N_i are the interpolation functions,

$$\begin{aligned} N_1 &= \frac{1}{4}\,(1 - \xi)\ (1 - \eta) \\ N_2 &= \frac{1}{4}\,(1 + \xi)\ (1 - \eta) \\ N_3 &= \frac{1}{4}\,(1 + \xi)\ (1 + \eta) \\ N_4 &= \frac{1}{4}\,(1 - \xi)\ (1 + \eta) \end{aligned} \tag{5}$$

and T_i are the nodal temperatures. The quantities ξ , η denote the isoparametric coordinates for a unit square. The conductance matrices are computed for the element by integration in the ξ , η plane; in TAP 1 the conductance integrals are evaluated by the four-point Gauss quadrature rule of numerical integration (ref. 5).

For rectangular elements, the conduction heat flux component q_x varies linearly with y, but it is independent of x; similarly the component q_y varies linearly with x, but it is independent of y. Conduction heat flux components are always calculated at the element centroid.

The quadrilateral element permits a laminated composite material. Each lamina is assumed to be orthotropic; input data for a lamina consist of a conductivity tensor, a material axis angle and the lamina thickness. An arbitrary number of lamina are permitted. For a nonlinear analysis the lamina properties are assumed to have the same temperature variation, i.e., an element is characterized by a single conductivity-temperature table.

The element permits internal heat generation, prescribed edge or surface heating, and convection heat transfer on all four edges and the top and bottom surfaces. Convection coefficients and fluid medium temperatures may be different at each node.

Mass Transport Element

The mass transport element represents energy transport downstream due to fluid flow. The element represents the first term in equation (2) and is based on the following assumptions (ref. 1): (1) the thermal energy state of the fluid is characterized by the fluid bulk temperature which varies only in the flow direction, and (2) the fluid velocity is represented by a mean velocity V which varies only in the flow direction. The basic input data is the mass flow rate, $\dot{m}$, and the fluid specific heat c_p.

The mass transport element has an indefinite, asymmetric conductance matrix (see ref. 1). As previously discussed (see Solution for Temperatures), some assemblies of mass transport elements may create zero diagonal terms in the system conductance matrix.

The computation of the element conductance matrix does not depend on the coordinates of the fluid nodes. Thus, fluid nodal coordinates are arbitrary and are used only in plots.

Surface Convection Elements

Surface convection elements (a quadrilateral and a triangle) represent the energy transfer between a coolant passage surface and the fluid. The heat transfer is based upon a convection coefficient for the fluid and a surface area of the passage. The surface area is computed as the product of the distance between wall nodes and an area factor supplied as input data. The fluid nodal coordinates are arbitrary and are used only in plots.

Tube/Fluid Integrated Element

The tube/fluid element consists of fluid within a thin tube of constant thickness and constant, arbitrary cross-section. The element has two fluid nodes I and J and two tube nodes L and K . The fluid node locations are arbitrary at a given flow section and are used only in plots. The following heat transfer modes are represented in the element:

1. Axial conduction in the tube between nodes L and K ;

2. Convection between the internal tube surface and the enclosed fluid (nodes L, K, and nodes I, J);

3. Mass transport convection due to fluid flow from I to J ; and

4. Heat transfer between the external tube surface and a surrounding medium which is represented by specifying a heat flux or the medium temperature and convective film coefficient.

The convection area between the internal tube surface and the enclosed fluid is computed as the product of the distance between tube nodes and the input tube perimeter. The external heating is assumed uniform around the perimeter of the tube. The surface area for external heat transfer is assumed equal to the internal convection area. The temperature and convection coefficient of the surrounding medium may be different at each tube node.

As user options. (1) the fluid convection coefficient may be modified for large temperature differences between the fluid and tube surface (ref. 8), and (2) fluid pressure drops may be calculated (see Heat Flux Calculations).

Plate-Fin/Fluid Integrated Element

The plate-fin/fluid element consists of two walls (plates) connected by an internal fin. For convenience a single plain fin is shown in figure 3; in practice other fin configurations (e.g., pin or offset fins) may be represented by using an equivalent thickness and surface area for the single fin. Fluid flows along both sides of the fins through an arbitrary flow cross section (shown trapezoidal for convenience), which may vary linearly along the element. The element has 6 nodes: two nodes to represent the fluid bulk temperatures (nodes N and K) and four wall/fin nodes (I, J, L, and M). The fluid node locations are arbitrary at a given flow section and are used only in plots. The following heat transfer modes are represented in the element:

1. Two-dimensional conduction in the fin between the nodes I, J, L, and M;

2. Convection between the fin surfaces (nodes I, J, L, and M) and the fluid (nodes N and K);

3. Convection between the wall surfaces (top nodes M and L; bottom nodes I and J) and the fluid (nodes N and K); and

4. Mass transport convection due to fluid flow from N to K.

The fin is modeled as an isoparametric quadrilateral element with surface convection to a fluid with unknown temperatures. Input data describing the fin includes its effective thickness and an area factor for convection. These quantities may be adjusted as input to permit the plain fin to represent other fin configurations.

Convection between the wall surfaces and fluid is based on areas computed using input wall widths, the fin thickness, and internally computed distances between wall nodes. The flow cross-sectional area may vary due to a difference in passage height at the element entrance (I to M) and exit (J to L).

User options are available to. (1) modify the convective heat transfer coefficient for large temperature differences between the fluid and wall surfaces (ref. 8), (2) modify the fin convective heat transfer by an efficiency factor η which accounts for deviations in the fin temperature variation from the assumed linear profile, and (3) compute fluid pressure drops (see Heat Flux Calculations).

NONLINEAR ALGORITHM

The finite element formulation employed in TAP 1 leads to a set of nonlinear algebraic equations of the form

$$[K\ (T)]\ \{T\} = \{Q\} \tag{6}$$

where $[K\ (T)]$ denotes the temperature dependent system conductance matrix, $\{T\}$ denotes the unknown nodal temperature vector, and $\{Q\}$ is the system nodal head load vector. If thermal properties are not a function of temperature, equation (6) reduces to a linear set of equations which may be solved directly. If the thermal parameters are a function of temperature, the Newton-Raphson iteration algorithm is used:

$$[J]_n\ \{\Delta T\}_{n+1} = \{R\}_n \tag{7}$$

$$\{T\}_{n+1} = \{T\}_n + \{\Delta T\}_{n+1} \tag{8}$$

where $[J]_n$ denotes the system Jacobian matrix, and $\{R\}_n$ represents nodal residual heat loads.

A key assumption employed in TAP 1 is that thermal parameters are constant within an element. This assumption permits the nonlinear algorithm to be based upon one initial computation of element conductance matrices for unit thermal parameters. If a particular element depends on more than one thermal parameter, the matrix is formed by summing component matrices, one for each thermal parameter, TP . Thus a typical conductance matrix is expressed as

$$[K] = \sum_m TP_m * [\bar{K}]_m \tag{9}$$

where the summation includes all thermal parameters, TP_m, affecting the element, and $[\overline{K}]_m$ denotes a typical unit conductance matrix. For a typical element with N nodes the average element temperature is computed from

$$T_a = \frac{1}{N} \sum_{\ell=1}^{N} T_\ell \tag{10}$$

and a thermal parameter is looked up in the table using linear interpolation.

The Jacobian matrix and residual load vector for a typical element are computed from

$$J_{ij} = TP^* \overline{K}_{ij} + \frac{1}{N} \frac{d(TP)}{dT_a} \sum_{\ell=1}^{N} \overline{K}_{i\ell} T_\ell \tag{11}$$

$$R_i = Q_i - TP^* \sum_{\ell=1}^{N} \overline{K}_{i\ell} T_\ell . \tag{12}$$

The quantity $d(TP)/dT_a$ represents the slope of the thermal parameter curve. The formulations for the Jacobian matrix and residual load vector have the following computational advantages: (1) the equations are valid for all element types (i.e., rods, quadrilaterals, thermal/fluid elements, etc.), (2) element matrices need to be computed only once, and (3) the Jacobian and residual load vector have common operations.

The Jacobian matrices and residual load vectors are computed for each element and assembled into system matrices at every iteration. The computations are performed as a part of the assembly operations in the subroutine ADDSTF called by the main program (see fig. 1).

TAP 1 automatically uses zero nodal temperatures to initiate the nonlinear solution process. The iteration process is terminated when: (1) a specified number of iterations has been performed, or (2) the largest change in nodal temperature (expressed as a percentage) is less than a specified value. For typical applications convergence has been obtained in from one to three iterations (i.e., two to four analyses) using a convergence criteria of 0.1 percent.

PLOTTING PROGRAM

A companion program, TAPPLT, is used to plot the finite element model and calculated temperature distributions. The program is based on the oblique orthographic projection program described in reference 10.

The program includes options for plots of finite element models annotated with grid point or element numbers. Another option allows boundaries of an isolated portion of the model to be specified by cutting planes to permit detailed inspection of the selected region. Also, exploded views can be generated which separate the elements in a finite element model to detect the absence or presence of elements. Temperature surfaces, i.e., $T = f(x, y)$, can be plotted superimposed on the nodes of the model, or temperatures can be represented as vectors extending from the nodes.

The program is limited to plotting elements with a maximum of four nodes so that the six-noded plate-fin/fluid element is plotted as two quadrilateral elements.

CONCLUDING REMARKS

A finite element computer program (TAP 1) for steady-state thermal analysis of convectively cooled structures has been presented. The program has a finite element library of six elements: two conduction/convection elements to model heat transfer in a solid, two convection elements to model heat transfer in a fluid, and two integrated conduction/convection elements to represent combined heat transfer in tubular and plate/fin fluid passages. Nonlinear thermal analysis due to temperature dependent thermal parameters is performed using the Newton-Raphson iteration method. Program output includes nodal temperatures and element heat fluxes. Pressure drops in fluid passages may be computed as an option.

A companion plotting program (TAPPLT) for displaying the finite element model and predicted temperature distributions has been presented.

APPENDIX A

PROGRAM DETAILS

Computer and System Requirements

TAP 1 and TAPPLT were written using standard FORTRAN IV and were developed on the CDC computer system at LRC. TAP 1 is almost system independent; only two system subroutines (JPARAMS and SIGN) are called. TAPPLT is dependent on the LRC computer graphics software for VARIAN and CALCOMP plots, but can be converted to other graphics systems (see reference 10 for a documented source listing).

Storage Allocation

Dynamic storage allocation is used by both programs. In TAP 1 all large arrays are stored in blank common designated as A; in TAPPLT large arrays are stored in blank common designed ZZZ. TAP 1 computes the blank common available from the job card field length and attempts to process the input data and perform a solution. The program terminates execution with an error message stating the additional storage required if insufficient storage is available. TAPPLT prints the required blank storage required for each execution; if insufficient storage is available, a system error message will result. The field length for both programs is problem dependent; the user may wish to estimate the required field length for any new problem attempted.

TAP 1 Field Length Requirements. An approximate formula for the required field length (in octal) on the Network Operation System (NOS) at LRC is

$$FL_8 = 77{,}400_8 + N_8 \tag{A-1}$$

where N is the additional blank common required which depends on: (1) the amount of nodal input data plus the storage required to process the element type with the maximum amount of material data, and (2) the storage constraint imposed by the equation solver.

For data imput the additional blank common required (in decimal) may be computed from

$$N_{10} = 5*NUMNP + M*NMAT \tag{A-2}$$

where NUMNP is the number of nodal points and NMAT is the number of materials to be used for an element. M depends on the number of material parameters which can be input for an element:

Element	M
Rod	3
Quadrilateral	5
Surface Convection	3
Mass Transport	3
Tube/Fluid	16
Plate-fin/Fluid	16

The second term in equation (A-2) is computed for each element group and the maximum value is used.

For solution of the equations the minimum storage is determined by the constraint that the number of equations in a block [see eq. (3)] be greater than or equal to the system bandwidth. This requirement will be met if

$$N_{10} = 4*MBAND**2 + 2*NUMNP + 2*NUMTB + NENT \tag{A-3}$$

where NUMTB is the number of tables and NENT is the number of table entries.

For optimum execution times it is usually desirable to have an amount of storage available larger than the minimum computed above (see Solution for Temperatures). This guideline normally will insure that sufficient storage is available to process the input data. It may be helpful to note that on the NOS a job card field length of $125,000_8$ will make available a blank common area of $11,000_{10}$ which is an adequate amount of storage for most moderate size problems (say, less than 300 nodes).

TAPPLT Field Length Requirements. A conservative formula for the required field length on the NOS is

$$FL_8 = 33,000_8 + (5*NUMNP)_8 .$$

Auxiliary Storage Files

TAP 1 uses 10 auxiliary storage files in a normal execution. The auxiliary storage files are identified in the table below.

TAP 1 Auxiliary Storage Files

File	Function
1	Element flux and pressure drop calculation data
2	Element conductance matrices
3	Temporary storage (TAPSOL)
4	System conductance and heat load matrices
5	Input data
6	Printer output
7	Temporary storage (ADDSTF, TEMPBC, TAPSOL)
8	Nodal data for plots
9	Thermal fluid modification data
10	Element data for plots

APPENDIX B

INPUT DATA FOR TAP 1

General Setup of Input Deck

The general setup of a typical input data deck is shown schematically in figure 4. A deck requires four basic data groups and a fifth optional group of data as follows:

(1) A single heading card containing any desired title information;

(2) A single master control card containing control values specifying various program options;

(3) A node input deck containing nodal coordinates, the boundary condition code, and specified nodal temperatures,

(4) An element input deck containing element data organized by groups. Each group consists of the following sequence of cards:
   (a) a control card containing control values and a heading to be printed for the element group,
   (b) a set of material property cards,
   (c) a set of element cards; and

(5) For a nonlinear analysis, the thermal parameter tables organized as a set of cards for each table.
   (a) a control card containing control values and a heading to be printed with the table, and
   (b) the data points in the thermal parameter table.

Several problems may be solved on one program execution by placing the problem data decks in sequence. Plots can be obtained for only the last problem in a sequence.

Input Data Cards

Data cards are described in detail in this section. Input data is expressed in standard FORTRAN I, F, or A formats. Integers must be right

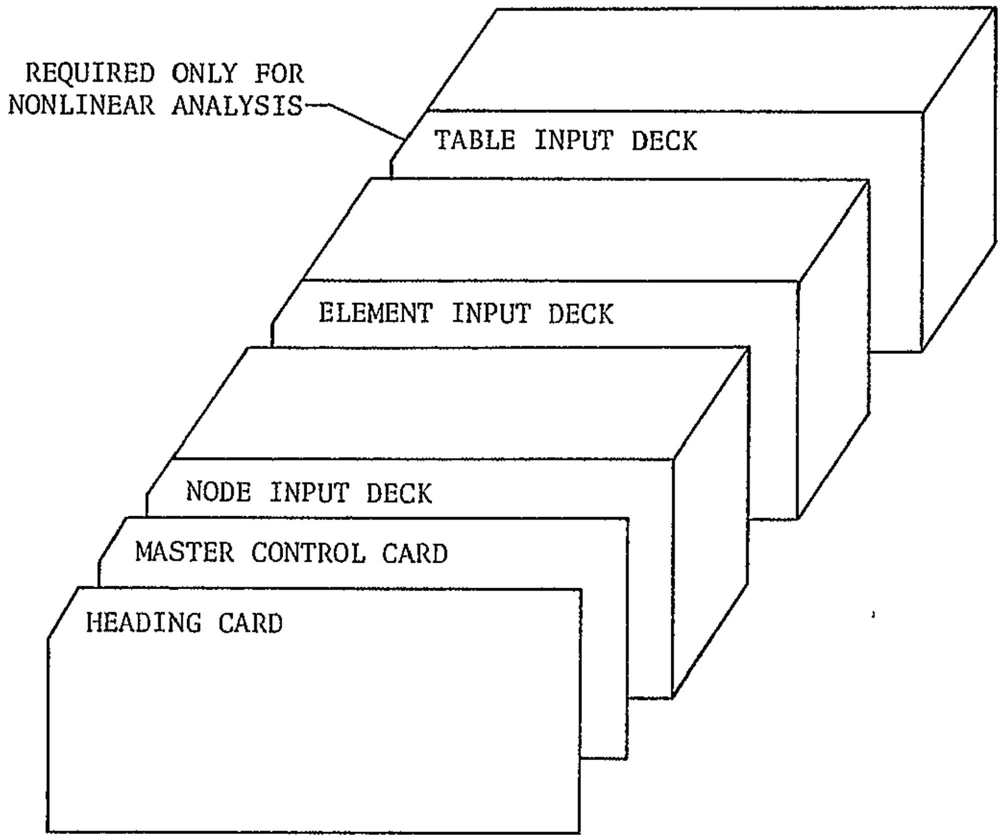


Figure 4. Input data sequence for TAP 1.

justified. The F format may be used to read real numbers expressed in an E format; however, numbers in an E format must be right justified.

Any consistent set of units may be used. In the input data instructions which follow sample units are given for illustrative purposes only.

I. HEADING CARD (12A6)

notes	columns	variable	entry
(1)	1 - 72	HED(12)	Enter the heading information to be printed with the output

NOTES/

(1) Begin each new problem with a heading card.

II. MASTER CONTROL CARD (7I5,F10.0)

notes	columns	variable	entry
(1)	1 - 5	NUMNP	Total number of nodal points in the model
(2)	6 - 10	NELTYP	Number of element groups
(3)	11 - 15	NUMTB	Number of thermal parameter tables (for nonlinear analysis)
(4)	16 - 20	NANA	Analysis type .EQ.0; Data check only .EQ.1; Linear .EQ.2; Nonlinear
(5)	21 - 25	NDIAG	Flag for diagnostic printing .EQ.0; No diagnostic output .GT.0; Diagnostic output
(6)	26 - 30	NPLOT	Plot control code .EQ.1; Thermal model and input temperature plots .EQ.2; Thermal model and computed temperature plots
(7)	31 - 35	NITER	Maximum number of Newton-Raphson iterations (default .EQ.6)
(8)	36 - 45	TOL	Convergence tolerance (default .EQ.0.1%)

NOTES/

(1) Nodes are labeled with integers ranging from "1" to the total number of nodes in the system, "NUMNP."

(2) For each different element type (ROD, QUAD, etc.) a new element group must be defined. Elements within groups are assigned integer labels ranging from "1" to the total number of elements in the group. Element groups are input in Section IV, below.

Element numbering must begin with one (1) in each different group. It is possible to use more than one group of the same element type.

(3) For a nonlinear thermal analysis, parameters are defined by thermal parameter tables. Thus for a nonlinear analysis (NANA .EQ.2) the number of tables should be entered. For a linear analysis (NANA .EQ.1), the number of tables may be left blank or entered as a zero.

II. MASTER CONTROL CARD (concluded)

(4) For NANA .EQ.0 the program reads all input data, generating nodes, and elements as requested, and generates element matrices. Plot files are created for checking input data. Exit is made before the system matrices are assembled and the solution is performed.

For NANA .EQ.1 the thermal parameters are constant, and a linear thermal analysis is performed. An unsymmetrical set of banded equations is solved using Gauss elimination.

For NANA .EQ.2 the thermal parameters vary with temperature and are entered in tabular form. The equations are solved by Newton-Raphson iteration.

For both linear and nonlinear thermal analyses conduction and convection heat fluxes are automatically recovered.

(5) Diagnostic output may be obtained using this integer. This output typically consists of all element matrices, the assembled matrices, and intermediate steps in the solution process. This option should only be selected for very small problems since a large quantity of data will be printed.

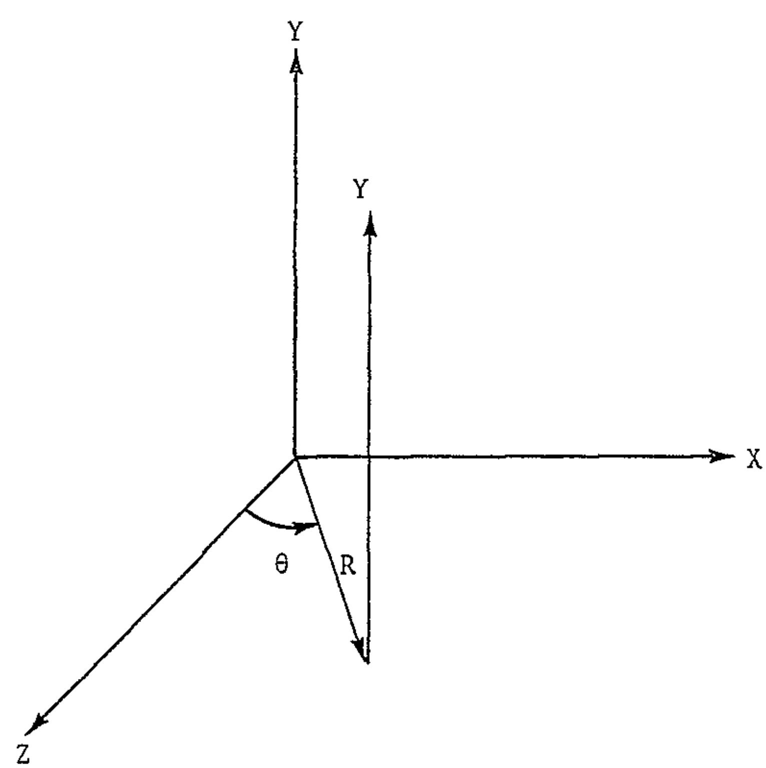
(6) Two major plot options are offered: (1) For NPLOT .EQ.1 plots of the thermal model may be obtained. In addition, plots of the temperatures input on the nodal cards may be made as either vector or surface plots (see plot instructions). (2) For NPLOT .EQ.2 plots of the thermal analysis model may be obtained, and plots of the final computed nodal temperatures may be made in either vector or surface forms.

(7) The Newton-Raphson iterative solution process will terminate when the number of iterations reaches the value NITER. Nodal temperatures are printed at each iteration, and element heat fluxes are calculated after the final iteration. The largest percentage change in nodal temperature will be printed at each iteration.

(8) Convergence will occur if the largest percentage change in nodal temperatures is found to be less than the convergence tolerence.

III. NODAL POINT DATA (2(A1,I4),25X,3F10.0,I5,F10.0)

notes	columns	variable	entry
(1)	1	CT	Symbol describing coordinate system for this node; EQ. ; (blank) cartesian (X,Y,Z) EQ.C; cylindrical (R,Y,Θ)
(2)	2 - 5	N	Node number
(3)	6	IPR	Print code EQ. ; (blank) normal printing EQ.A; suppress second printing of nodal data
(4)	7 - 10	ID(N)	Boundary condition code EQ.0; No temperature specified EQ.1; Temperature specified
(5)	36 - 45 46 - 55 56 - 65	X(N) Y(N) Z(N)	X (or R) coordinate Y coordinate Z (or Θ) coordinate (degrees)
(6)	66 - 70	KN	Node number increment
(7)	71 - 80	T(N)	Nodal temperature



III. NODAL POINT DATA (continued)

NOTES/

(1) A special cylindrical coordinate system is allowed for the global description of nodal point locations. If a "C" is entered in card column one (1), then the entries given in columns 36-65 are taken to be references to a global (R,Y,Θ) system rather than to the standard (X,Y,Z) system. The program converts cylindrical coordinate references to Cartesian coordinates using the formulae:

$$X = R \sin \Theta$$
$$Y = Y$$
$$Z = R \cos \Theta$$

Cylindrical coordinate input is merely a user convenience for locating nodes in the standard (X,Y,Z) system, and no other references to the cylindrical system are implied.

(2) Nodal point data must be defined for all (NUMNP) nodes. Node data may be input directly (i.e., each node on its own individual card), or the generation option may be used if applicable (see note 6, below).

Admissible nodal point numbers range sequentially from "1" to the total number of nodes "NUMNP." Illegal references are: N.LE.0 or N.GT.NUMNP. NUMNP must be the last card input.

(3) The IPR variable is used to suppress a second printing of the nodal data. This would be desirable in the event that all nodal data was input with no internal generation. If data is generated internally, the default printing is all input data cards and a second printing of input data plus generated data.

(4) The boundary condition code is used to designate those nodes which will have fixed values of temperature in the solution process. The fixed value of temperature is entered in the T(N) array.

(5) When CT (Col. 1) is equal to the character "C," the values input in columns 36-65 are interpreted as the cylindrical (R,Y,Θ) coordinates of node "N." Y is the axis of symmetry. R is the distance of a point from the Y-axis. The angle Θ is measured clockwise from the positive Z-axis when looking in the positive Y direction. The cylindrical coordinate values are printed as entered on the card, but immediately after printing the global Cartesian values are computed from the input entries.

(6) Nodal point cards need not be input in node-order sequence; eventually, however, all nodes in the integer set {1, NUMNP} must be defined. Nodal data for a series of nodes

III. NODAL POINT DATA (concluded)

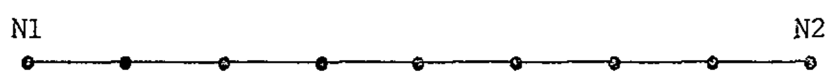
$$\{N_1,\ N_1 + (1 \times KN_2),\ N_1 + (2 \times KN_2),\ .\ .\ .,\ N_2\}$$

may be generated from information given on two cards in sequence:

CARD 1 / N_1, $ID(N_1)$, $X(N_1)$, . . ., KN_1, $T(N_1)$ /

CARD 2 / N_2, $(D(N_2)$, $X(N_2)$, . . ., KN_2, $T(N_2)$ /

KN_2 is the mesh generation parameter given on the second card of a sequence. The first generated node is $N_1 + (1 \times KN_2)$; the second generated node is $N_1 + (2 \times KN_2)$, etc. Generation continues until node number $N_2 - KN_2$ is established. Note that the node difference $N_2 - N_1$ must be evenly divisible by KN_2 . Intermediate nodes between N_1 and N_2 are located at equal intervals along the straight line between the two points. Boundary condition codes for the generated data are set equal to the values given on the first card. Node temperatures are found by linear interpolation between $T(N_1)$ and $T(N_2)$. Coordinate generation is <u>always</u> performed in the (X,Y,Z) system, and no generation is performed if KN_2 is zero (blank).



(7) The nodal temperatures are used to specify temperatures which are fixed in the solution process. In the nonlinear analysis, the first iteration is performed with the thermal parameters evaluated for <u>all</u> nodes at a zero temperature value. Thereafter nodal temperatures including the fixed values specified here are used to evaluate the thermal parameters for the next iteration.

IV. ELEMENT DATA

TYPE 1 - CONDUCTION/CONVECTION ROD ELEMENT

Rod elements (fig. 5) are identified by the number 1. A linear temperature variation is assumed between nodes. Internal heat generation, prescribed surface heating or convective surface heating are incorporated into the element formulation.

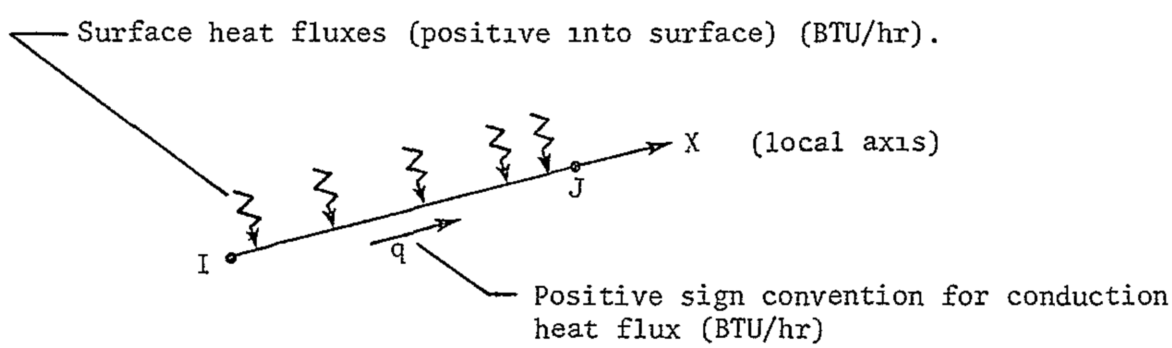
A. Control Card (8I5,8A5)

Columns	1 - 5	The number 1
	6 - 10	Total number of rod elements in this element group
	11 - 15	Number of material property cards
	16 - 40	Blank
	41 - 80	Any desired identification to be printed with output

B. Material Property Cards (2I5,F10.0)

The program expects the number of material property cards given above.

Notes	Columns	
	1 - 5	Material identification number
(1)	6 - 10	Table number for thermal conductivity (nonlinear analysis only)
	11 - 20	Thermal conductivity (k) (required for linear analysis only)



C. Element Data Cards

One card per element in sequential order of element number starting with one. If there is surface heating or convection heat transfer two cards are required.

IV. ELEMENT DATA (continued)

Card 1 (Required) (5I5,3F10.0)

Notes	Columns	
	1 - 5	Element number
(2)	6 - 10	Node number I
	11 - 15	Node number J
	16 - 20	Material identification number
(3)	21 - 25	Optional element generation parameter KG for automatic generation of element data
	26 - 35	Cross-sectional area for conduction
	36 - 45	Heat generation per unit volume (e.g., BTU/HR-FT**3)
(4)	46 - 55	Area factor for surface heating or convection

Card 2 (Optional - required only if the area factor is greater than zero) (5F10.0)

Notes	Columns	
	1 - 10	Specified surface heat transfer rate (e.g., BTU/HR-FT**2) (positive into element)
	11 - 20	Convective medium heat transfer coefficient H_I at node I
	21 - 30	Convective medium temperature T_I at node I
(5)	31 - 40	Convective medium heat transfer coefficient H_J at node J
	41 - 50	Convective medium temperature T_J at node J

NOTES/

(1) For a linear analysis the thermal conductivity k input on the material property card is used to compute the thermal conductance matrix and the heat flux recovery matrix for an element. For a nonlinear analysis and a table number greater than zero, the thermal conductance matrices are initially computed using k as unity. Later, after the thermal parameter tables have been read in, the matrices are multiplied by appropriate values of k determined from the parameter tables. The temperature used in the table is the average temperature of the element, i.e., $(T_I + T_J)/2$.

(2) The order of I and J determines the direction of the local X-axis (see fig. 5). Conduction heat fluxes are positive in the direction of the local X-axis.

(3) If a series of elements exists such that the element number, N_i , is one greater than the previous element number (i.e., $N_i = N_{i-1} + 1$) and the nodal point number can be given by

$$I_i = I_{i-1} + KG$$

$$J_i = J_{i-1} + KG ,$$

then only the first and last elements in the series need be provided. The material identification number and the temperature for the generated elements are set equal to the values on the last card. If KG (given on the last card) is input as zero, it is set to one by the program.

(4) If the area factor is greater than zero, the second card will be read. The area factor is used to compute the surface area for surface heat transfer, i.e., A (surface) = Area factor * length of element.

(5) If H_J or T_J is left blank, the program will set $H_J = H_I$ and $T_J = T_I$.

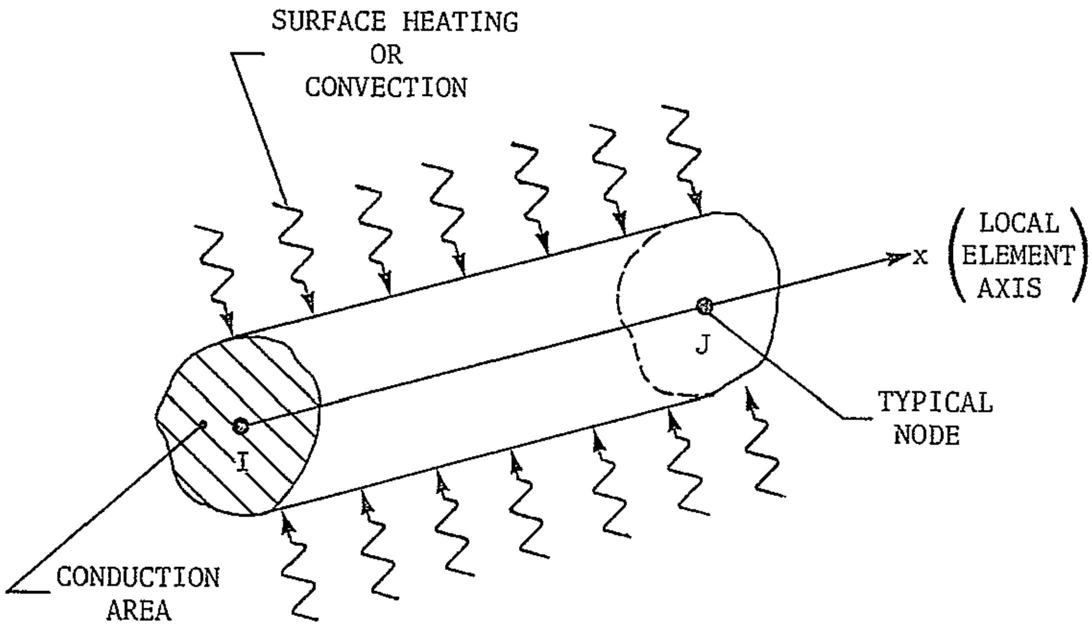


Figure 5. Conduction/convection rod element.

IV. ELEMENT DATA (continued)

TYPE 3 - CONDUCTION/CONVECTION QUADRILATERAL ELEMENT

Quadrilateral elements (fig. 6) are identified by the number 3. The element is based on an isoparametric formulation. The nodes can be located at general points in space, but they must lie in a plane. The element conduction heat fluxes are computed at the element centroid in local coordinates. The element may be laminated with an arbitrary number of different layers with different conduction tensors for each layer. Internal heat generation, prescribed edge or surface heating, or convective heating on all four edges and the top and bottom surfaces of the element are included in the element.

A. Control Card (8I5,8A5)

Columns	1 - 5	The number 3
	6 - 10	Total number of quadrilateral elements in this group
	11 - 15	Number of material property card sets
	16 - 40	Blank
	41 - 80	Any desired identification to be printed with output

B. Material Property Card Sets

One card is required per set. Cards 2, 3, . . . number of laminae is optional.

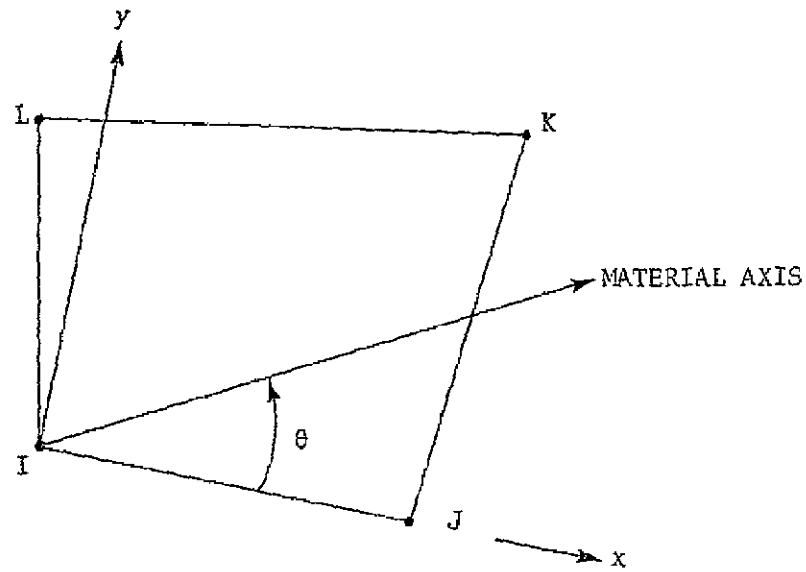
Card 1 (3I5,5F10.0)

Notes	Columns		
	1 - 5	Material identification number	
(1)	6 - 10	Table number for thermal conductivity tensor temperature variation (nonlinear analysis only)	
(2)	11 - 15	Number of laminae	
	16 - 25	Lamina thickness, t	Lamina 1
(3)	26 - 35	Conductivity tensor component, K_{xx}	Lamina 1
	36 - 45	Conductivity tensor component, K_{xy}	Lamina 1
	46 - 55	Conductivity tensor component, K_{yy}	Lamina 1
	56 - 65	Material axis angle, Θ (degrees)	Lamina 1

IV. ELEMENT DATA (continued)

Conduction fluxes

$$\begin{Bmatrix} q_x \\ q_y \end{Bmatrix} = -t \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \end{Bmatrix} \left(\frac{BTU}{HR\text{-}FT}\right)$$



Card (2, 3, . . . No. of Laminae) (15X,5F10.0)

Columns			
Columns	16 - 25	Lamina thickness	Lamina 2, 3, . . . No. of Laminae
	26 - 35	Conductivity tensor component, K_{xx}	
	36 - 45	Conductivity tensor component, K_{xy}	
	46 - 55	Conductivity tensor component, K_{yy}	
	56 - 65	Material axis angle, θ	

C. Element Data Card Sets

One card per element is required in increasing numerical order. Missing elements are generated. If there is edge or surface heating, additional element cards are required.

IV. ELEMENT DATA (continued)

Card 1 (9I5,F10.0)

Notes	Columns		
	1 - 5	Element number	
(4)	6 - 10	Node I	
	11 - 15	Node J	
	16 - 20	Node K	
	21 - 25	Node L	
	26 - 30	Material identification number	
	31 - 35	Element generation parameter KG	
	36 - 40	IEDGE .EQ.0	No edge heating or edge convection
		.EQ.1,2,3,4	Number of edges for which there is edge heating or edge convection
	41 - 45	ISURF .EQ.0	No surface heating or surface convection
		.EQ.1	Heating or convection on top surface
		.EQ.2	Heating or convection on top and bottom surfaces
	46 - 55	Volumetric heat generation rate (e.g., BTU/HR-FT^3)	

Card Set 2 (IEDGE cards) (2I5,5F10.0)

Notes	Columns	
	1 - 5	Edge node, N1
	6 - 10	Edge node, N2
	11 - 20	Edge heat loading, q, (e.g., BTU/HR-FT^3) (heat flux is positive into element)
	21 - 30	Convection coefficient, h_1, at node N1
	31 - 40	Convective medium temperature, T_1, at node N1
(6)	41 - 50	Convection coefficient, h_2, at node N2
	51 - 60	Convective medium temperature, T_2, at node N2

Card Set 3 (ISURF cards) (8F10.0)

Notes	Columns	
(7)	1 - 10	Convection coefficient h_I at node I, or convective surface heating, $q\left(\frac{BTU}{HR\text{-}FT^2}\right)$
	11 - 20	Convective medium temperature T_I at node I
	21 - 30	Convection coefficient, h_J at node J
	31 - 40	Convective medium temperature T_J at node J
	41 - 50	Convection coefficient, h_K, at node K
	51 - 60	Convective medium temperature T_K at node K
	61 - 70	Convection coefficient, h_L, at node L
	71 - 80	Convective medium temperature, T_L, at node L

NOTES/

(1) All of the components of the conductivity tensor are assumed to have the same temperature variation in a nonlinear analysis so that only

one table is input for the entire tensor. The look-up temperature is $(T_I + T_J + T_K + T_L)/4$. For a nonlinear analysis, the element conductance matrix is formed for the first iteration using the conductivity tensor entered as input data. On subsequent iterations the thermal conductivity table is used as a multiplier of this tensor. Thus, for a single layer the user may input a conductivity tensor with the largest value normalized to 1.0 and enter the actual conductivity values in the table.

(2) For an element with one homogeneous layer, only the first card is required.

(3) For an isotropic material, the conductivity value K should be entered as K_{xx} . The remaining entries may be left blank. The program will set $K_{xy} = 0$, $K_{yy} = K_{xx}$.

(4) The orientation of the local X-axis is from I to J (see fig. 6). The local y-axis then lies in the IJKL plane, and the direction of the local z-axis is determined by the right-hand rule. Element conduction heat fluxes are positive in the local coordinate system.

(5) Element cards must be in element number sequence. If cards are omitted, element data will be generated. The node numbers will be generated with respect to the first card in the series as follows,

$$I_n = I_{n-1} + KG$$

$$J_n = J_{n-1} + KG$$

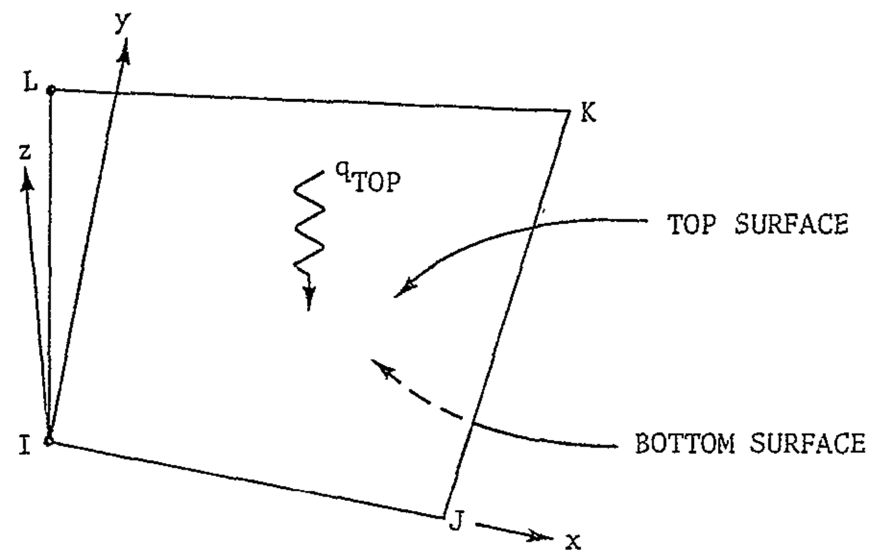
$$K_n = K_{n-1} + KG$$

$$L_n = L_{n-1} + KG \ .$$

All other element information will be set equal to information on the <u>last</u> card.

(6) If h_2 and T_2 are left blank, the program will set $h_2 = h_1$, $T_2 = T_1$.

(7) The top surface is located on the positive local z axis:



Surface heating is positive into the element. If there is surface heating, the heat flow is entered in columns 1-10, and the remainder of the card is blank. For uniform convection, if h_J , T_J , etc. are left blank, the program will set

$$h_J = h_K = h_L = h_I$$

$$T_J = T_K = T_L = T_I \ .$$

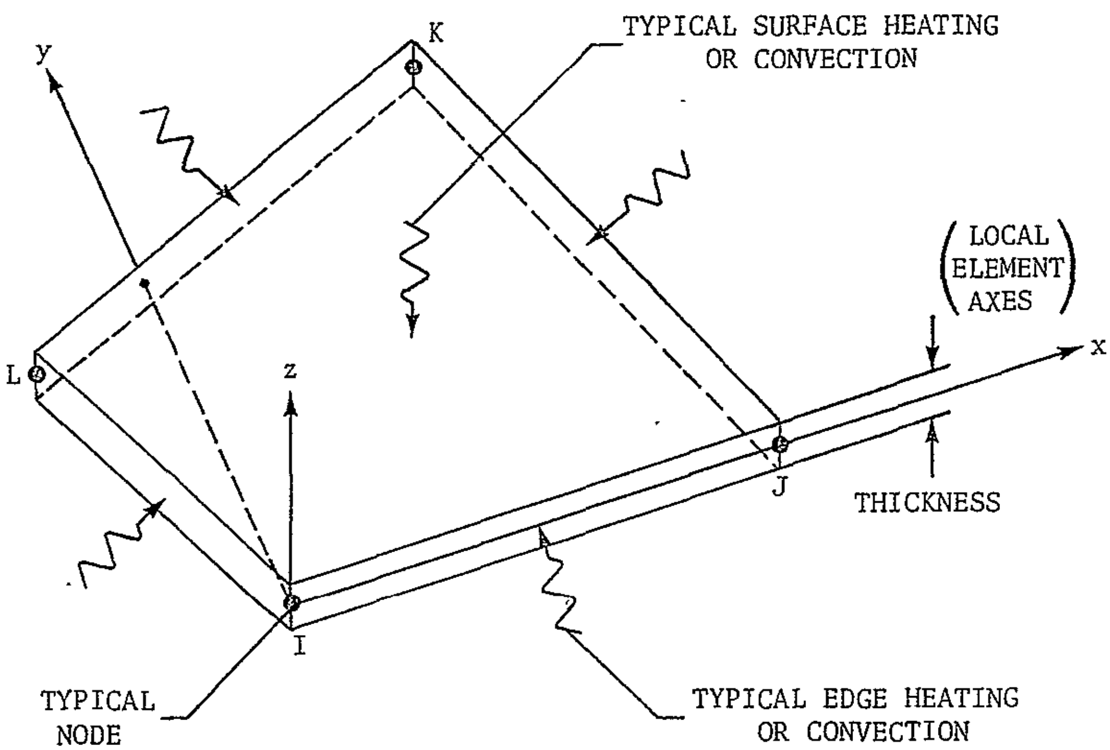


Figure 6. Conduction/convection quadrilateral element.

IV. ELEMENT DATA (continued)

TYPE 8 - MASS-TRANSPORT ELEMENT

Mass transport elements (fig. 7) are identified by the number 8. The element is used to represent convective energy transport due to a mass flow rate $\dot{m}$.

A. Control Card (8I5,8A5)

Columns	1 - 5	The number 8
	6 - 10	Total number of elements in this group
	11 - 15	Number of thermal-fluid property card sets
	41 - 80	Any desired identification to be printed with the element output data

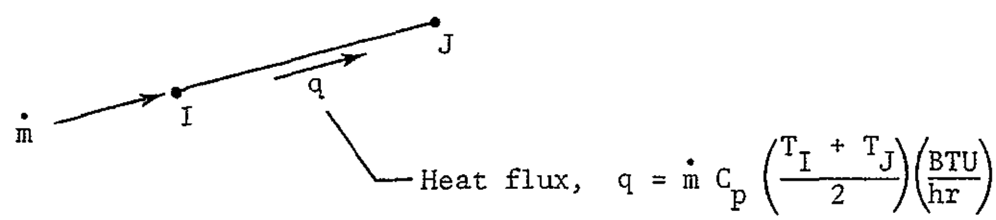
B. Fluid Properties (I5,F10.0,I5)

Notes	Columns		
		1 - 5	Property identification number
(1)		6 - 15	Fluid specific heat, C_p
		16 - 20	Table number for fluid specific heat

C. Element Data Cards (5I5,F10.0)

One card per element is required in increasing numerical order. Missing elements are generated.

Notes	Columns		
		1 - 5	Element number
(2)		6 - 10	Node number, I
		11 - 15	Node number, J
		16 - 20	Property identification number
(3)		21 - 25	Element generation parameter, KG
		26 - 35	Fluid mass flow rate (e.g., lbm/hr)



NOTES/

(1) For a linear analysis, the fluid specific heat read-in on the fluid property card is used in element computations. For a non-linear analysis, values from a specific heat table are used if the table number is greater than zero.

IV. ELEMENT DATA (continued)

(2) The nodal coordinates are arbitrary and are used only in the plot output. The order of the element nodes determines the direction of fluid flow, i.e., the fluid flow is from node I to J.

(3) Missing elements are generated using the same scheme as for the rod element, i.e., node numbers will be generated with respect to the first card as follows:

$$I_1 = I_{i-1} + KG$$

$$J_1 = J_{i-1} + KG \; .$$

All other element information will be set equal to data from the last card.

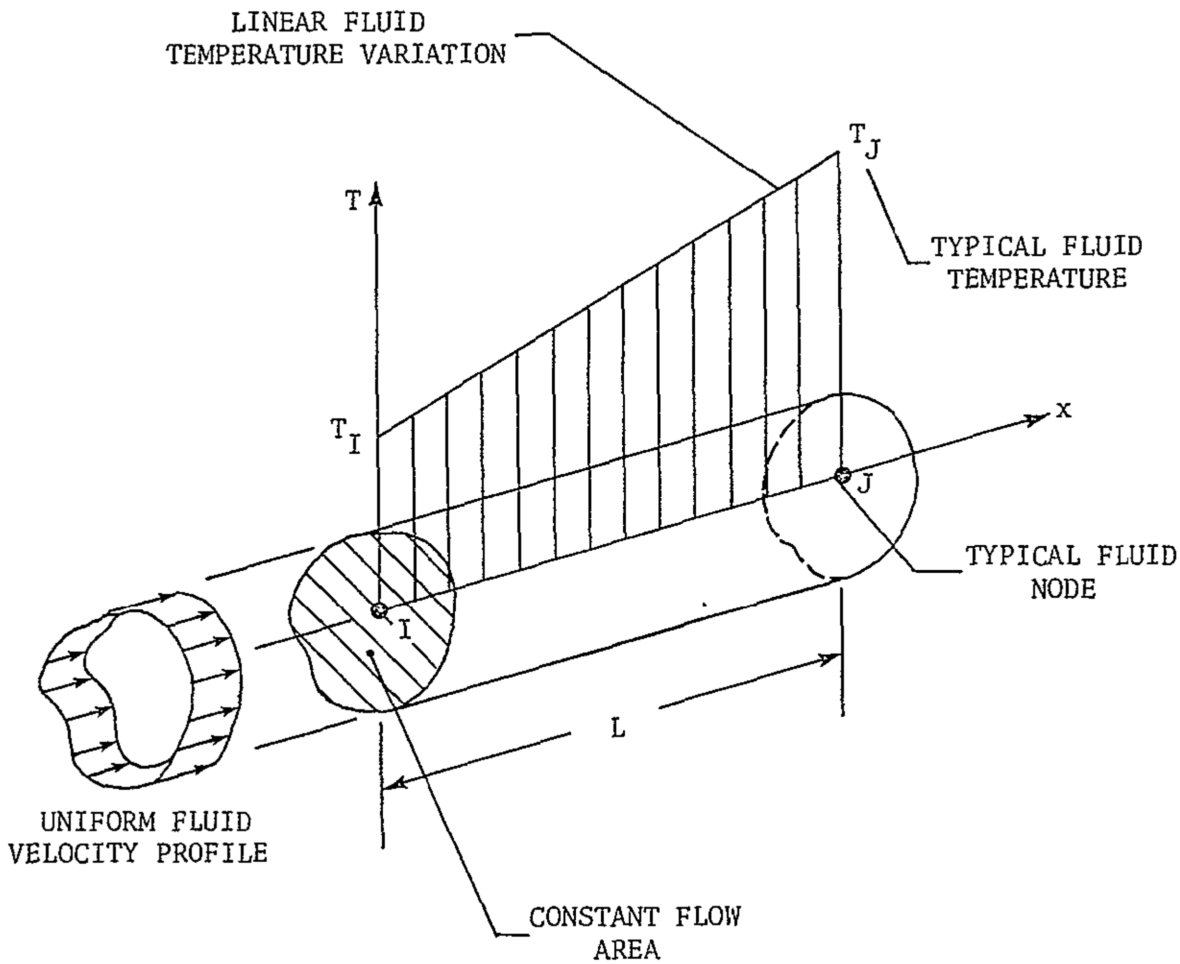


Figure 7. Mass transport element.

IV. ELEMENT DATA (continued)

TYPE 9 - SURFACE-CONVECTION ELEMENTS

Surface-convection elements (fig. 8) are identified by the number 9. The elements are used to represent convective heat transfer between a surface and a fluid with unknown temperature. Two elements, a quadrilateral and a triangle, are available.

A. Control Card (8I5,8A5)

Columns	1 - 5	The number 9
	6 - 10	The number of surface convection elements in this group
	11 - 15	Number of thermal-fluid property card sets
	41 - 80	Any desired identification to be printed with the element output data

B. Fluid Properties (I5,F10.0,I5)

Notes	Columns		
		1 - 5	Property identification number
(1)		6 - 15	Convection coefficient, h
		16 - 20	Table number for convection coefficient

C. Element Parameter Data Cards (7I5,F10.0)

One card per element is required in increasing numerical order. Missing elements are generated.

Notes	Columns		
		1 - 5	Element number
(2)		6 - 10	Node number, I
		11 - 15	Node number, J
		16 - 20	Node number, K
(3)		21 - 25	Node number, L (default .EQ.0)
		26 - 30	Property identification number
(4)		31 - 35	Element generation parameter, KG
(5)		36 - 45	Area factor for convection (default .EQ.1.0)

NOTES/

(1) For a linear analysis, the fluid convection coefficient read-in on the fluid property card is used in element computations. For a nonlinear analysis, values from a convection coefficient table are used if the table number is greater than zero.

(2) For the quadrilateral element, nodes I and J always denote fluid nodes; for the triangle, I denotes the fluid node.

(3) For a triangular element, leave L blank or enter L as zero.

(4) Missing elements are generated using this same scheme as for the quadrilateral conduction element, i.e., node numbers will be generated with respect to the first card as follows:

$$I_i = I_{i-1} + KG$$

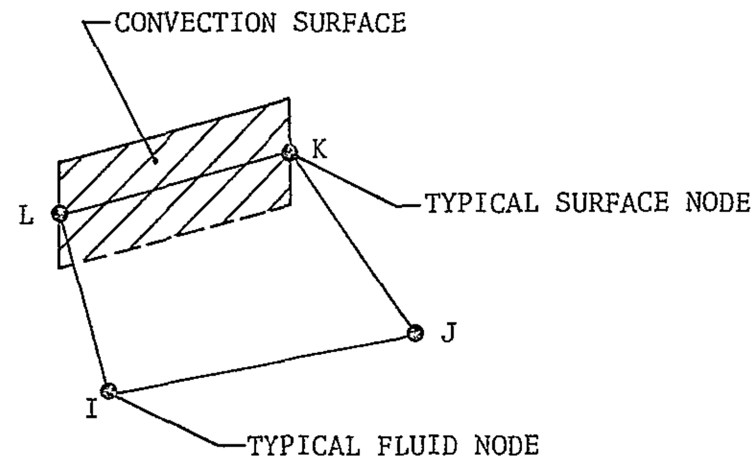
$$J_i = J_{i-1} + KG$$

$$K_i = K_{i-1} + KG$$

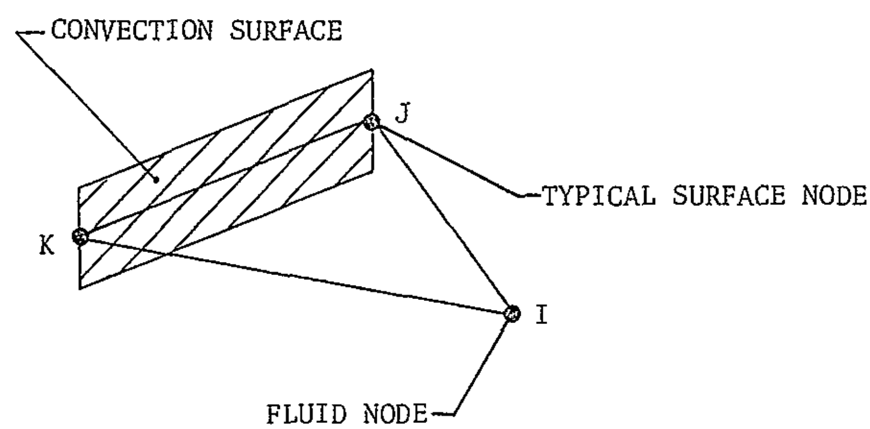
$$L_i = L_{i-1} + KG \ .$$

All other element information will be set equal to data from the last card.

(5) The area factor is used to compute the convection surface area, e.g., for the quadrilateral, A (surface) = area factor * distance K-L .



(a) Quadrilateral Element.



(b) Triangular Element.

Figure 8. Surface convection elements with unknown fluid temperatures.

TYPE 10 - TUBE/FLUID INTEGRATED ELEMENT

Tube/fluid integrated elements (fig. 9) are identified by the number 10. The element represents conduction/convection heat transfer in a thin tube of constant thickness and flow area enclosing a fluid with mass flow rate $\dot{m}$. Heat loading on the tube external surface due to a specified heating or a convective exchange with a surrounding media is included. Pressure drop computations are performed as an option.

A. Control Card (8I5,8A5)

Columns	
1 - 5	The number 10
6 - 10	Total number of tube/fluid elements in this group
11 - 15	Number of thermal-fluid property card sets
16 - 20	Flag for pressure drop calculations .EQ.0; Pressures are not calculated .GT.0; Pressures are calculated
21 - 40	Blank
41 - 80	Any desired identification to be printed with the element output data

B. Thermal-Fluid Property Card Sets

Card 1 - Tube Properties (I5,F10.0,I5)

Notes	Columns	
	1 - 5	Property identification number
(1)	6 - 15	Thermal conductivity, k
	16 - 20	Table number for tube thermal conductivity

Card 2 - Fluid Properties (F10.0,2(F10.0,I5),I5)

Notes	Columns	
(2)	1 - 10	Fluid convection coefficient, h
(3)	11 - 20	Exponent in equation for modification of convection coefficient, n (real)
	21 - 25	Table number for convection coefficient
(4)	26 - 35	Fluid specific heat, C_p
	36 - 40	Table number for fluid specific heat
(5)	41 - 45	Table number for fluid viscosity

(Optional) Card 3 - Tube-Fluid Properties for Pressure Recovery (2F10.0,2(F10.0,I5),2F10.0)

Notes	Columns	
(6)	1 - 10	Tube hydraulic diameter, D_H
(7)	11 - 20	Fluid friction factor, f
(8)	21 - 30	Exponent in equation for correction of friction factor, m (real)
	31 - 35	Table number for fluid friction factor

IV. ELEMENT DATA (continued)

Notes			
(9)	Columns	36 - 45	Fluid density, ρ
		46 - 50	Table number for fluid density
		51 - 60	Gas constant, R
		61 - 70	Proportionaility constant in Newton's second law, g_c

C. Element Data Cards

One card per element is required in increasing numerical order. Missing elements are generated. If there is external surface heating on the tube, two cards per element are required.

Card 1 - Element Parameters (8I5,4F10.0)

Notes	Columns		
		1 - 5	Element number
(10)		6 - 10	Node number, I } Fluid nodes
		11 - 15	Node number, J } Fluid nodes
		16 - 20	Node number, K } Tube nodes
		21 - 25	Node number, L } Tube nodes
		26 - 30	Property identification number
(11)		31 - 35	Element generation parameter, KG
(12)		36 - 40	ISURF.EQ.0; No surface heating or convection .GT.0; Surface heating or convection
		41 - 50	Tube cross-sectional conduction area
(13)		51 - 60	Perimeter of tube for internal convective heat transfer to fluid
		61 - 70	Fluid mass flow rate (e.g., lbm/hr)
(14)		71 - 80	Element inlet pressure, P_I

Card 2 - External Tube Heating or Convection Data (6F10.0)

Notes			
(15)	Columns	1 - 10	Area factor for surface heating or convection (default .EQ.1.0)
		11 - 20	Specified surface heating rate (e.g., BTU/HR-FT**2) (positive into surface)
		21 - 30	Convective heat transfer coefficient, h_L, at node L
		31 - 40	Surrounding medium temperature, T_L, at node L
(16)		41 - 50	Convective heat transfer coefficient, h_K, at node K
		51 - 60	Surrounding medium temperature, T_K, at node K

NOTES/

(1) The thermal conductivity is used to represent the axial conduction of heat in the tube wall. The thermal conductivity of the tube wall may be constant or may be entered in tabular form for a nonlinear analysis. The look-up temperature is $(T_K + T_L)/2$.

(2) The fluid convection coefficient h is used to represent convective heat transfer between the tube and fluid. The convection coefficient may be constant or may be entered in tabular form for a nonlinear analysis. The look-up temperature is $(T_I + T_J)/2$.

(3) In the nonlinear analysis, the convection coefficient may be modified at each iteration for a variation of fluid temperature at the flow section. The correction takes the form:

$$\text{Gases:} \quad h' = h\,(T_b) \left(\frac{T_w}{T_b}\right)^n$$

$$\text{Liquids:} \quad h' = h\,(T_b) \left(\frac{\mu_w}{\mu_b}\right)^n$$

For a gas, T_w denotes the wall temperature and T_b denotes the bulk fluid temperature. For a liquid, μ_w denotes the viscosity evaluated at the wall temperature and μ_b denotes the viscosity evaluated at the fluid bulk temperature. No modification is performed if the exponent n (real) is entered as blank or zero.

(4) The specific heat C_p is used in representing the heat transfer due to mass transport and may be entered as a constant or as a tabular function of temperature.

(5) The fluid viscosity is required only if the correction described above in note (3) is to be performed for a liquid. Otherwise, a table number for viscosity is not required.

(6) The tube hydraulic diameter is defined by

$$D_H = 4 * \frac{\text{Flow cross-sectional area}}{\text{wetted perimeter}} \quad .$$

(7) The fluid friction factor f is used to compute the pressure drop in an element. The pressure drop is computed from the equation,

$$\Delta P = f \frac{L}{D_H} \frac{G^2}{2g_c} \frac{1}{\rho_m} + \frac{G^2}{g_c} \left(\frac{1}{\rho_J} - \frac{1}{\rho_I} \right)$$

where

ΔP - pressure drop, $(P_I - P_J)$

f - friction factor

L - element length

D_H - hydraulic diameter

G - mass flow rate/flow area (e.g., $lbm/hr/ft^2$)

ρ_m - element mean density, $(\rho_I + \rho_J)/2$

ρ_I, ρ_J - fluid densities evaluated at the temperatures of the fluid at nodes I, J

g_c - proportionality constant in Newton's second law $\left(\text{e.g., } g_c = \frac{32.17 \text{ ft - lbm}}{\text{lb}_f \text{ - sec2}} \right)$

(8) In the calculation of pressures for a nonlinear analysis, the friction factor may be modified for a variation of fluid temperature at the flow cross section. The correction takes the form:

$$\text{Gases:} \quad f' = f\,(T_b) \left(\frac{T_w}{T_b} \right)^m$$

$$\text{Liquids:} \quad f' = f\,(T_b) \left(\frac{\mu_w}{\mu_b} \right)^m$$

where the quantities have the same definition as in note (3). The modification is not performed if the exponent m (real) is entered as blank or zero.

(9) Pressure drops are computed for three density cases: (1) constant density, (2) variable density as specified by a density-temperature table, and (3) an idea gas. If the density table number is entered as zero, case (1) is assumed. If the density table number is greater than zero, case (2) is assumed.

If the gas constant R is entered as a positive quantity, case (3) is assumed. For case (3) the pressure drop equation above is solved simultaneously with the gas law $P = \rho RT$.

(10) The direction of fluid flow is determined by the node numbering sequence. Flow is from node I to node J (see fig. 9).

(11) Element cards must be in element number sequence. If cards are omitted, element data will be generated. The node numbers will be generated with respect to the first card in the series as follows:

$$I_n = I_{n-1} + KG$$

$$J_n = J_{n-1} + KG$$

$$K_n = K_{n-1} + KG$$

$$L_n = L_{n-1} + KG \ .$$

All other information will be set equal to the data on the last card.

(12) ISURF.GT.0 indicates the tube is heated externally by a specified heat flux or convectively. The program expects to read a second card with the heating data.

(13) The perimeter of the tube is used to compute the wetted area for convective heat transfer to the internal fluid by multiplying it by the element length.

(14) Pressures are computed at successive nodes by $P_J = P_I - \Delta P$ until a new inlet pressure is specified for an element.

(15) The surface area for external heating is computed as the product of the area factor times the perimeter times the element length.

(16) If h_K and T_K are left blank, the program will set $h_K = h_L$ and $T_K = T_L$.

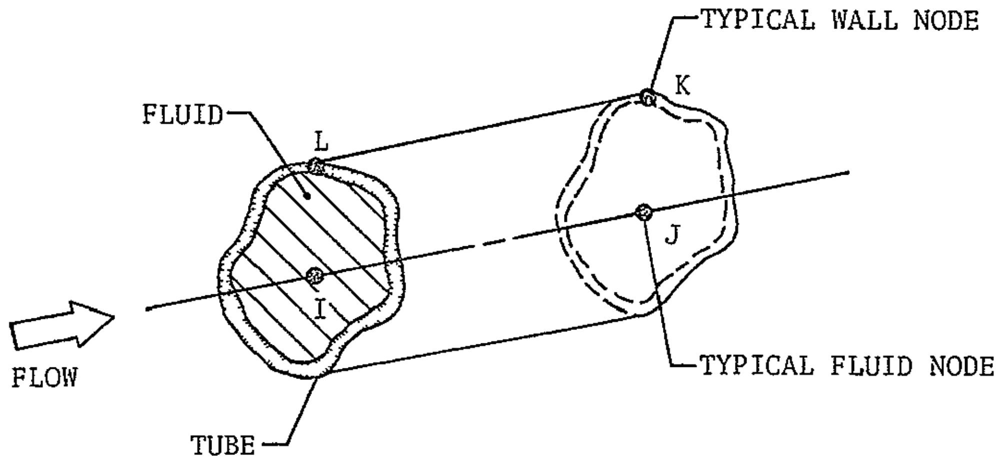


Figure 9. Integrated tube/fluid element.

IV. ELEMENT DATA (continued)

TYPE 11 - PLATE-FIN/FLUID INTEGRATED ELEMENT

Plate-fin/fluid integrated elements (fig. 10) are identified by the number 11. The elements represent conduction/convection heat transfer in a coolant passage defined by two plates connected by an internal fin. Fluid flows through the passage with mass flow rate $\dot{m}$.

A. Control Card (8I5,8A5)

Columns	1 - 5	The number 11
	6 - 10	Total number of plate-fin/fluid elements in this group
	11 - 15	Number of thermal-fluid property card sets
	16 - 20	Flag for pressure calculations .EQ.0; Pressures are not calculated .GT.0; Pressures are calculated
	21 - 40	Blank
	41 - 80	Any desired identification to be printed with the element input data echo.

B. Thermal-fluid Property Card Sets

Card 1 - Fin Properties (I5,F10.0,I5)

Notes	Columns		
	Columns	1 - 5	Property identification number (Fin and fluid properties)
(1)		6 - 15	Thermal conductivity
		16 - 20	Table number for fin thermal conductivity

Card 2 - Fluid Properties (F10.0,2(F10.0,I5),I5)

Notes			
(2)	Columns	1 - 10	Fluid convection coefficient, h
(3)		11 - 20	Exponent in equation for modification of convection coefficient, n (real)
		21 - 25	Table number for convection coefficient
(4)		26 - 35	Fluid specified heat, C_p
		36 - 40	Table number for fluid specific heat
(5)		41 - 45	Table number for fluid viscosity

(Optional) Card 3 - Properties for Pressure Calculations (2F10.0,2(F10.0,I5),2F10.0)

Notes			
(6)	Columns	1 - 10	Hydraulic diameter, D_H
(7)		11 - 20	Fluid friction factor, f
(8)		21 - 30	Exponent in equation for modification of friction factor, m (real)
		31 - 35	Table number for fluid friction factor

IV. ELEMENT DATA (continued)

Notes			
(9)	Columns	36 - 45	Fluid density, ρ
		46 - 50	Table number for fluid density
		51 - 60	Gas constant R
		61 - 70	Proportionality constant in Newton's second law, g_c

C. <u>Element Parameter Data Cards</u>

Two cards per element are required in increasing numerical order. Missing elements are generated.

Element Parameters (10I5,2F10.0,/,3F10.0)

Card 1

Notes	Columns	1 - 5	Element number
(10)		6 - 10	Node number, I
		11 - 15	Node number, J
		16 - 20	Node number, K (Fluid node)
		21 - 25	Node number, L
		26 - 30	Node number, M
		31 - 35	Node number, N (Fluid node, inlet)
		36 - 40	Property identification number
(11)		41 - 45	Element generation parameter, KG
(12)		46 - 50	Flag for fin efficiency .EQ.0; Fin efficiency computed .NE.0; Fin efficiency set equal to one
		51 - 60	Fluid mass flow rate (e.g., lbm/hr)
(13)		61 - 70	Element inlet pressure, P_N

Card 2

Notes			
(14)	Columns	1 - 10	Effective fin thickness
(15)		11 - 20	Effective width of top wall for convection (default, 1.0)
		21 - 30	Effective width of bottom wall for convection (default, 1.0)
(16)		31 - 40	Fin area factor (default, 1.0)

NOTES/

(1) The thermal conductivity is used to calculate two-dimensional heat conduction in the fin. The fin connects the top and bottom walls, and heat conduction is represented by an isoparametric quadrilateral finite element formulation. The thermal conductivity may be constant or entered in tabular form for a nonlinear analysis. The look-up temperature is $(T_I + T_J + T_L + T_M)/4$.

(2) The fluid convection coefficient h is used to represent convective heat transfer between the top and bottom walls and between both sides of the fin and the fluid. The convection coefficient may be constant or be entered in tabular form for a nonlinear analysis. The look-up temperature is $(T_N + T_K)/2$.

(3) In the nonlinear analysis, the convection coefficient may be modified at each iteration for a variation of fluid temperature at the flow section. The correction takes the form:

$$\text{Gases:} \quad h' = h\,(T_b) \left(\frac{T_w}{T_b}\right)^n$$

$$\text{Liquids:} \quad h' = h\,(T_b) \left(\frac{\mu_w}{\mu_b}\right)^n \quad .$$

For a gas, T_w denotes the wall temperature and T_b denotes the bulk fluid temperature; for a liquid, μ_w denotes the viscosity evaluated at the wall temperature and μ_b denotes the viscosity evaluated at the fluid bulk temperature. No modification is performed if the exponent n (real) is entered as blank or zero.

(4) The specific heat C_p is used in representing the heat transfer due to fluid flow and may be entered as a constant or as a tabular function of temperature.

(5) The fluid viscosity is required only if the modification described above in note (3) is to be performed for a liquid. Otherwise, a table number for viscosity is not required.

(6) The passage hydraulic diameter is defined by

$$D_H = 4 \cdot \frac{\text{Flow cross-sectional area}}{\text{wetted perimeter}} \quad .$$

(7) The fluid friction factor f is used in computing the pressure drop in an element. The pressure drop is computed from the equation

$$\Delta P = f\,\frac{L}{D_H}\,\frac{G^2}{2g_c}\,\frac{1}{\rho_m} + \frac{G^2}{g_c}\left(\frac{1}{\rho_K} - \frac{1}{\rho_N}\right)$$

where

ΔP - pressure drop, $(P_N - P_K)$

f - friction factor

L - element length

D_H - hydraulic diameter

G - mass flow rate/flow area (e.g., $lbm/hr/ft^2$)

ρ_m - element mean density, $(\rho_K + \rho_N)/2$

ρ_K, ρ_N - fluid densities evaluated at the temperatures of the fluid nodes K, N

g_c - proportionality constant in Newton's second law $\left(\text{e.g., } g_c = \dfrac{32.17 \text{ ft - lbm}}{\text{lb}_f \text{ - sec}^2}\right)$

(8) In the calculation of pressures for a nonlinear analysis, the friction factor may be corrected for a variation of fluid temperature at the flow cross section. The correction takes the form:

Gases: $$f' = f\ (T_b) \left(\frac{T_w}{T_b}\right)^m$$

Liquids: $$f' = f\ (T_b) \left(\frac{\mu_w}{\mu_b}\right)^m$$

where the quantities have the same definition as in note (3). The modification is not performed if the exponent m (real) is entered as blank or zero.

(9) Pressure drops are computed for three density cases. (1) constant density, (2) variable density as specified by a density-temperature table, and (3) an ideal gas. If the density table number is entered as zero, case (1) is assumed. If the density table number is greater than zero, case (2) is assumed.

If the gas constant R is entered as a positive quantity case (3) is assumed. For case (3) the pressure drop equation above is solved simultaneously with the gas law $P = \rho RT$.

(10) The direction of fluid flow is determined by the node numbering sequence. Flow is from node N to node K (see fig. 10).

(11) Element cards must be in element number sequence. If cards are omitted, element data will be generated. The node numbers will be generated with respect to the first card in the series as follows:

$$I_n = I_{n-1} + KG$$

$$J_n = J_{n-1} + KG$$

$$K_n = K_{n-1} + KG$$

$$L_n = L_{n-1} + KG$$

$$M_n = M_{n-1} + KG$$

$$N_n = N_{n-1} + KG \; .$$

All other information will be set equal to the data on the last card.

(12) The fin efficiency η is computed by the equation

$$\eta = \frac{2}{m\ell} \frac{\cosh m\ell - 1}{\sinh m\ell}$$

where ℓ is the average height of the fin and

$$m = \sqrt{\frac{2}{t_{Fin}}} \sqrt{\frac{h}{k}} \; .$$

The fin efficiency is used to modify the convective heat transfer between the fin and fluid for the linear temperature distribution assumed in the surface convection finite element (see note (16) below).

(13) Pressures are computed at successive nodes by $P_K = P_N - \Delta P$ until a new inlet pressure is specified for an element.

(14) The fin thickness is used in two ways. The thickness is used in representing the conduction heat transfer of the fin. In addition, the fin thickness is subtracted from the widths of the top and bottom walls in the computation of convection areas. For multiple

fins, an effective fin thickness equal to the number of fins times the thickness of a single fin should be used.

(15) The top and bottom widths are used to compute the convection areas from the walls to the fluid (see note 14). The average of these widths is also used in the computation of the flow areas at the inlet and outlet of an element.

(16) The fin area factor for convection may be used to account for multiple fins. The fin surface area is multiplied by this factor. The convective heat transfer between the fin and fluid is based upon the equation

$$q = \eta h \ (A_S * A_F) \left[\frac{T_I + T_J + T_L + T_M}{4} - T_{BULK} \right]$$

where

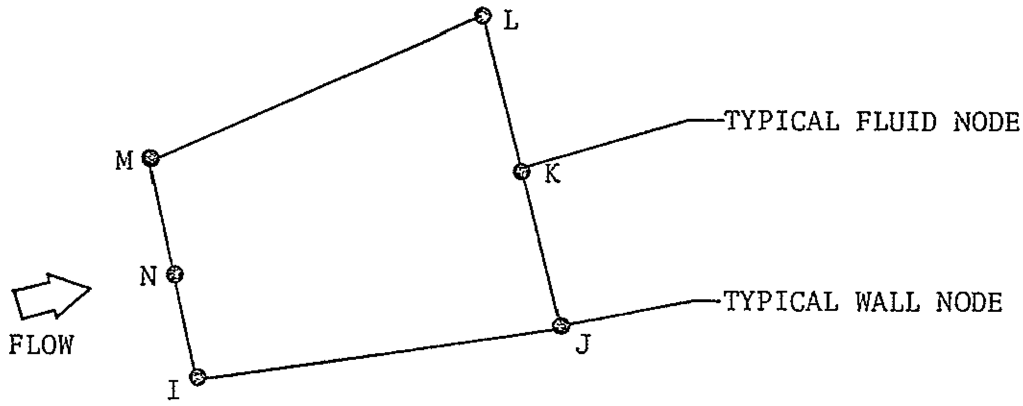
η = fin efficiency (see note 12)

h = convection coefficient

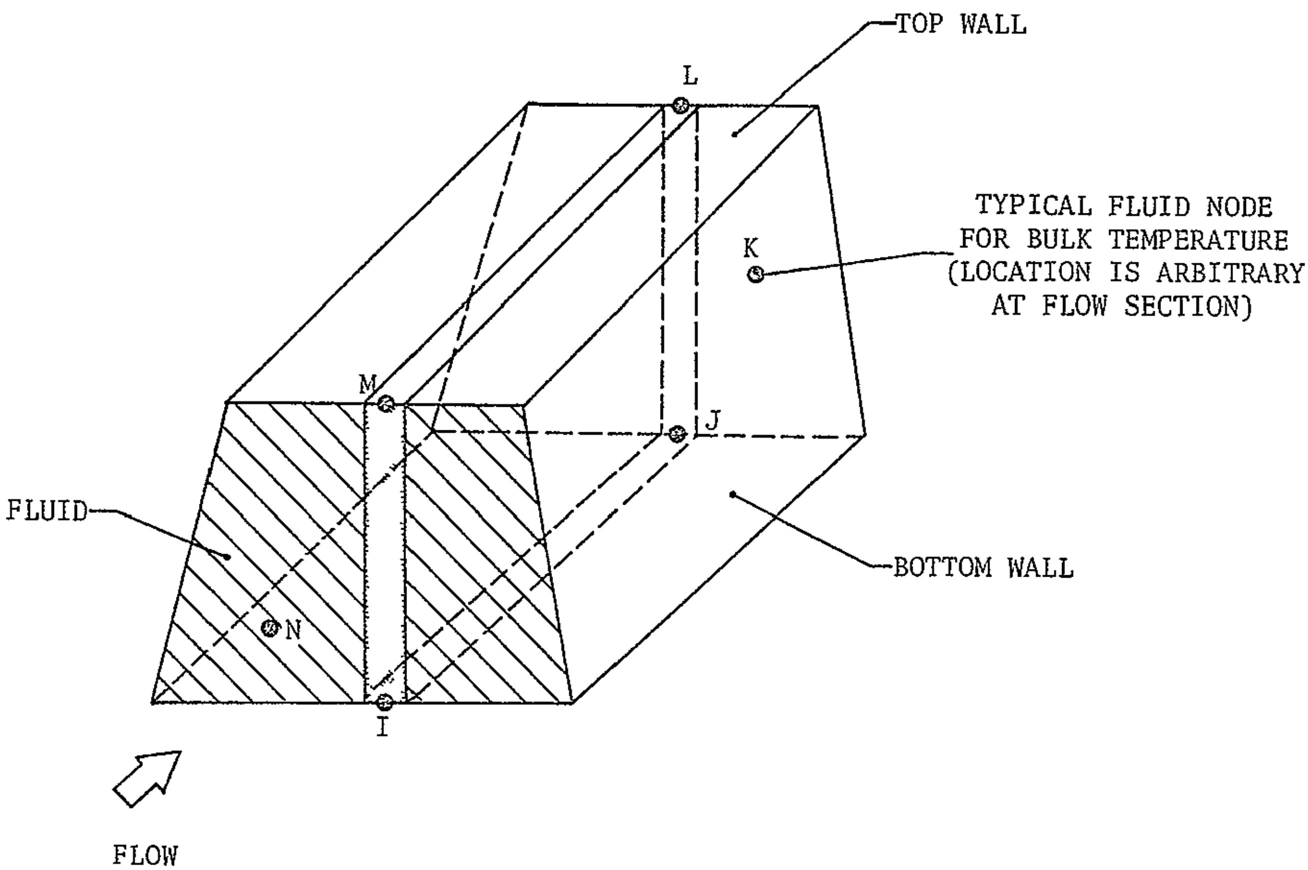
A_S = surface area of fin (2 sides)

A_F = fin area factor

$T_{BULK} = (T_N + T_K)/2$.



(a) Side View.



(b) Oblique View.

Figure 10. Integrated plate-fin/fluid element.

V. THERMAL PARAMETER TABLES

Thermal parameter tables are required for nonlinear thermal analysis. The total number of thermal parameter tables is entered on the master control card as NUMTB (see section II). Individual table numbers for reference to the data input here are read in as part of the element input data. The thermal parameter data tables are described by the following sequence of data cards:

A. Control Card (2I5,7A10) (one card for each table)

Columns	1 - 5	Table number
	6 - 10	Number of data points given in table
	11 - 80	Any desired table heading information

B. Thermal Parameter Table (8F10.0) (4 points per card, as many cards as required) (typical card)

Columns	1 - 10	Temperature for point 1	Point 1
	11 - 20	Thermal parameter for point 1	
	21 - 30	Temperature for point 2	Point 2
	31 - 40	Thermal parameter for point 2	
	41 - 50	Temperature for point 3	Point 3
	51 - 60	Thermal parameter for point 3	
	61 - 70	Temperature for point 4	Point 4
	71 - 80	Thermal parameter for point 4	

APPENDIX C

INPUT DATA FOR TAPPLT

General Setup of Deck

In general the input deck for the plotting program consists of three separate groups of data as shown schematically in figure 11. These groups are as follows:

(1) A single card containing any desired title information,

(2) NAMELIST OPTION containing values to allocate storage in blank common and control values specifying various program options, and

(3) NAMELIST PICT containing values to specify the type of plot desired and information to be included on the plots.

Input Data Cards

I. HEADING CARD - This single card contains any desired alphanumeric information in columns 1 to 80. The title will appear at the beginning of the plots.

II. NAMELIST OPTION - This NAMELIST contains values to allocate storage in blank common and control values specifying various program options.

FORTRAN name	Default value	Description
NNDEST	200	Estimated number of nodes, must be equal to or greater than the actual number of nodes
NWDISP	0	0 no temperature data 1 temperature data
KPLOT	1	Specifies the type of output device to be used 1 CalComp 2 CalComp with plotting speed reduced for Leroy pens 3 VARIAN
XSPACE	10.0	Space between plots in x-direction, in inches

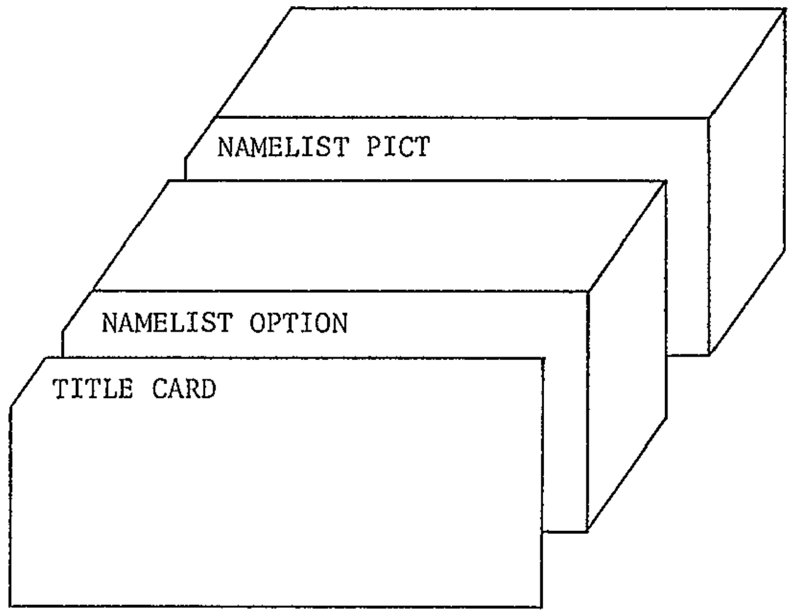


Figure 11. Input data sequence for TAPPLT.

FORTRAN name	Default value	Description
PSIZE	25.0	Paper size in y-direction, in inches (used in scaling of plots to insure this dimension is not exceeded)

III. NAMELIST PICT - This NAMELIST contains values to specify the type of plots desired and the information that is to be included on the plots.

FORTRAN name	Default value	Description
KHORZ	1	Integer designating the horizontal axis of the viewing plane where 1 = X_o , 2 = Y_o , and 3 = Z_o
KVERT	2	Integer designating the vertical axis of the viewing plane where 1 = X_o , 2 = Y_o , and 3 = Z_o
PHI	0.0	Angular rotation of model about its x-axis in degrees (must be performed third)
THETA	0.0	Angular rotation of model about its y-axis in degrees (must be performed second)
PSI	0.0	Angular rotation of model about its z-axis in degrees (must be performed first)
NEWFR	1	1 frame change before plotting (a frame change resets the x-origin past previous plot by XSPACE given in NAMELIST OPTION and resets the y-origin at 0.0) 0 no frame change before plotting
ISCALE	1	1 automatic computation of proper origin location and scaling of plot 2 user-specified origin and scaling
PLOTSZ	10.0	Maximum dimension desired on completed plot, in inches (used for scaling if ISCALE = 1)
XORGN	0.0	x-location of plot origin (used if ISCALE = 2)
YORGN	0.0	y-location of plot origin (used if ISCALE = 2)
PSCALE	1.0	Model size reduction factor (i.e., PSCALE is equal to actual model size divided by desired plot size (used if ISCALE = 2))

FORTRAN name	Default value	Description
NOTAT	0	0 no numbering on plots 1 numbering of nodes 2 numbering of elements
XLHT	0.15	Height of integers specified by NOTAT, in inches (must be $\geq$ 0.07)
KDISP	0	0 plot of thermal model 1 plot of temperature surface 2 exploded plot of model 3 temperatures represented by vectors
IDMAG	2	1 direct magnification of temperature data by DMAGS 2 scaling of temperature data to a maximum value of DMAGS
DMAGS	1.0	Magnification of temperatures (if KDISP = 1 or 3) Reduction factor of elements (if KDISP = 2)
KSYMXY	0	1 symmetry about X-Y plane
KSYMXZ	0	1 symmetry about X-Z plane
KSYMYZ	0	1 symmetry about Y-Z plane

Symmetries are performed consecutively (i.e., a plate quadrant with KSYMXZ and KSYMYZ equal to one would yield a complete plate).

XXMAX, YYMAX, ZZMAX	1.0 E+20	Locate cutting planes parallel to principal planes (X-Y, X-Z, Y-Z) to limit plot
XXMIN, YYMIN, ZZMIN	-1.0 E+20	
NDMAX	9999999999	Maximum node identification number to be included in plot
NDMIN	0	Minimum node identification number to be included in plot
NELMAX	9999999999	Maximum element identification number to be included in plot
NELMIN	0	Minimum element identification number to be included in plot

FORTRAN name	Default value	Description
KODE	0	Specifies control option after plot is complete 0 last plot, exit from program 1 read another NAMELIST PICT

This section describes a complete basic set of input data if KODE = 0 in NAMELIST PICT.

The deck must end with NAMELIST PICT having a value of KODE = 0 .

APPENDIX D

INPUT DATA AND PROGRAM OUTPUT FOR SAMPLE PROBLEMS

Four sample problems are presented: (1) a linear conduction analysis of a transverse cross-section of a panel with a "D" tube, (2) a nonlinear analysis of a convectively heated, water cooled pipe, (3) a nonlinear analysis of a simplified heat exchanger, and (4) a linear analysis and plots of conduction in a simple fin. The sample problems are presented in figures 12 to 15. Plotter output for sample problem (4) is shown in figure 16.

SAMPLE PROBLEM 1

Linear Conduction Analysis of a D Tube Cross Section

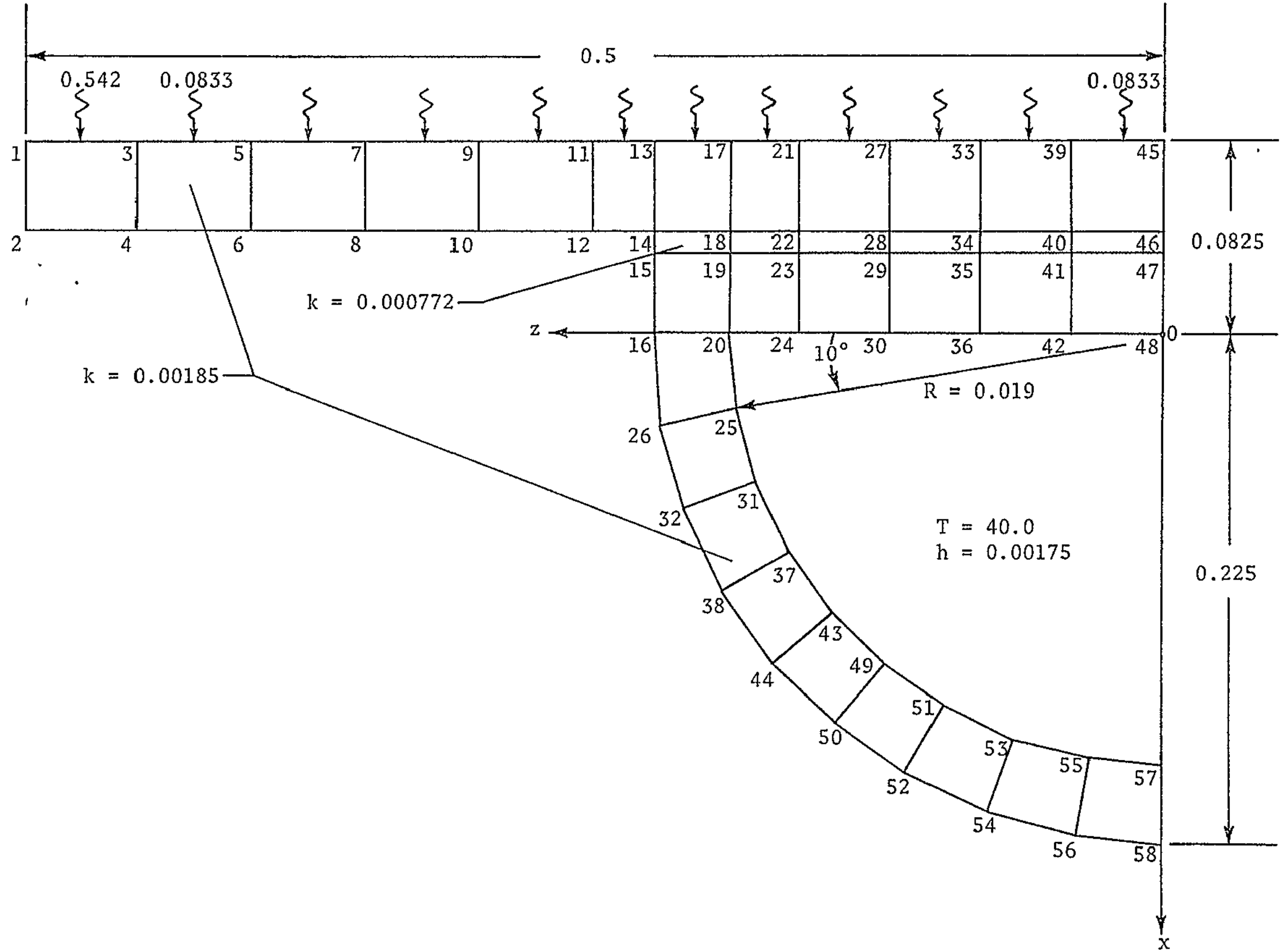


Figure 12. Conduction analysis of a panel - "D" tube section (sample problem 1).

INPUT DATA (SAMPLE PROBLEM 1)

```
   D TUBE CROSS SECTION   3/16/76
    58    2    0    1    0    0
     1    0                         -0.0825     0.0       0.5
    11    0                         -0.0825     0.0       0.25      2
     2    0                         -0.045      0.0       0.5
    12    0                         -0.045      0.0       0.25      2
    13    0                         -0.0825     0.0       0.225
    14    0                         -0.045      0.0       0.225
    15    0                         -0.035      0.0       0.225
    16    0                          0.0        0.0       0.225
    17    0                         -0.0825     0.0       0.190
    18    0                         -0.045      0.0       0.190
    19    0                         -0.035      0.0       0.190
    20    0                          0.0        0.0       0.190
    21    0                         -0.0825     0.0       0.160
    22    0                         -0.0450     0.0       0.160
    23    0                         -0.035      0.0       0.160
    24    0                          0.0        0.0       0.160
    27    0                         -0.0825     0.0       0.120
    28    0                         -0.0450     0.0       0.120
    29    0                         -0.035      0.0       0.120
    30    0                          0.0        0.0       0.120
    33    0                         -0.0825     0.0       0.080
    34    0                         -0.0450     0.0       0.080
    35    0                         -0.0350     0.0       0.080
    36    0                          0.0        0.0       0.080
    39    0                         -0.0825     0.0       0.040
    40    0                         -0.0450     0.0       0.040
    41    0                         -0.0350     0.0       0.040
    42    0                          0.0        0.0       0.040
    45    0                         -0.0825     0.0       0.0
    46    0                         -0.0450     0.0       0.0
    47    0                         -0.0350     0.0       0.0
    48    0                          0.0        0.0       0.0
C   57    0                          0.190      0.0      90.0
C   55    0                          0.190      0.0      80.
C   53    0                          0.190      0.0      70.
C   51    0                          0.190      0.0      60.
C   49    0                          0.190      0.0      50.
C   43    0                          0.190      0.0      40.
C   37    0                          0.190      0.0      30.
C   31    0                          0.190      0.0      20.
C   25    0                          0.190      0.0      10.
C   26    0                          0.225      0.0      10.
```

```
C  32   0                                      0.225     0.0     20.
C  38   0                                      0.225     0.0     30.
C  44   0                                      0.225     0.0     40.
C  50   0                                      0.225     0.0     50.
C  52   0                                      0.225     0.0     60.
C  54   0                                      0.225     0.0     70.
C  56   0                                      0.225     0.0     80.
C  58   0                                      0.225     0.0     90.
    3  27    1                                   EID 1-12 PANEL . 13-27 TUBE
    1   0    1    1.0     1.852E-03
    1   4    3    1    2    1    0    1    0
    3   1  0.5415
    2   6    5    3    4    1    0    1    0
    5   3  0.0833
    6  14   13   11   12    1    2    1    0
   13  11  0.0833
    7  18   17   13   14    1    0    1    0
   17  13  0.0833
    8  22   21   17   18    1    0    1    0
   21  17  0.0833
    9  28   27   21   22    1    0    1    0
   27  21  0.0833
   10  34   33   27   28    1    0    1    0
   33  27  0.0833
   11  40   39   33   34    1    0    1    0
   39  33  0.0833
   12  46   45   39   40    1    0    1    0
   45  39   0.0833
   13  20   19   15   16    1    0    0    0
   14  24   23   19   20    1    0    1    0
   20  24            0.001745      40.0
   15  30   29   23   24    1    0    1    0
   24  30            0.001745      40.0
   18  48   47   41   42    1    6    1    0
   42  48            0.001745      40.0
   19  26   25   20   16    1    0    1    0
   25  20            0.001745      40.0
   20  32   31   25   26    1    0    1    0
   31  25            0.001745      40.0
   23  50   49   43   44    1    6    1    0
   49  43            0.001745      40.0
   24  52   51   49   50    1    0    1    0
   51  49            0.001745      40.0
   27  58   57   55   56    1    2    1    0
```

```
57    55            0.001745      40.0
 3     6     6                               TUBE TO PANEL BOND
 1     0     1     1.0     7.715E-04
 2     0     1     1.0     7.715E-04
 3     0     1     1.0     7.715E-04
 4     0     1     1.0     7.715E-04
 5     0     1     1.0     7.715E-04
 6     0     1     1.0     0.100E-20
 1    47    46    40    41     1
 2    41    40    34    35     2
 3    35    34    28    29     3
 4    29    28    22    23     4
 5    23    22    18    19     5
 6    19    18    14    15     5
```

PROGRAM OUTPUT (SAMPLE PROBLEM 1)

D TUBL CROSS SECTION 3/16/76

C O N T R O L   I N F O R M A T I O N

```
NUMBER OF NODAL POINTS       =   58
NUMBER OF ELEMENT TYPES      =    2
NUMBER OF TABLES             =    0
ANALYSIS CODE(NANA)          =    1
   EQ.0, DATA CHECK ONLY,
   EQ.1, LINEAR,
   EQ.2, NONLINEAR
PLOT CODE(NPLOT)             =    0
   EQ.0, NO PLOTS GENERATED
   EQ.1, UNDEFORMED PLOT
   EQ.2, TEMPERATURE PLOT
ITERATION PARAMETERS
   MAXIMUM ITERATIONS        =    6
   TOLERANCE                 = .10000E+00

BLANK COMMON LOCATIONS = 10967
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	0	-.083	0.000	.500	0	0.000
11	0	-.083	0.000	.250	2	0.000
2	0	-.045	0.000	.500	0	0.000
12	0	-.045	0.000	.250	2	0.000
13	0	-.083	0.000	.225	0	0.000
14	0	-.045	0.000	.225	0	0.000
15	0	-.035	0.000	.225	0	0.000
16	0	0.000	0.000	.225	0	0.000
17	0	-.083	0.000	.190	0	0.000
18	0	-.045	0.000	.190	0	0.000
19	0	-.035	0.000	.190	0	0.000
20	0	0.000	0.000	.190	0	0.000
21	0	-.083	0.000	.160	0	0.000
22	0	-.045	0.000	.160	0	0.000
23	0	-.035	0.000	.160	0	0.000
24	0	0.000	0.000	.160	0	0.000
27	0	-.083	0.000	.120	0	0.000
28	0	-.045	0.000	.120	0	0.000
29	0	-.035	0.000	.120	0	0.000
30	0	0.000	0.000	.120	0	0.000
33	0	-.083	0.000	.04[illegible]	0	0.000

	34	0	-.045	0.000	.080	0	0.000
	35	0	-.035	0.000	.080	0	0.000
	36	0	0.000	0.000	.080	0	0.000
	39	0	-.083	0.000	.040	0	0.000
	40	0	-.045	0.000	.040	0	0.000
	41	0	-.035	0.000	.040	0	0.000
	42	0	0.000	0.000	.040	0	0.000
	45	0	-.083	0.000	0.000	0	0.000
	46	0	-.045	0.000	0.000	0	0.000
	47	0	-.035	0.000	0.000	0	0.000
	48	0	0.000	0.000	0.000	0	0.000
C	57	0	.190	0.000	90.000	0	0.000
C	55	0	.190	0.000	80.000	0	0.000
C	53	0	.190	0.000	70.000	0	0.000
C	51	0	.190	0.000	60.000	0	0.000
C	49	0	.190	0.000	50.000	0	0.000
C	43	0	.190	0.000	40.000	0	0.000
C	37	0	.190	0.000	30.000	0	0.000
C	31	0	.190	0.000	20.000	0	0.000
C	25	0	.190	0.000	10.000	0	0.000
C	26	0	.225	0.000	10.000	0	0.000
C	32	0	.225	0.000	20.000	0	0.000
C	38	0	.225	0.000	30.000	0	0.000
C	44	0	.225	0.000	40.000	0	0.000
C	50	0	.225	0.000	50.000	0	0.000
C	52	0	.225	0.000	60.000	0	0.000
C	54	0	.225	0.000	70.000	0	0.000
C	56	0	.225	0.000	80.000	0	0.000
C	58	0	.225	0.000	90.000	0	0.000

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	0	-.083	0.000	.500		0.000
2	0	-.045	0.000	.500		0.000
3	0	-.083	0.000	.450		0.000
4	0	-.045	0.000	.450		0.000
5	0	-.083	0.000	.400		0.000
6	0	-.045	0.000	.400		0.000
7	0	-.083	0.000	.350		0.000
8	0	-.045	0.000	.350		0.000
9	0	-.083	0.000	.300		0.000
10	0	-.045	0.000	.300		0.000
11	0	-.083	0.000	.250		0.000
12	0	-.045	0.000	.250		0.000
13	0	-.083	0.000	.225		0.000

14	0	-.045	0.000	.225	0.000
15	0	-.035	0.000	.225	0.000
16	0	0.000	0.000	.225	0.000
17	0	-.083	0.000	.190	0.000
18	0	-.045	0.000	.190	0.000
19	0	-.035	0.000	.190	0.000
20	0	0.000	0.000	.190	0.000
21	0	-.083	0.000	.160	0.000
22	0	-.045	0.000	.160	0.000
23	0	-.035	0.000	.160	0.000
24	0	0.000	0.000	.160	0.000
25	0	.033	0.000	.187	0.000
26	0	.039	0.000	.222	0.000
27	0	-.083	0.000	.120	0.000
28	0	-.045	0.000	.120	0.000
29	0	-.035	0.000	.120	0.000
30	0	0.000	0.000	.120	0.000
31	0	.065	0.000	.179	0.000
32	0	.077	0.000	.211	0.000
33	0	-.083	0.000	.080	0.000
34	0	-.045	0.000	.080	0.000
35	0	-.035	0.000	.080	0.000
36	0	0.000	0.000	.080	0.000
37	0	.095	0.000	.165	0.000
38	0	.112	0.000	.195	0.000
39	0	-.083	0.000	.040	0.000
40	0	-.045	0.000	.040	0.000
41	0	-.035	0.000	.040	0.000
42	0	0.000	0.000	.040	0.000
43	0	.122	0.000	.146	0.000
44	0	.145	0.000	.172	0.000
45	0	-.083	0.000	0.000	0.000
46	0	-.045	0.000	0.000	0.000
47	0	-.035	0.000	0.000	0.000
48	0	0.000	0.000	0.000	0.000
49	0	.146	0.000	.122	0.000
50	0	.172	0.000	.145	0.000
51	0	.165	0.000	.095	0.000
52	0	.195	0.000	.113	0.000
53	0	.179	0.000	.065	0.000
54	0	.211	0.000	.077	0.000
55	0	.187	0.000	.033	0.000
56	0	.222	0.000	.039	0.000
57	0	.190	0.000	.000	0.000
58	0	.225	0.000	.000	0.000

I S O P A R A M E T R I C   Q U A D R I L A T E R A L   E L E M E N T S

NUMBER OF QUADRILATERIAL ELEMENTS = 27
NUMBER OF DIFFERENT MATERIALS = 1

EID 1-12 PANEL , 13-27 TUBE

MATERIAL	CONDUCTIVITY TABLE	LAYERS	THICKNESS	CONDUCTIVITY TENSOR KXX	KXY	KYY	THETA
1	0	1	.1000E+01	.1852E-02	0.	0.	0.

ELEMENT INPUT DATA

```
  N    I    J    K    L     MATID   KG   IEDGE    ISURF    Q
  1    4    3    1    2     1       1    1        0        0.
       EDGE   3    1     QS= .5415E+00  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  2    6    5    3    4     1       1    1        0        0.
       EDGE   5    3     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  3    8    7    5    6     1       2    1        0        0.
       EDGE   7    5     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  4   10    9    7    8     1       2    1        0        0.
       EDGE   9    7     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  5   12   11    9   10     1       2    1        0        0.
       EDGE  11    9     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  6   14   13   11   12     1       2    1        0        0.
       EDGE  13   11     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  7   18   17   13   14     1       1    1        0        0.
       EDGE  17   13     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  8   22   21   17   18     1       1    1        0        0.
       EDGE  21   17     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
  9   28   27   21   22     1       1    1        0        0.
       EDGE  27   21     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
 10   34   33   27   28     1       1    1        0        0.
       EDGE  33   27     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
 11   40   39   33   34     1       1    1        0        0.
       EDGE  39   33     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
 12   46   45   39   40     1       1    1        0        0.
       EDGE  45   39     QS= .8330E-01  H1= 0.   T1= 0.   H2= 0.   T2= 0.
 13   20   19   15   16     1       1    0        0        0.
 14   24   23   19   20     1       1    1        0        0.
       EDGE  20   24     QS= 0.   H1= .1745E-02   T1= .4000E+02   H2= .1745E-02   T2= .4000E+02
 15   30   29   23   24     1       1    1        0        0.
       EDGE  24   30     QS= 0.   H1= .1745E-02   T1= .4000E+02   H2= .1745E-02   T2= .4000E+02
```

```
 16   36   35   29   30     1     6     1           0     0.
      EDGE   30   36        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 17   42   41   35   36     1     6     1           0     0.
      EDGE   36   42        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 18   48   47   41   42     1     6     1           0     0.
      EDGE   42   48        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 19   26   25   20   16     1     1     1           0     0.
      EDGE   25   20        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 20   32   31   25   26     1     1     1           0     0.
      EDGE   31   25        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 21   38   37   31   32     1     6     1           0     0.
      EDGE   37   31        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 22   44   43   37   38     1     6     1           0     0.
      EDGE   43   37        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 23   50   49   43   44     1     6     1           0     0.
      EDGE   49   43        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 24   52   51   49   50     1     1     1           0     0.
      EDGE   51   49        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 25   54   53   51   52     1     2     1           0     0.
      EDGE   53   51        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 26   56   55   53   54     1     2     1           0     0.
      EDGE   55   53        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
 27   58   57   55   56     1     2     1           0     0.
      EDGE   57   55        QS= 0.          H1=  .1745E-02   T1=  .4000E+02   H2=  .1745E-02   T2=  .4000E+02
```

I S O P A R A M E T R I C   Q U A D R I L A T E R A L   E L E M E N T S

NUMBER OF QUADRILATERIAL ELEMENTS =   6
NUMBER OF DIFFERENT MATERIALS   =   6

TUBE TO PANEL BOND

MATERIAL	CONDUCTIVITY TABLE	LAYERS	THICKNESS	CONDUCTIVITY TENSOR KXX	KXY	KYY	THETA
1	0	1	.1000E+01	.7715E-03	0.	0.	0.
2	0	1	.1000E+01	.7715E-03	0.	0.	0.
3	0	1	.1000E+01	.7715E-03	0.	0.	0.
4	0	1	.1000E+01	.7715E-03	0.	0.	0.
5	0	1	.1000E+01	.7715E-03	0.	0.	0.
6	0	1	.1000E+01	.1000E-20	0.	0.	0.

ELEMENT INPUT DATA

N	I	J	K	L	MATID	KG	IEDGE	ISURF	Q
1	47	46	40	41	1	1	0	0	0.
2	41	40	34	35	2	1	0	0	0.
3	35	34	28	29	3	1	0	0	0.
4	29	28	22	23	4	1	0	0	0.
5	23	22	18	19	5	1	0	0	0.
6	19	18	14	15	5	1	0	0	0.

S O L U T I O N   P A R A M E T E R S

TOTAL NUMBER OF EQUATIONS	=	58
SEMI BANDWIDTH.	=	11
NUMBER OF EQUATIONS IN A BLOCK	=	58
NUMBER OF BLOCKS	=	1

T E M P E R A T U R E   V E C T O R

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE
1	.308296E+03	.302064E+03	.296985E+03	.293883E+03	.274681E+03
6	.274203E+03	.250905E+03	.250000E+03	.223872E+03	.223054E+03
11	.193948E+03	.193003E+03	.180758E+03	.173957E+03	.158251E+03
16	.142108E+03	.165575E+03	.159427E+03	.154015E+03	.142965E+03
21	.157723E+03	.154087E+03	.150422E+03	.146206E+03	.126453E+03
26	.127939E+03	.152174E+03	.149648E+03	.147580E+03	.144229E+03
31	.114069E+03	.115092E+03	.149113E+03	.146887E+03	.145084E+03
36	.142065E+03	.103918E+03	.104829E+03	.147450E+03	.145284E+03
41	.143564E+03	.140622E+03	.958405E+02	.966330E+02	.146911E+03
46	.144759E+03	.143053E+03	.140133E+03	.895571E+02	.902609E+02
51	.848683E+02	.855054E+02	.816228E+02	.822139E+02	.797164E+02
56	.802804E+02	.790877E+02	.796427E+02		

I S O P A R A M E T R I C   Q U A D R I L A T E R A L   E L E M E N T S

ELEMENT	CONDUCTION FLUXES (LOCAL AXES) QX	QY	SURFACE FLUXES (POSITIVE INTO SURFACE) TOP	BOTTOM	EDGE FLUXES (POSITIVE INTO EDGE) IJ	JK	KL	LI
1	-.2305E+00	-.3610E+00	0.	0.	0.	0.	0.	0.
2	-.8840E-01	-.7775E+00	0.	0.	0.	0.	0.	0.
3	-.3415E-01	-.8886E+00	0.	0.	0.	0.	0.	0.
4	-.4254E-01	-.9997E+00	0.	0.	0.	0.	0.	0.
5	-.4353E-01	-.1111E+01	0.	0.	0.	0.	0.	0.
6	-.1913E+00	-.1194E+01	0.	0.	0.	0.	0.	0.
7	-.3198E+00	-.7861E+00	0.	0.	0.	0.	0.	0.
8	-.2416E+00	-.4072E+00	0.	0.	0.	0.	0.	0.
9	-.1522E+00	-.2312E+00	0.	0.	0.	0.	0.	0.
10	-.1174E+00	-.1348E+00	0.	0.	0.	0.	0.	0.
11	-.1085E+00	-.7559E-01	0.	0.	0.	0.	0.	0.
12	-.1066E+00	-.2464E-01	0.	0.	0.	0.	0.	0.
13	-.7195E+00	-.8941E-01	0.	0.	0.	0.	0.	0.
14	-.4039E+00	-.1085E-01	0.	0.	0.	0.	0.	0.
15	-.2002E+00	-.1116E+00	0.	0.	0.	0.	0.	-.5475E-02
16	-.1685E+00	-.1079E+00	0.	0.	0.	0.	0.	-.7344E-02
17	-.1577E+00	-.6860E-01	0.	0.	0.	0.	0.	-.7200E-02
18	-.1551E+00	-.2315E-01	0.	0.	0.	0.	0.	-.7074E-02
19	-.5182E-01	-.7839E+00	0.	0.	0.	-.5474E-02	0.	0.
20	.1008E-01	-.6493E+00	0.	0.	0.	-.4639E-02	0.	0.
21	.5616E-02	-.5251E+00	0.	0.	0.	-.3987E-02	0.	0.
22	.8756E-02	-.4190E+00	0.	0.	0.	-.3461E-02	0.	0.
23	.1135E-01	-.3262E+00	0.	0.	0.	-.3046E-02	0.	0.
24	.1440E-01	-.2440E+00	0.	0.	0.	-.2729E-02	0.	0.
25	.1791E-01	-.1696E+00	0.	0.	0.	-.2499E-02	0.	0.
26	.2199E-01	-.1006E+00	0.	0.	0.	-.2350E-02	0.	0.
27	.2678E-01	-.3489E-01	0.	0.	0.	-.2277E-02	0.	0.

I S O P A R A M E T R I C   Q U A D R I L A T E R A L   E L E M E N T S

ELEMENT	CONDUCTION FLUX-S (LOCAL AXES) QX	QY	SURFACE FLUXES (POSITIVE INTO SURFACE) TOP	BOTTOM	EDGE FLUXES (POSITIVE INTO EDGE) IJ	JK	KL	LI
1	-.1322E+00	-.9993E-02	0.	0.	0.	0.	0.	0.
2	-.1359E+00	-.3011E-01	0.	0.	0.	0.	0.	0.
3	-.1493E+00	-.5070E-01	0.	0.	0.	0.	0.	0.
4	-.2212E+00	-.7023E-01	0.	0.	0.	0.	0.	0.
5	-.3507E+00	-.1149E+00	0.	0.	0.	0.	0.	0.
6	-.8146E+00	-.2068E+00	0.	0.	0.	0.	0.	0.

O V E R A L L   T I M E   L O G

NODAL POINT INPUT..............	.36
FORM ELEMENT STIFFNESSES........	.73
FORM TOTAL STIFFNESS............	.10
IMPOSE BOUNDARY CONDITIONS......	.03
EQUATION SOLVING................	.10
ELEMENT FLUXES..................	.15
TOTAL SOLUTION TIME.............	1.47

SAMPLE PROBLEM 2

Nonlinear Analysis of a Convectively Heated, Water Cooled Steel Pipe

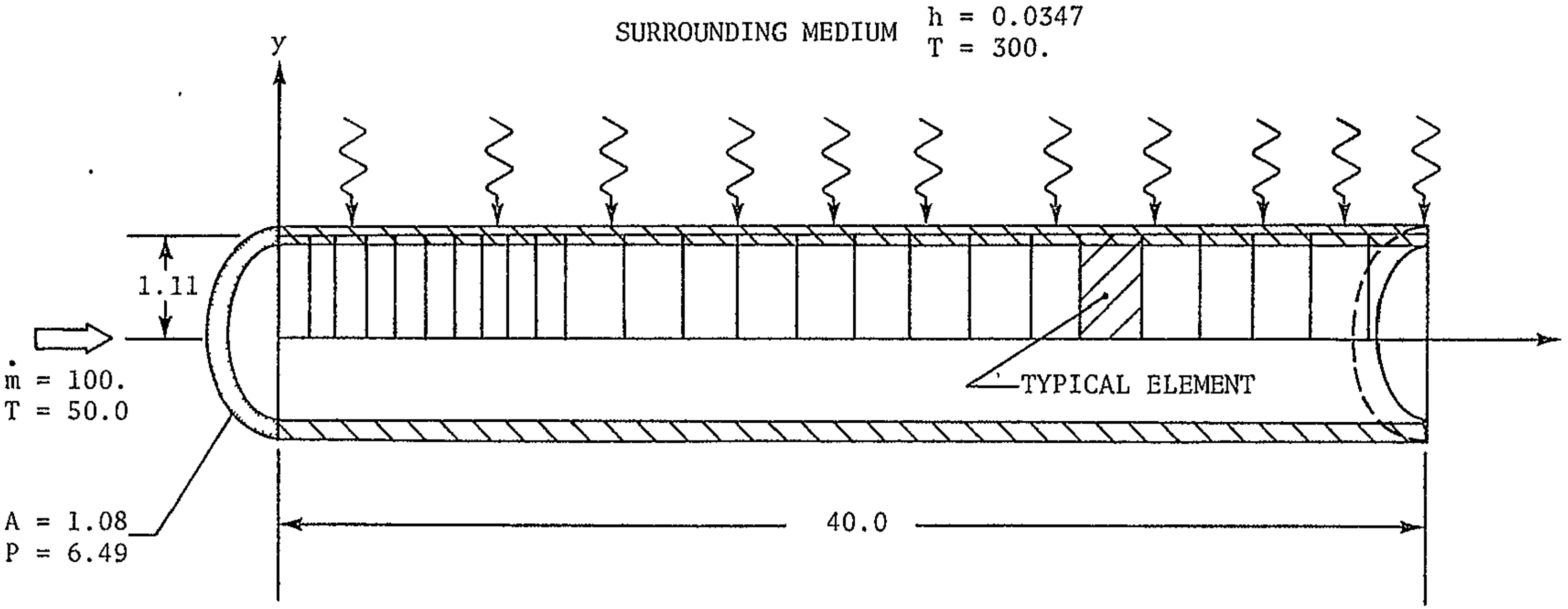


Figure 13. Convectively heated, water-cooled steel pipe (sample problem 2).

INPUT DATA (SAMPLE PROBLEM 2)

```
25 THFL1 **2 INCH PIPE WITH WATER ** NONLINEAR ANALYSIS 2/13/1976
 52    1    3    2    0    0    0    0.0
  1    1                             0.        0.        0.0             50.
  3    0                             1.        0.        0.0
 21    0                            10.        0.        0.0        2
 51    0                            40.        0.        0.0        2
  2    0                             0.        1.11      0.0            0.0
 22    0                            10.        1.11      0.0        2
 52    0                            40.        1.11      0.0        2   0.0
 10   25    1    0
  1   0.0        1
0.0584     0.0       3   1.0        2    0
  1    1    3    4    2    1    2    1   1.0750    6.4940      10.00   0.0
 1.0       0.0       0.03472    300.
 25   49   51   52   50    1    2    1   1.0750    6.4940      10.00   0.0
 1.0       0.0       0.03472    300.
  1    4       THERMAL CONDUCTIVITY FOR TUBE--STEEL
 32.       2.208     212.       2.167     572.      2.083     932.      1.833
  2    7       SPECIFIC HEAT FOR FLUID--WATER
  32.      1.01      50.        1.0       100.      0.998     200.      1.00
  300.     1.03      400.       1.08      500.      1.19
  3    7       CONVECTION COEFFICIENT FOR TUBE TO FLUID
  32.      0.0561    50.        0.0584    100.      0.064     200.      0.0693
  300.     0.0694    400.       0.0670    500.      0.0614
```

PROGRAM OUTPUT (SAMPLE PROBLEM 2)

```
25 THEL1 **2 INCH PIPE WITH WATER ** NONLINEAR ANALYSIS 2/13/1976

C O N T R O L   I N F O R M A T I O N

     NUMBER OF NODAL POINTS   =    52
     NUMBER OF ELEMENT TYPES  =     1
     NUMBER OF TABLES         =     3
     ANALYSIS CODE(NANA)      =     2
        EQ.0, DATA CHECK ONLY,
        EQ.1, LINEAR,
        EQ.2, NONLINEAR
     PLOT CODE(NPLOT)         =     0
        EQ.0, NO PLOTS GENERATED
        EQ.1, UNDEFORMED  PLOT
        EQ.2, TEMPERATURE PLOT
     ITERATION PARAMETERS
        MAXIMUM ITERATIONS    =     6
        TOLERANCE             =    .10000E+00

     BLANK COMMON LOCATIONS = 10967
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000	0	50.000
3	0	1.000	0.000	0.000	0	0.000
21	0	10.000	0.000	0.000	2	0.000
51	0	40.000	0.000	0.000	2	0.000
2	0	0.000	1.110	0.000	0	0.000
22	0	10.000	1.110	0.000	2	0.000
52	0	40.000	1.110	0.000	2	0.000

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000		50.000
2	0	0.000	1.110	0.000		0.000
3	0	1.000	0.000	0.000		0.000
4	0	1.000	1.110	0.000		0.000
5	0	2.000	0.000	0.000		0.000
6	0	2.000	1.110	0.000		0.000
7	0	3.000	0.000	0.000		0.000

8	0	3.000	1.110	0.000	0.000
9	0	4.000	0.000	0.000	0.000
10	0	4.000	1.110	0.000	0.000
11	0	5.000	0.000	0.000	0.000
12	0	5.000	1.110	0.000	0.000
13	0	6.000	0.000	0.000	0.000
14	0	6.000	1.110	0.000	0.000
15	0	7.000	0.000	0.000	0.000
16	0	7.000	1.110	0.000	0.000
17	0	8.000	0.000	0.000	0.000
18	0	8.000	1.110	0.000	0.000
19	0	9.000	0.000	0.000	0.000
20	0	9.000	1.110	0.000	0.000
21	0	10.000	0.000	0.000	0.000
22	0	10.000	1.110	0.000	0.000
23	0	12.000	0.000	0.000	0.000
24	0	12.000	1.110	0.000	0.000
25	0	14.000	0.000	0.000	0.000
26	0	14.000	1.110	0.000	0.000
27	0	16.000	0.000	0.000	0.000
28	0	16.000	1.110	0.000	0.000
29	0	18.000	0.000	0.000	0.000
30	0	18.000	1.110	0.000	0.000
31	0	20.000	0.000	0.000	0.000
32	0	20.000	1.110	0.000	0.000
33	0	22.000	0.000	0.000	0.000
34	0	22.000	1.110	0.000	0.000
35	0	24.000	0.000	0.000	0.000
36	0	24.000	1.110	0.000	0.000
37	0	26.000	0.000	0.000	0.000
38	0	26.000	1.110	0.000	0.000
39	0	28.000	0.000	0.000	0.000
40	0	28.000	1.110	0.000	0.000
41	0	30.000	0.000	0.000	0.000
42	0	30.000	1.110	0.000	0.000
43	0	32.000	0.000	0.000	0.000
44	0	32.000	1.110	0.000	0.000
45	0	34.000	0.000	0.000	0.000
46	0	34.000	1.110	0.000	0.000
47	0	36.000	0.000	0.000	0.000
48	0	36.000	1.110	0.000	0.000
49	0	38.000	0.000	0.000	0.000
50	0	38.000	1.110	0.000	0.000
51	0	40.000	0.000	0.000	0.000
52	0	40.000	1.110	0.000	0.000

O N E D I M E N S I O N A L T H E R M A L - F L U I D E L E M E N T

NUMBER OF THERMAL-FLUID ELEMENTS = 25
NUMBER OF THERMAL-FLUID PROPERTIES= 1

THERMAL-FLUID PROPERTIES

T U B E F L U I D P R O P E R T I E S

PROPERTY ID	CONDUCTIVITY K	CONDUCTIVITY TABLE	CONVECTION H	CONVECTION EXPONENT	CONVECTION TABLE	SPECIFIC HEAT	SPECIFIC HEAT TABLE	VISCOSITY TABLE
1	0.	1	.5840E-01	0.	3	.1000E+01	2	0

ELEMENT INPUT DATA

```
                                               CONDUCTION  CONVECTION   MASS FLOW    INLET
  N    I    J    K    L   PID   KG  ISURF        AREA       PERIMETER     RATE      PRESSURE

  1    1    3    4    2    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  2    3    5    6    4    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  3    5    7    8    6    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  4    7    9   10    8    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  5    9   11   12   10    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  6   11   13   14   12    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  7   13   15   16   14    1    2    1        .1075E+01   .6494E+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03

  8   15   17   18   16    1    2    1        .1075E+01   .6494F+01   .1000E+02   0.
 AF=   .1000E+01  SURFQ=  0.           HK=   .3472E-01  TEMPK=   .3000E+03  HL=   .3472E-01  TEMPL=   .3000E+03
```

```
 9   17   19   20   18   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

10   19   21   22   20   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

11   21   23   24   22   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

12   23   25   26   24   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

13   25   27   28   26   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

14   27   29   30   28   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

15   29   31   32   30   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

16   31   33   34   32   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

17   33   35   36   34   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03

18   35   37   38   36   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=  .1000E+01  SURFQ=  0.   HK=  .3472E-01  TEMPK=  .3000E+03  HL=  .3472E-01  TEMPL=  .3000E+03
```

```
19   37   39   40   38   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

20   39   41   42   40   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

21   41   43   44   42   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

22   43   45   46   44   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

23   45   47   48   46   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

24   47   49   50   48   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03

25   49   51   52   50   1   2   1   .1075E+01   .6494E+01   .1000E+02   0.
AF=   .1000E+01   SURFQ=   0.   HK=   .3472E-01   TEMPK=   .3000E+03   HL=   .3472E-01   TEMPL=   .3000E+03
```

C-2

MATERIAL PROPERTIES TABLES

TABLE NUMBER 1 THERMAL CONDUCTIVITY FOR TUBE--STEEL

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
32.0	.2208E+01,	212.0	.2167E+01,	572.0	.2083E+01,	932.0	.1833E+01,

TABLE NUMBER 2 SPECIFIC HEAT FOR FLUID--WATER

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
32.0	.1010E+01,	50.0	.1000E+01,	100.0	.9980E+00,	200.0	.1000E+01,
300.0	.1030E+01,	400.0	.1080E+01,	500.0	.1190E+01,		

TABLE NUMBER 3 CONVECTION COEFFICIENT FOR TUBE TO FLUID

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
32.0	.5610E-01,	50.0	.5840E-01,	100.0	.6400E-01,	200.0	.6930E-01,
300.0	.6940E-01,	400.0	.6700E-01,	500.0	.6140E-01,		

S O L U T I O N   P A R A M E T E R S

TOTAL NUMBER OF EQUATIONS	=	52
SEMI BANDWIDTH	=	4
NUMBER OF EQUATIONS IN A BLOCK	=	52
NUMBER OF BLOCKS	=	1

TEMPERATURE VECTOR

NONLINEAR ANALYSIS ITERATION NUMBER 1

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	.500000E+02	.154050E+03	.533261E+02	.154457E+03	.566534E+02
6	.155450E+03	.598251E+02	.156788E+03	.630282E+02	.158325E+03
11	.660914E+02	.159973E+03	.691989E+02	.161680E+03	.721716E+02
16	.163412E+03	.751953E+02	.165151E+03	.780855E+02	.166885E+03
21	.810310E+02	.168608E+03	.866835E+02	.172001E+03	.922465E+02
26	.175318E+03	.976060E+02	.178549E+03	.102887E+03	.181700E+03
31	.107969E+03	.184767E+03	.112982E+03	.187757E+03	.117801E+03
36	.190667E+03	.122560E+03	.193503E+03	.127129E+03	.196260E+03
41	.131647E+03	.198942E+03	.135977E+03	.201534E+03	.140263E+03
46	.204014E+03	.144357E+03	.206296E+03	.148397E+03	.208172E+03
51	.152198E+03	.209047E+03			

LARGEST CHANGE .1000000E+03 PERCENT AT NODE 2

T E M P E R A T U R E   V E C T O R

NONLINEAR ANALYSIS ITERATION NUMBER 2

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	.500000E+02	.147180E+03	.535535E+02	.147584E+03	.571364E+02
6	.148556E+03	.605377E+02	.149860E+03	.639999E+02	.151359E+03
11	.672946E+02	.152968E+03	.706636E+02	.154639E+03	.738685E+02
16	.156340E+03	.771548E+02	.158056E+03	.802763E+02	.159773E+03
21	.834842E+02	.161486E+03	.896196E+02	.164912E+03	.956770E+02
26	.168294E+03	.101509E+03	.171631E+03	.107281E+03	.174987E+03
31	.112807E+03	.178353E+03	.118261E+03	.181673E+03	.123480E+03
36	.184917E+03	.128640E+03	.188089E+03	.133569E+03	.191178E+03
41	.138451E+03	.194190E+03	.143103E+03	.197109E+03	.147717E+03
46	.199918E+03	.152095E+03	.202530E+03	.156424E+03	.204720E+03
51	.160447E+03	.205772E+03			

LARGEST CHANGE .5141430E+01 PERCENT AT NODE 51

TEMPERATURE VECTOR

NONLINEAR ANALYSIS ITERATION NUMBER 3

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE
1	.500000E+02	.146779E+03	.535620E+02	.147184E+03	.571547E+02
6	.148157E+03	.605642E+02	.149462E+03	.640361E+02	.150963E+03
11	.673390E+02	.152573E+03	.707179E+02	.154245E+03	.739310E+02
16	.155949E+03	.772271E+02	.157667E+03	.803569E+02	.159388E+03
21	.835746E+02	.161106E+03	.897276E+02	.164550E+03	.958045E+02
26	.167969E+03	.101658E+03	.171395E+03	.107429E+03	.174838E+03
31	.112958E+03	.178238E+03	.118416E+03	.181575E+03	.123638E+03
36	.184832E+03	.128802E+03	.188014E+03	.133734E+03	.191113E+03
41	.138618E+03	.194135E+03	.143272E+03	.197063E+03	.147889E+03
46	.199881E+03	.152268E+03	.202502E+03	.156598E+03	.204699E+03
51	.160621E+03	.205755E+03			

LARGEST CHANGE .2729551E+00 PERCENT AT NODE 2

T E M P E R A T U R E   V E C T O R

NONLINEAR ANALYSIS ITERATION NUMBER 4

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE.
1	.500000E+02	.146758E+03	.535625E+02	.147163E+03	.571557E+02
6	.148136E+03	.605657E+02	.149442E+03	.640380E+02	.150943E+03
11	.673414E+02	.152553E+03	.707207E+02	.154226E+03	.739343E+02
16	.155930E+03	.772309E+02	.157649E+03	.803610E+02	.159370E+03
21	.835792E+02	.161089E+03	.897330E+02	.164535E+03	.958107E+02
26	.167957E+03	.101665E+03	.171388E+03	.107436E+03	.174835E+03
31	.112965E+03	.178237E+03	.118422E+03	.181575E+03	.123645E+03
36	.184832E+03	.128809E+03	.188015E+03	.133740E+03	.191113E+03
41	.138625E+03	.194136E+03	.143279E+03	.197064E+03	.147895E+03
46	.199883E+03	.152274E+03	.202503E+03	.156604E+03	.204701E+03
51	.160627E+03	.205757E+03			

LARGEST CHANGE .1440769E-01 PERCENT AT NODE 2

CONVERGENCE ACHIEVED

O N E   D I M E N S I O N A L   T H E R M A L - F L U I D   E L E M E N T S

	H E A T F L U X E S			F L U I D P R E S S U R E D A T A			
ELEMENT	FLUID HEAT FLUX	TUBE CONDUCTION	EXTERNAL CONVECTION FLUX	FRICTION PRESSURE DROP	FLOW ACCELERATION PRESSURE DROP	PRESSURE NODE-I	PRESSURE NODE-J
1	.5178E+03	-.9491E+00	.3451E+02	0.	0.	0.	0.
2	.5535E+03	-.2283E+01	.3435E+02	0.	0.	0.	0.
3	.5884E+03	-.3061E+01	.3409E+02	0.	0.	0.	0.
4	.6227E+03	-.3519E+01	.3378E+02	0.	0.	0.	0.
5	.6565E+03	-.3775E+01	.3343E+02	0.	0.	0.	0.
6	.6898E+03	-.3922E+01	.3306E+02	0.	0.	0.	0.
7	.7226E+03	-.3992E+01	.3268E+02	0.	0.	0.	0.
8	.7551E+03	-.4029E+01	.3229E+02	0.	0.	0.	0.
9	.7871E+03	-.4031E+01	.3190E+02	0.	0.	0.	0.
10	.8187E+03	-.4026E+01	.3151E+02	0.	0.	0.	0.
11	.8653E+03	-.4034E+01	.6186E+02	0.	0.	0.	0.
12	.9261E+03	-.4005E+01	.6032E+02	0.	0.	0.	0.
13	.9855E+03	-.4014E+01	.5877E+02	0.	0.	0.	0.
14	.1044E+04	-.4031E+01	.5722E+02	0.	0.	0.	0.
15	.1100E+04	-.3977E+01	.5568E+02	0.	0.	0.	0.
16	.1155E+04	-.3901E+01	.5416E+02	0.	0.	0.	0.
17	.1208E+04	-.3805E+01	.5267E+02	0.	0.	0.	0.
18	.1260E+04	-.3718E+01	.5122E+02	0.	0.	0.	0.
19	.1311E+04	-.3618E+01	.4980E+02	0.	0.	0.	0.
20	.1360E+04	-.3528E+01	.4842E+02	0.	0.	0.	0.
21	.1408E+04	-.3416E+01	.4708E+02	0.	0.	0.	0.
22	.1454E+04	-.3288E+01	.4578E+02	0.	0.	0.	0.
23	.1499E+04	-.3056E+01	.4456E+02	0.	0.	0.	0.
24	.1543E+04	-.2562E+01	.4347E+02	0.	0.	0.	0.
25	.1585E+04	-.1231E+01	.4274E+02	0.	0.	0.	0.

O V E R A L L   T I M E   L O G

NODAL POINT INPUT...............	.15
FORM ELEMENT STIFFNESSES.......	.49
FORM TOTAL STIFFNESS...........	.93
IMPOSE BOUNDARY CONDITIONS.....	.06
EQUATION SOLVING...............	.14
ELEMENT FLUXES.................	.15
TOTAL SOLUTION TIME............	1.93

SAMPLE PROBLEM 3

Nonlinear Analysis of a Simplified Heat Exchanger

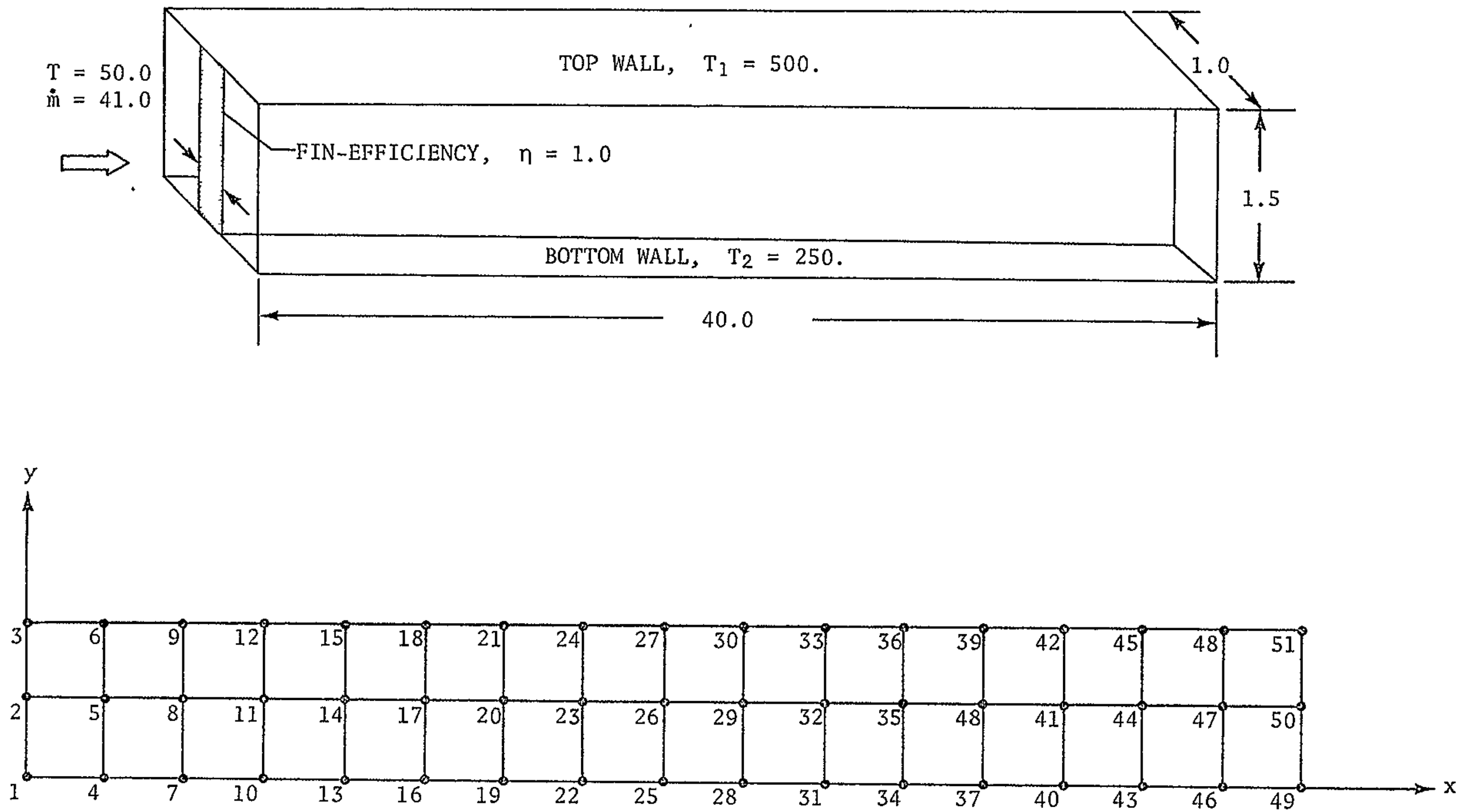


Figure 14. Simplified heat exchanger (sample problem 3).

INPUT DATA (SAMPLE PROBLEM 3)

```
 SIMPLIFIED HEAT EXCHANGER **EAT**  **NONLINEAR**MEMORIAL DAY, 1976
51     1     6     2     0     0
 1     1                                  0.0          0.0          0.0         3  250.
49     1                                 40.0          0.0          0.0         3  250.
 2     1                                  0.0          0.75         0.0         3   50.
 5     0                                  2.5          0.75         0.0         3    0.
50     0                                 40.0          0.75         0.0         3    0.
 3     1                                  0.0          1.50         0.0         3  500.
51     1                                 40.0          1.50         0.0         3  500.
11    16     1     0                                INTERNAL FIN
 1  0.0231         6.
0.2513      0.0        1   0.7        2     3
 1     1     4     5     6     3     2     1     3     0   41.04
 0.3         1.0         1.0
16    46    49    50    51    48    47     1     3     0   41.04
 0.3         1.0         1.0
 1    12     FLUID TO WALL CONVECTION COEFFICIENT -H(BTU/FT2SF)
  40.0     0.2513     46.80     0.2627      53.53     0.2737     60.18      0.2848
  66.77    0.2956     73.29     0.3066      79.75     0.3175     86.15      0.3284
  92.49    0.3397     98.77     0.3501     105.00     0.4011    105.       0.4011
 2     6     SPECIFIC HEAT - C SUB P (BTU/LBM-F)
 -50.0     0.63        0.0      0.675      60.0       0.735     120.0       0.805
 140.0     0.84      220.0      0.850
 3    20     FLUID  VISCOSITY - MU  (LBM/FT-SEC)
 -50.   0.2450      -40.      0.1350     -20.0      0.05213      0.0      0.02352
  20.   0.01220      40.      0.007299    60.0      0.004649    80.0      0.003049
 100.   0.002081    120.      0.001581   130.0      0.001395   138.0      0.001269
 140.   0.001243    142.      0.001219   160.0      0.0009878  180.0      0.0007849
 200.   0.0006248   220.      0.0005131  240.0      0.0004394  300.0      0.0002960
 4    11     FRICTION FACTOR  - F
  40.0     0.01228  46.80     0.01192   53.53      0.01161    60.18     0.01133
  66.77    0.01109  73.29     0.01174   79.25      0.01142    86.15     0.01109
  92.49    0.01072  98.77     0.01040  105.00      0.01012
 5     8     FLUID DENSITY - RHO  (LBM/FT3)
 -50.0     70.0       0.0        69.1      50.0       68.2       100.       67.15
 150.0     65.8     175.0        65.0     200.0       64.25      225.       63.5
 6     4      THERMAL CONDUCTIVITY, K-(BTU/SEC-FT-F)
32.0      0.02194   212.      0.02306    392.      0.02444     572.      0.02583
```

PROGRAM OUTPUT (SAMPLE PROBLEM 3)

```
SIMPLIFIED HEAT EXCHANGER **EAT**  **NONLINEAR**MEMORIAL DAY, 1976

C O N T R O L   I N F O R M A T I O N

NUMBER OF NODAL POINTS      =    51
NUMBER OF ELEMENT TYPES     =     1
NUMBER OF TABLES            =     6
ANALYSIS CODE(NANA)         =     2
    EQ.0, DATA CHECK ONLY,
    EQ.1, LINEAR,
    EQ.2, NONLINEAR
PLOT CODE(NPLOT)            =     0
    EQ.0, NO PLOTS GENERATED
    EQ.1, UNDEFORMED PLOT
    EQ.2, TEMPERATURE PLOT
ITERATION PARAMETERS
    MAXIMUM ITERATIONS      =     6
    TOLERANCE               =   .10000E+00

BLANK COMMON LOCATIONS = 10967
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000	3	250.000
49	1	40.000	0.000	0.000	3	250.000
2	1	0.000	.750	0.000	3	50.000
5	0	2.500	.750	0.000	3	0.000
50	0	40.000	.750	0.000	3	0.000
3	1	0.000	1.500	0.000	3	500.000
51	1	40.000	1.500	0.000	3	500.000

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000		250.000
2	1	0.000	.750	0.000		50.000
3	1	0.000	1.500	0.000		500.000
4	1	2.500	0.000	0.000		250.000
5	0	2.500	.750	0.000		0.000
6	1	2.500	1.500	0.000		500.000
7	1	5.000	0.000	0.000		250.000

8	0	5.000	.750	0.000	0.000
9	1	5.000	1.500	0.000	500.000
10	1	7.500	0.000	0.000	250.000
11	0	7.500	.750	0.000	0.000
12	1	7.500	1.500	0.000	500.000
13	1	10.000	0.000	0.000	250.000
14	0	10.000	.750	0.000	0.000
15	1	10.000	1.500	0.000	500.000
16	1	12.500	0.000	0.000	250.000
17	0	12.500	.750	0.000	0.000
18	1	12.500	1.500	0.000	500.000
19	1	15.000	0.000	0.000	250.000
20	0	15.000	.750	0.000	0.000
21	1	15.000	1.500	0.000	500.000
22	1	17.500	0.000	0.000	250.000
23	0	17.500	.750	0.000	0.000
24	1	17.500	1.500	0.000	500.000
25	1	20.000	0.000	0.000	250.000
26	0	20.000	.750	0.000	0.000
27	1	20.000	1.500	0.000	500.000
28	1	22.500	0.000	0.000	250.000
29	0	22.500	.750	0.000	0.000
30	1	22.500	1.500	0.000	500.000
31	1	25.000	0.000	0.000	250.000
32	0	25.000	.750	0.000	0.000
33	1	25.000	1.500	0.000	500.000
34	1	27.500	0.000	0.000	250.000
35	0	27.500	.750	0.000	0.000
36	1	27.500	1.500	0.000	500.000
37	1	30.000	0.000	0.000	250.000
38	0	30.000	.750	0.000	0.000
39	1	30.000	1.500	0.000	500.000
40	1	32.500	0.000	0.000	250.000
41	0	32.500	.750	0.000	0.000
42	1	32.500	1.500	0.000	500.000
43	1	35.000	0.000	0.000	250.000
44	0	35.000	.750	0.000	0.000
45	1	35.000	1.500	0.000	500.000
46	1	37.500	0.000	0.000	250.000
47	0	37.500	.750	0.000	0.000
48	1	37.500	1.500	0.000	500.000
49	1	40.000	0.000	0.000	250.000
50	0	40.000	.750	0.000	0.000
51	1	40.000	1.500	0.000	500.000

T W O   D I M E N S I O N A L   T H E R M A L - F L U I D   E L E M E N T

NUMBER OF THERMAL-FLUID ELEMENTS = 16
NUMBER OF THERMAL-FLUID PROPERTIES = 1

INTERNAL FIN

THERMAL-FLUID PROPERTIES

	F I N		F L U I D P R O P E R T I E S					
PROPERTY ID	CONDUCTIVITY K	CONDUCTIVITY TABLE	CONVECTION H	CONVECTION EXPONENT	CONVECTION TABLE	SPECIFIC HEAT	SPECIFIC HEAT TABLE	VISCOSITY TABLE
1	.2310E-01	6	.2513E+00	0.	1	.7000E+00	2	3

ELEMENT INPUT DATA

EID	I	J	K	L	M	N	PID	KG	FIN THICKNESS	FIN EFFICIENCY	AREA FACTOR	TOP WIDTH	BOTTOM WIDTH	MASS FLOW RATE	INLET PRESSURE
1	1	4	5	6	3	2	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
2	4	7	8	9	6	5	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
3	7	10	11	12	9	8	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
4	10	13	14	15	12	11	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
5	13	16	17	18	15	14	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
6	16	19	20	21	18	17	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
7	19	22	23	24	21	20	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
8	22	25	26	27	24	23	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
9	25	28	29	30	27	26	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
10	28	31	32	33	30	29	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
11	31	34	35	36	33	32	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
12	34	37	38	39	36	35	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
13	37	40	41	42	39	38	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
14	40	43	44	45	42	41	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
15	43	46	47	48	45	44	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.
16	46	49	50	51	48	47	1	3	.3000E+00	.1000E+01	.1000E+01	.7000E+00	.7000E+00	.4104E+02	0.

M A T E R I A L   P R O P E R T I E S   T A B L E S

TABLE NUMBER 1 FLUID TO WALL CONVECTION COEFFICIENT -H(BTU/FT2SF)

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
40.0	.2513E+00,	46.8	.2627E+00,	53.5	.2737E+00,	60.2	.2848E+00,
66.8	.2956E+00,	73.3	.3066E+00,	79.8	.3175E+00,	86.2	.3284E+00,
92.5	.3397E+00,	98.8	.3501E+00,	105.0	.4011E+00,	105.0	.4011E+00,

TABLE NUMBER 2 SPECIFIC HEAT - C SUB P (BTU/LBM-F)

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
-50.0	.6300E+00,	0.0	.6750E+00,	60.0	.7350E+00,	120.0	.8050E+00,
140.0	.8400E+00,	220.0	.8500E+00,				

TABLE NUMBER 3 FLUID VISCOSITY - MU (LBM/FT-SEC)

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
-50.0	.2450E+00,	-40.0	.1350E+00,	-20.0	.5213E-01,	0.0	.2352E-01,
20.0	.1220E-01,	40.0	.7299E-02,	60.0	.4649E-02,	80.0	.3049E-02,
100.0	.2081E-02,	120.0	.1581E-02,	130.0	.1395E-02,	138.0	.1269E-02,
140.0	.1243E-02,	142.0	.1219E-02,	160.0	.9878E-03,	180.0	.7849E-03,
200.0	.6248E-03,	220.0	.5131E-03,	240.0	.4394E-03,	300.0	.2960E-03,

TABLE NUMBER 4 FRICTION FACTOR - F

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
40.0	.1228E-01,	46.8	.1192E-01,	53.5	.1161E-01,	60.2	.1133E-01,
66.8	.1102E-01,	73.3	.1174E-01,	79.3	.1142E-01,	86.2	.1109E-01,
92.5	.1072E-01,	98.8	.1040E-01,	105.0	.1012E-01,		

TABLE NUMBER 5 FLUID DENSITY - RHO (LBM/FT3)

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
-50.0	.7000E+02,	0.0	.6910E+02,	50.0	.6820E+02,	100.0	.6715E+02,
150.0	.6580E+02,	175.0	.6500E+02,	200.0	.6425E+02,	225.0	.6350E+02,

TABLE NUMBER 6 THERMAL CONDUCTIVITY, K-(BTU/SEC-FT-F)

TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY	TEMP.	PROPERTY
32.0	.2194E-01,	212.0	.2306E-01,	392.0	.2444E-01,	572.0	.2583E-01,

S O L U T I O N   P A R A M E T E R S

TOTAL NUMBER OF EQUATIONS	=	51
SEMI BANDWIDTH	=	6
NUMBER OF EQUATIONS IN A BLOCK	=	51
NUMBER OF BLOCKS	=	1

T E M P E R A T U R E   V E C T O R

NONLINEAR ANALYSIS ITERATION NUMBER 1

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	.250000E+03	.500000E+02	.500000E+03	.250000E+03	.603029E+02
6	.500000E+03	.250000E+03	.702241E+02	.500000E+03	.250000E+03
11	.798882E+02	.500000E+03	.250000E+03	.891895E+02	.500000E+03
16	.250000E+03	.982547E+02	.500000E+03	.250000E+03	.106975E+03
21	.500000E+03	.250000E+03	.115478E+03	.500000E+03	.250000E+03
26	.123653E+03	.500000E+03	.250000E+03	.131630E+03	.500000E+03
31	.250000E+03	.139294E+03	.500000E+03	.250000E+03	.146777E+03
36	.500000E+03	.250000E+03	.153961E+03	.500000E+03	.250000E+03
41	.160981E+03	.500000E+03	.250000E+03	.167715E+03	.500000E+03
46	.250000E+03	.174301E+03	.500000E+03	.250000E+03	.180613E+03
51	.500000E+03				

LARGEST CHANGE .1000000E+03 PERCENT AT NODE 5

T E M P E R A T U R E   V E C T O R

NONLINEAR ANALYSIS ITERATION NUMBER 2

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	.250000E+03	.500000E+02	.500000E+03	.250000E+03	.637866E+02
6	.500000E+03	.250000E+03	.772645E+02	.500000E+03	.250000E+03
11	.908493E+02	.500000E+03	.250000E+03	.104004E+03	.500000E+03
16	.250000E+03	.117158E+03	.500000E+03	.250000E+03	.132354E+03
21	.500000E+03	.250000E+03	.145004E+03	.500000E+03	.250000E+03
26	.156702E+03	.500000E+03	.250000E+03	.167487E+03	.500000E+03
31	.250000E+03	.177430E+03	.500000E+03	.250000E+03	.187416E+03
36	.500000E+03	.250000E+03	.196773E+03	.500000E+03	.250000E+03
41	.205764E+03	.500000E+03	.250000E+03	.214176E+03	.500000E+03
46	.250000E+03	.222276E+03	.500000E+03	.250000E+03	.229841E+03
51	.500000E+03				

LARGEST CHANGE .2176458E+02 PERCENT AT NODE 41

TEMPERATURE VECTOR

NONLINEAR ANALYSIS ITERATION NUMBER 3

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	.250000E+03	.500000E+02	.500000E+03	.250000E+03	.637703E+02
6	.500000E+03	.250000E+03	.775219E+02	.500000E+03	.250000E+03
11	.913021E+02	.500000E+03	.250000E+03	.104910E+03	.500000E+03
16	.250000E+03	.119341E+03	.500000E+03	.250000E+03	.132569E+03
21	.500000E+03	.250000E+03	.144895E+03	.500000E+03	.250000E+03
26	.156443E+03	.500000E+03	.250000E+03	.167499E+03	.500000E+03
31	.250000E+03	.177872E+03	.500000E+03	.250000E+03	.187821E+03
36	.500000E+03	.250000E+03	.197144E+03	.500000E+03	.250000E+03
41	.206104E+03	.500000E+03	.250000E+03	.214487E+03	.500000E+03
46	.250000E+03	.222561E+03	.500000E+03	.250000E+03	.230103E+03
51	.500000E+03				

LARGEST CHANGE .1829206E+01 PERCENT AT NODE 17

TEMPERATURE VECTOR

NONLINEAR ANALYSIS ITERATION NUMBER 4

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE.
1	.250000E+03	.500000E+02	.500000E+03	.250000E+03	.637706E+02
6	.500000E+03	.250000E+03	.775265E+02	.500000E+03	.250000E+03
11	.913209E+02	.500000E+03	.250000E+03	.104950E+03	.500000E+03
16	.250000E+03	.119376E+03	.500000E+03	.250000E+03	.132606E+03
21	.500000E+03	.250000E+03	.144930E+03	.500000E+03	.250000E+03
26	.156475E+03	.500000E+03	.250000E+03	.167530E+03	.500000E+03
31	.250000E+03	.177901E+03	.500000E+03	.250000E+03	.187849E+03
36	.500000E+03	.250000E+03	.197171E+03	.500000E+03	.250000E+03
41	.206129E+03	.500000E+03	.250000E+03	.214511E+03	.500000E+03
46	.250000E+03	.222584E+03	.500000E+03	.250000E+03	.230124E+03
51	.500000E+03				

LARGEST CHANGE .3878953E-01 PERCENT AT NODE 14

CONVERGENCE ACHIEVED

TWO DIMENSIONAL THERMAL-FLUID ELEMENTS

	HEAT FLUXES			FLUID PRESSURE DATA			
ELEMENT	FLUID HEAT FLUX	FIN CONDUCTION FLUXES QX	QY	FRICTION PRESSURE DROP	FLOW ACCELERATION PRESSURE DROP	PRESSURE NODE-I	PRESSURE NODE-J
1	.1709E+04	0.	-.1215E+01	0.	0.	0.	0.
2	.2167E+04	0.	-.1215E+01	0.	0.	0.	0.
3	.2645E+04	0.	-.1215E+01	0.	0.	0.	0.
4	.3139E+04	0.	-.1215E+01	0.	0.	0.	0.
5	.3663E+04	0.	-.1215E+01	0.	0.	0.	0.
6	.4217E+04	0.	-.1215E+01	0.	0.	0.	0.
7	.4772E+04	0.	-.1215E+01	0.	0.	0.	0.
8	.5204E+04	0.	-.1215E+01	0.	0.	0.	0.
9	.5603E+04	0.	-.1215E+01	0.	0.	0.	0.
10	.5983E+04	0.	-.1215E+01	0.	0.	0.	0.
11	.6345E+04	0.	-.1215E+01	0.	0.	0.	0.
12	.6688E+04	0.	-.1215E+01	0.	0.	0.	0.
13	.7015E+04	0.	-.1215E+01	0.	0.	0.	0.
14	.7326E+04	0.	-.1215E+01	0.	0.	0.	0.
15	.7622E+04	0.	-.1215E+01	0.	0.	0.	0.
16	.7904E+04	0.	-.1215E+01	0.	0.	0.	0.

O V E R A L L   T I M E   L O G

NODAL POINT INPUT...............	.15
FORM ELEMENT STIFFNESSES........	.74
FORM TOTAL STIFFNESS............	1.14
IMPOSE BOUNDARY CONDITIONS......	.13
EQUATION SOLVING................	.12
ELEMENT FLUXES..................	.12
TOTAL SOLUTION TIME.............	2.40

SAMPLE PROBLEM 4

Linear Conduction Analysis of a Fin with Plots

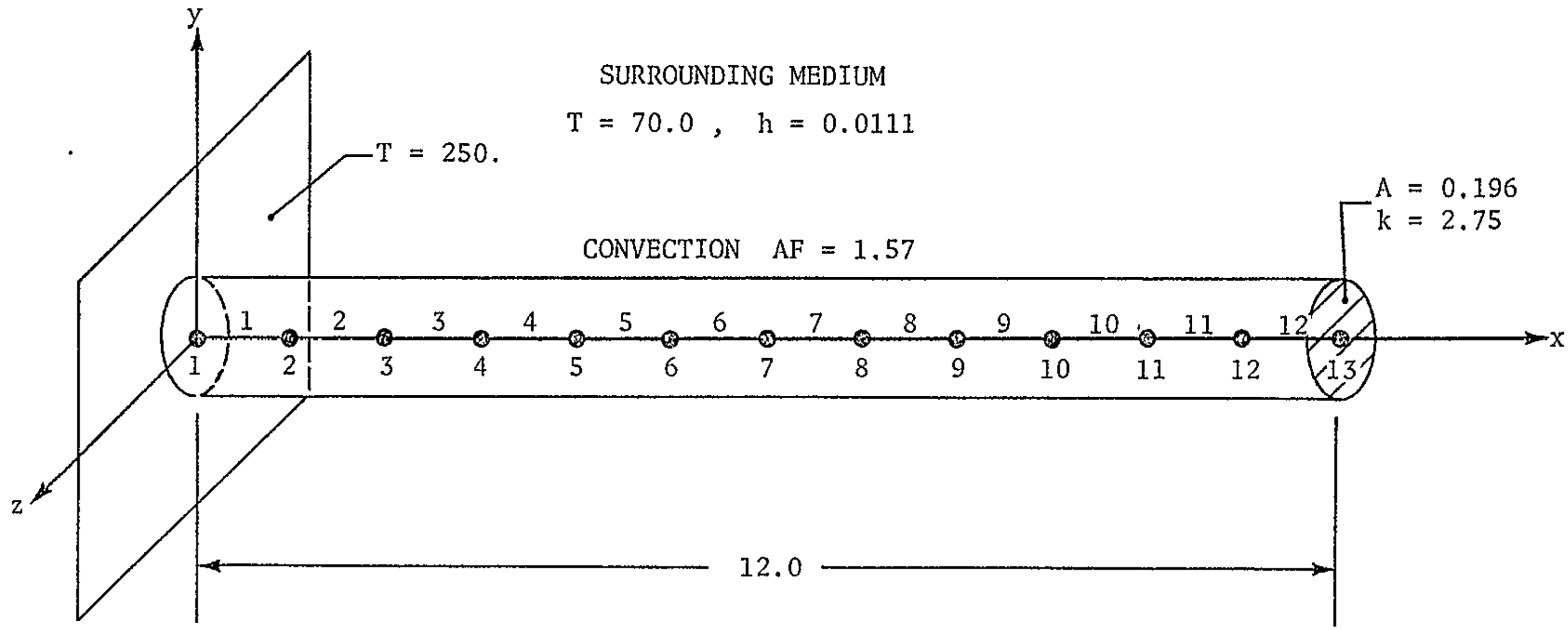


Figure 15. Conduction in a simple fin (sample problem 4).

INPUT DATA (SAMPLE PROBLEM 4)

```
   FIN PROBLEM    CHAPMAN TEXT PAGE 76,     EAT   NOVEMBER 14,1975
 13     1     0     1     0     1
  1     1                             0.0        0.0       0.0        0   250.
  2     0                             1.0        0.0       0.0             0.
 13     0                            12.0        0.0       0.0        1      0.
  1    12     1
  1     0   2.75
  1     1     2     1     0 0.19635   0.0        1.5708
0.0      0.011111      70.0
 12    12    13     1     1 0.19635   0.0        1.5708
0.0      0.011111      70.0
```

```
   FIN PROBLEM .  CHAPMAN TEXT PAGE 76,     EAT   NOVEMBER 14,1975
$OPTION
 NNDEST = 13 ,NWDISP =1, KPLOT =3,
$
$PICT
  NOTAT=1,KODE=1,
$
$PICT
  NOTAT=2,KODE=1,
$
$PICT
  NOTAT =1, KDISP =2,DMAGS=0.7, KODE =1,
$
$PICT
  NOTAT =2, KDISP =2,DMAGS=0.7, KODE =1,
$
$PICT
  NOTAT=0,KDISP=1,KVERT=3,KODE=1,
$
$PICT
  KDISP=3,KODE=0,
$
```

PROGRAM OUTPUT (SAMPLE PROBLEM 4)

FIN PROBLEM   CHAPMAN TEXT PAGE 76,   EAT NOVEMBER 14,1975

C O N T R O L   I N F O R M A T I O N

NUMBER OF NODAL POINTS = 13
NUMBER OF ELEMENT TYPES = 1
NUMBER OF TABLES = 0
ANALYSIS CODE(NANA) = 1
EQ.0, DATA CHECK ONLY,
EQ.1, LINEAR,
EQ.2, NONLINEAR
PLOT CODE(NPLOT) = 1
EQ.0, NO PLOTS GENERATED
EQ.1, UNDEFORMED PLOT
EQ.2, TEMPERATURE PLOT
ITERATION PARAMETERS
MAXIMUM ITERATIONS = 6
TOLERANCE = .10000E+00

BLANK COMMON LOCATIONS = 10967

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000	0	250.000
2	0	1.000	0.000	0.000	0	0.000
13	0	12.000	0.000	0.000	1	0.000

GENERATED NODAL DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	KN	TEMPERATURE
1	1	0.000	0.000	0.000		250.000
2	0	1.000	0.000	0.000		0.000
3	0	2.000	0.000	0.000		0.000
4	0	3.000	0.000	0.000		0.000
5	0	4.000	0.000	0.000		0.000
6	0	5.000	0.000	0.000		0.000
7	0	6.000	0.000	0.000		0.000
8	0	7.000	0.000	0.000		0.000
9	0	8.000	0.000	0.000		0.000
10	0	9.000	0.000	0.000		0.000
11	0	10.000	0.000	0.000		0.000

12	0	11.000	0.000	0.000	0.000
13	0	12.000	0.000	0.000	0.000

O N E   D I M E N S I O N A L   R O D   E L E M E N T

NUMBER OF ROD ELEMENTS = 12
NUMBER OF MATERIALS   = 1

MATERIAL	CONDUCTIVITY TABLE	CONDUCTIVITY K
1	0	.2750E+01

N	I	J	MAT	CONDUCTION AREA	VOLUME Q	SURFACE Q	CONVECTION AREA	HI	CONVECTION DATA TI	HJ	TJ
1	1	2	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
2	2	3	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
3	3	4	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
4	4	5	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
5	5	6	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
6	6	7	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
7	7	8	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
8	8	9	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
9	9	10	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
10	10	11	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
11	11	12	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02
12	12	13	1	.1964E+00	0.	0.	.1571E+01	.1111E-01	.7000E+02	.1111E-01	.7000E+02

S O L U T I O N   P A R A M E T E R S

TOTAL NUMBER OF EQUATIONS	=	13
SEMI BANDWIDTH	=	2
NUMBER OF EQUATIONS IN A BLOCK	=	13
NUMBER OF BLOCKS	=	1

TEMPERATURE VECTOR

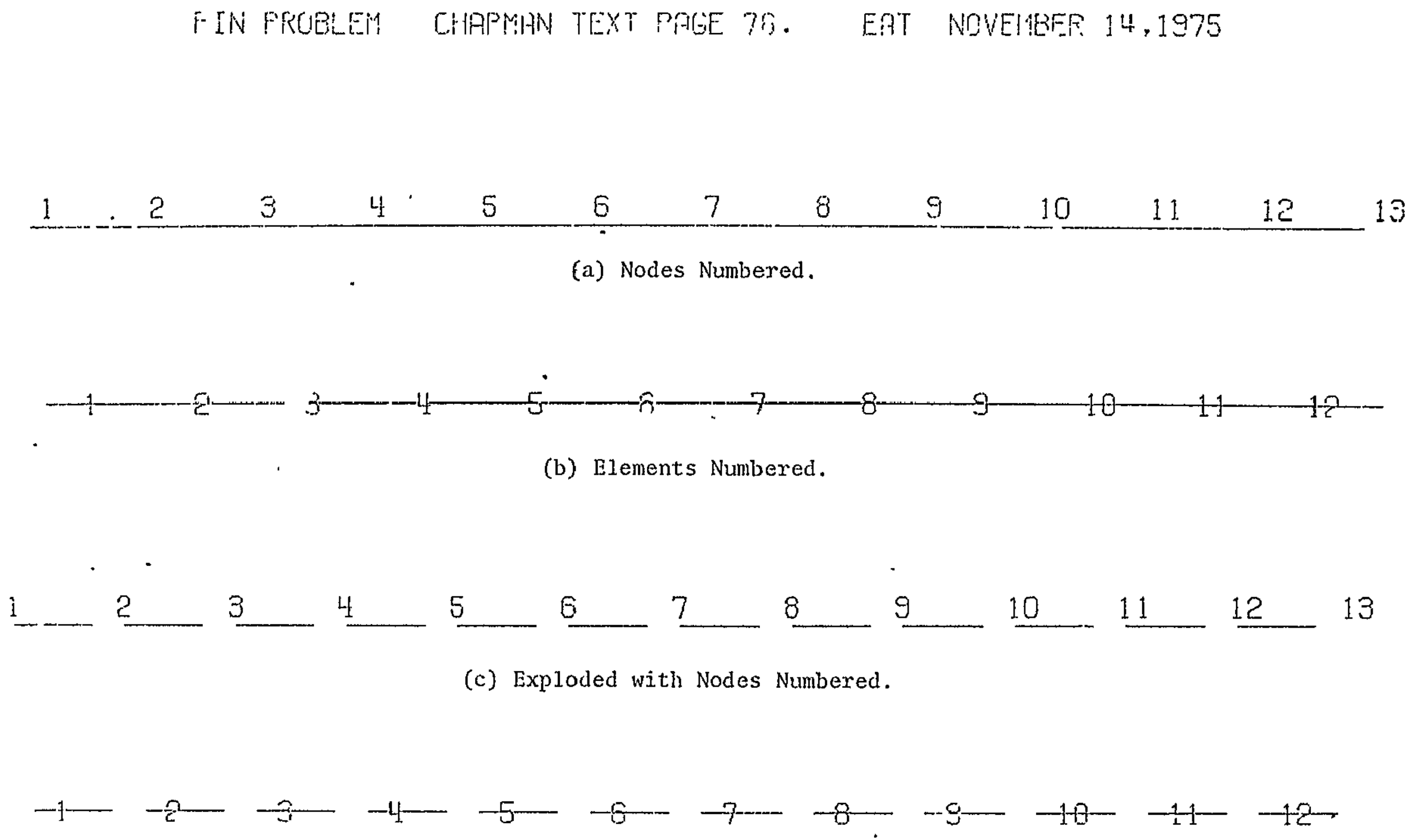
NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE.
1	.250000E+03	.221199E+03	.197312E+03	.177562E+03	.161307E+03
6	.148020E+03	.137268E+03	.128703E+03	.122045E+03	.117079E+03
11	.113642E+03	.111624E+03	.110958E+03		

ONE-DIMENSIONAL ROD ELEMENTS

ELEMENT	CONDUCTION FLUX	SURFACE CONVECTION FLUX
1	.15551E+02	-.28902E+01
2	.12898E+02	-.24304E+01
3	.10664E+02	-.20496E+01
4	.87768E+01	-.17354E+01
5	.71746E+01	-.14776E+01
6	.58055E+01	-.12679E+01
7	.46251E+01	-.10993E+01
8	.35950E+01	-.96645E+00
9	.26817E+01	-.86501E+00
10	.18556E+01	-.79168E+00
11	.10898E+01	-.74408E+00
12	.35936E+00	-.72066E+00

O V E R A L L   T I M E   L O G

NODAL POINT INPUT................	.07
FORM ELEMENT STIFFNESSES........	.11
FORM TOTAL STIFFNESS............	.02
IMPOSE BOUNDARY CONDITIONS......	.01
EQUATION SOLVING................	.01
ELEMENT FLUXES..................	.05
TOTAL SOLUTION TIME.............	.26



(a) Nodes Numbered.

(b) Elements Numbered.

(c) Exploded with Nodes Numbered.

(d) Exploded with Elements Numbered.

Figure 16. Plotter output for sample problem 4.

REFERENCES

1. Thornton, Earl A.; and Weiting, Allan R.· Finite Element Methodology for Thermal Analysis of Convectively Cooled Structure, to be presented at AIAA 15th Aerospace Sciences Meeting (Los Angeles, CA), January 24-26, 1977. AIAA Paper No. 77-187.

2. Hsu, M. B.; and Nickell, R. E.: Coupled Convective and Conductive Heat Transfer by Finite Element Methods. Finite Element Methods in Flow Problems, edited by J. T. Oden et al. Paper presented at the International Symposium on Finite Element Methods in Flow Problems held in January 1974 in Swansea, United Kingdom, University of Alabama in Huntsville, pp. 427-449.

3. Wilson, Edward L.: SOLID SAP, A Static Analysis Program for Three-Dimensional Solid Structures. Report to Denver Mining Research Center, U.S. Department of the Interior, Bureau of Mines. Structural Engineering Laboratory, University of California. UC SESM 71-19, September 1971, revised March 1972.

4. Bathe, K. J.; Wilson, E. L.; and Peterson, F. E.: SAPIV, A Structural Analysis Program for Static and Dynamic Response of Linear Systems. Earthquake Engineering Research Center, University of California. Report No. EERC 73-11, June 1973.

5. Cook, Robert D.: Concepts and Applications of Finite Element Analysis. John Wiley and Sons, 1974.

6. Zienkiewicz, O. C.: The Finite Element Method in Engineering Science. McGraw-Hill, 1971, p. 457.

7. Segui, William T.: Computer Programs for the Solution of Systems of Linear Algebraic Equations. NASA CR-2173, January 1973; also appears in International J. of Numerical Methods in Eng., Vol. 7, no. 4, 1973.

8. Kays, W. M.; and London, A. L.: Compact Heat Exchangers, 2nd ed., McGraw-Hill Book Co., p. 33.

9. Lee, H. P.: NASTRAN Thermal Analyzer, Vol. I: The NASTRAN Thermal Analyzer Manual. NASA, Goddard Space Flight Center, X-322-76-16, December 1975.

10. Giles, G. L.: Digital Computer Programs for Generating Oblique Orthographic Projections and Contour Plots. NASA TN D-7797, January 1975.