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TAP 2: A FINITE ELEMENT PROGRAM FOR THERMAL ANALYSIS OF CONVECTIVELY COOLED STRUCTURES

Earl A. Thornton

OLD DOMINION UNIVERSITY RESEARCH FOUNDATION
Norfolk, Virginia 23508

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NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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SUMMARY

A finite element computer program (TAP 2) for steady-state and transient thermal analyses 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. Transient analyses are performed using an implicit Crank-Nicolson time integration scheme with consistent or lumped capacitance matrices as an option. Program output includes nodal temperatures and element heat fluxes. Pressure drops in fluid passages may be computed as an option. User instructions and sample problems are presented in appendixes.

INTRODUCTION

TAP 2 (Thermal Analysis Program) was written in the course of research focused on 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 references 1 to 3.

The main body of this report presents the salient features of the finite element theory, the computer program organization, the finite element library, the nonlinear solution algorithm, and the transient time integration algorithm. Directions for program use are presented in Appendixes A and B. Program input data and output are illustrated with sample problems in Appendix C.

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. 1). The equations are derived for a typical flow passage consisting of a thin tube containing a fluid with a specified mass flow rate $\dot{m}$ (fig. 1). Heat transfer is expressed in terms of the wall temperature $T_w(x,t)$ and fluid bulk temperature $T_f(x,t)$. The governing equations are

$$- \frac{\partial}{\partial x} \left(k_f A_f \frac{\partial T_f}{\partial x}\right) + \dot{m} c_f \frac{\partial T_f}{\partial x} - hp \, (T_w - T_f)$$

$$+ \rho_f c_f A_f \frac{\partial T_f}{\partial t} = 0 \quad \text{(fluid)} \tag{1}$$

$$- \frac{\partial}{\partial x} \left(k_w A_w \frac{\partial T_w}{\partial x}\right) + hp \, (T_w - T_f)$$

$$+ \rho_w c_w \frac{\partial T_w}{\partial t} = 0 \quad \text{(wall)} \tag{2}$$

where k_f, c_f, ρ_f are the fluid thermal conductivity, specific heat, and density, respectively; k_w, c_w, ρ_w are the corresponding quantities for the wall. A_f is flow cross-sectional area, and A_w is the tube conduction area. Heat exchange between the wall is expressed in terms of the convection coefficient h and the convection perimeter of the tube p. Since the thermal parameters can be temperature dependent, equations (1) and (2) constitute a nonlinear set of partial differential equations.

The solid region wall 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

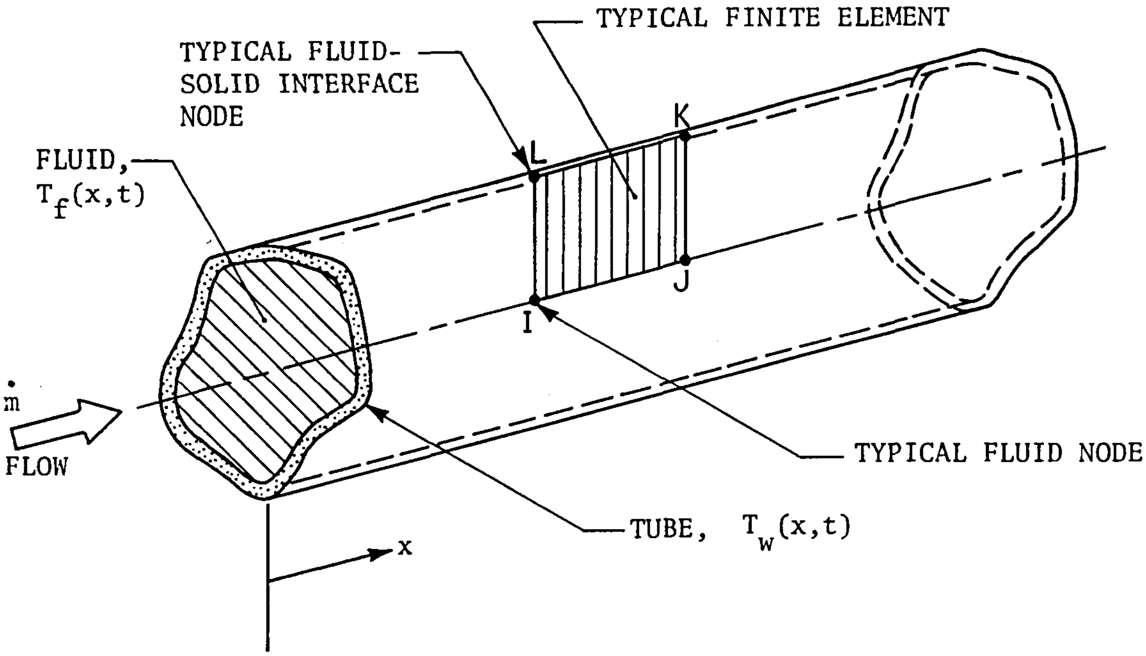


Figure 1. Finite element representation of coupled conduction-convection in a fluid passage.

the coolant passages. Basic convective finite elements were developed for the fluid to represent equation (1): a mass transport convection element and surface convection elements with unknown fluid temperatures. Special integrated conduction/convection finite elements were also developed: a tube/fluid element and 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. The program performs four types of analyses: (1) linear steady-state, (2) linear transient, (3) nonlinear steady-state, and (4) nonlinear transient.

PROGRAM ORGANIZATION

The organization of TAP 2 is based on an earlier program (TAP 1) for steady-state thermal analysis of convectively cooled structures (ref. 4). A flow chart of the TAP 2 main program is presented in figure 2. The main program consists of subroutines which are sequentially called in a normal program execution. Sets of subroutines, called solution modules, which perform the four basic types of analyses are shown in figures 3 and 4. These subroutines 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. 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 data.

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 (or card image) containing the node number, a boundary condition code (zero or one), the nodal coordinates, a generation parameter,

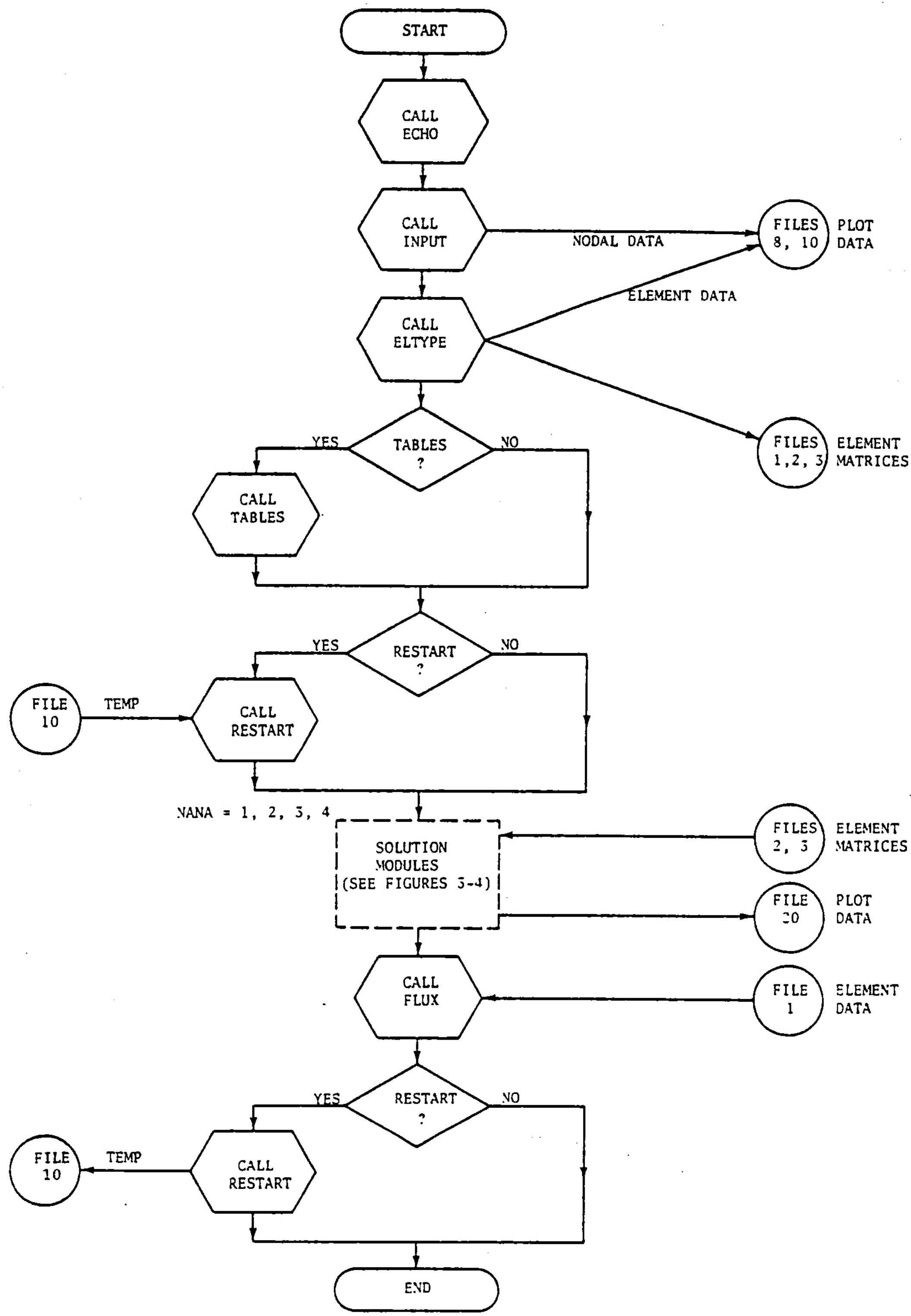
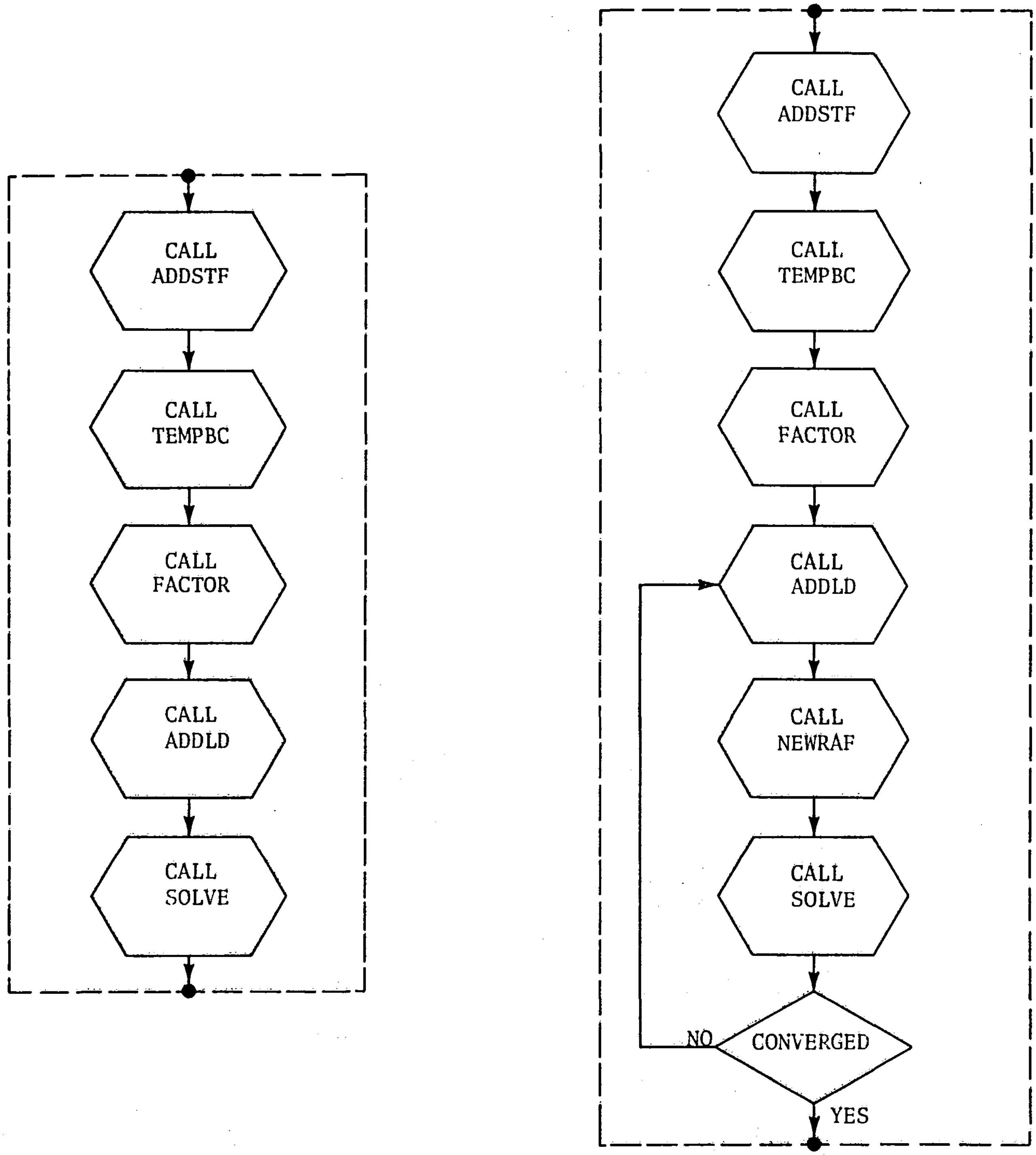


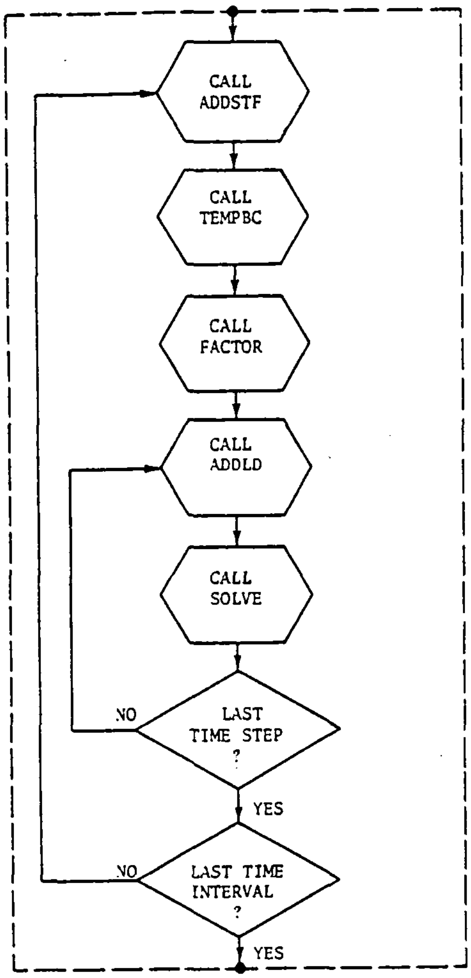
Figure 2. TAP 2 main program flow chart.



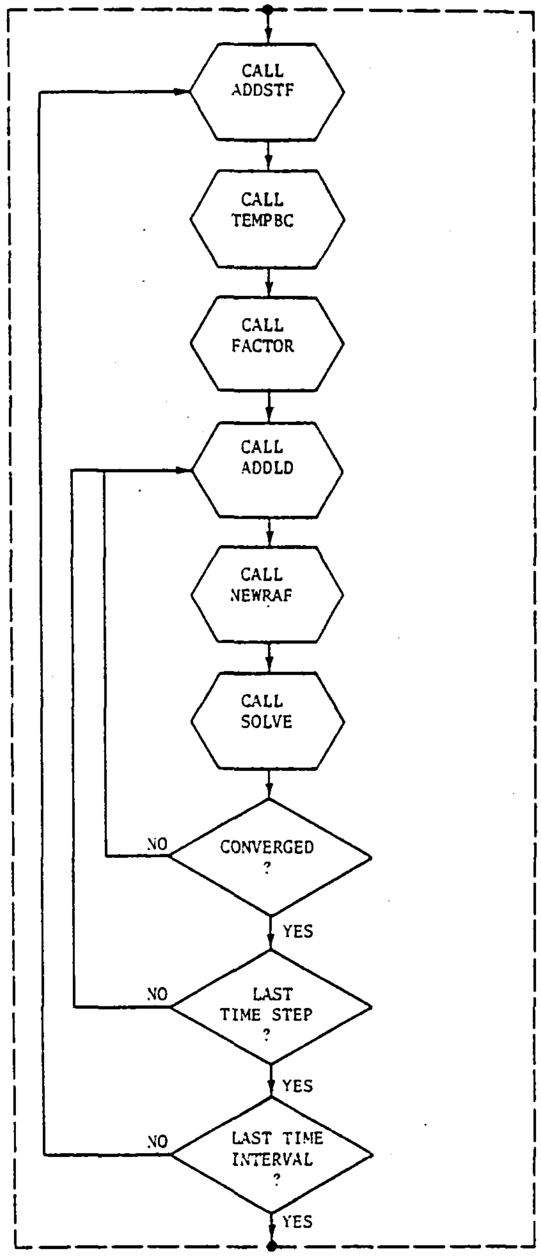
(a) Linear, NANA = 1.

(b) Nonlinear, NANA = 3.

Figure 3. Steady-state solution modules.



(a) Linear, NANA = 2.



(b) Nonlinear, NANA = 4.

Figure 4. Transient solution modules.

and a specified or initial nodal temperature if required. Nodal points are entered in rectangular Cartesian coordinates (x,y,z). 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 matrices. Nodal point data are also saved on an auxillary 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 and capacitance 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 matrices are resolved into components, one for each thermal parameter. For a linear analysis, the element conductance and capacitance matrices are formed for the thermal parameters entered; for a nonlinear analysis, element matrices are formed initially for unit thermal parameters. Element conductivity 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 matrices. 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).

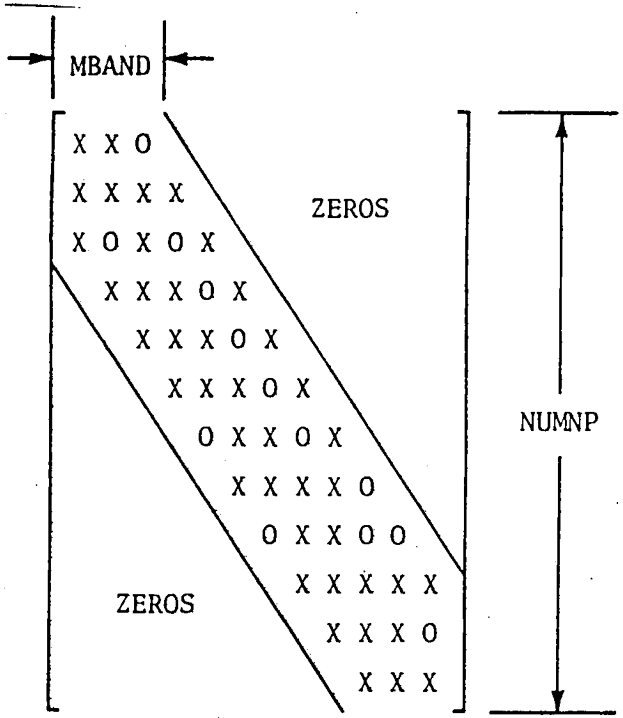
After all element data have been processed, the nodal coordinates are no longer needed, and the corresponding core storage area is used for other variables. The nodal boundary conditions are, however, retained in core since they are required later in the solution process.

Thermal Data Tables (TABLES)

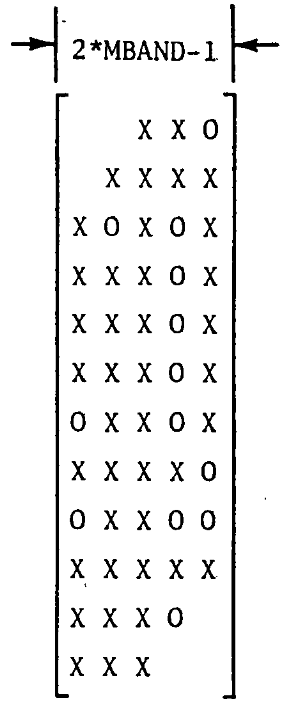
For a nonlinear or a transient analysis thermal data tables may be required. The input data consists of a control card for each table and a set of cards containing data points. The tabular data are retained in core during the balance of the solution process. Ordinarily, the amount of core storage required 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 values in the tables.

Assembly of System Matrices (ADDSTF)

The system matrices are formed in banded form as shown in figure 5. Because of mass transport convection and the upwind finite element formulation, system matrices may, in general, be asymmetrical. Hence, the advantage of matrix symmetry cannot be taken as in structural analysis. In steady-state analyses (see fig. 3), system matrices are assembled only once. In transient



(a) Actual system matrices.



(b) Banded storage of system matrices.

Figure 5. Program storage of system matrices.

analyses (see fig. 4), the equations are reassembled when the time step is changed, i.e., if there is more than one time interval. In a time interval the time step is constant, but an arbitary number of time intervals may be used.

Boundary Conditions (TEMPBC)

In finite element thermal analysis with TAP 2 the only nodal boundary conditions required are specified temperatures (i.e., temperature gradients cannot 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 needs to be 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 5. 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 2 thermal analysis temperature is the only degree of freedom per node, hence the penalty is not very large since usually only a small percentage of the equations have specified temperatures.

Solution for Temperatures (FACTOR and SOLVE)

The general, banded, simultaneous equations are solved by Gauss elimination. 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 or if fluid conduction is included.

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.

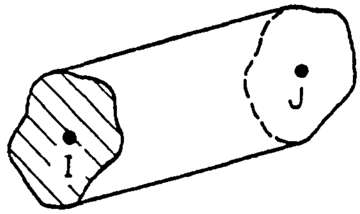
For the integrated thermal/fluid elements, pressure drops are computed as a user option in the heat flux computations. Pressure drop computations include flow-friction and flow-acceleration effects (see ref. 6). Pressure drops are computed for three user options: constant density, variable density using a density-temperature table, or an ideal gas.

Restart Capability (RESTART)

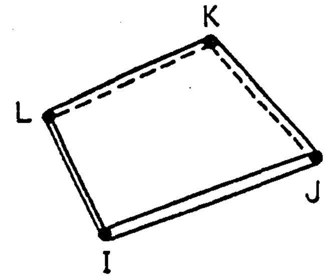
A limited restart capability is available. As an option, the time and temperature at the completion of an analysis may be written on a file for use in a subsequent analysis. This feature is useful, for example, when the results of a steady-state analysis are to be used as initial conditions for a subsequent transient analysis.

THE ELEMENT LIBRARY

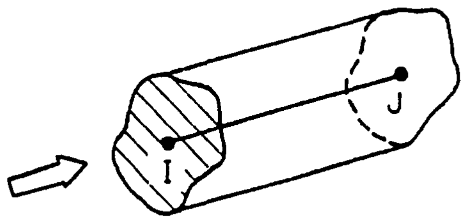
The library consists of six elements (fig. 6) for either steady-state or transient thermal analysis. Lumped or consistent capacitance



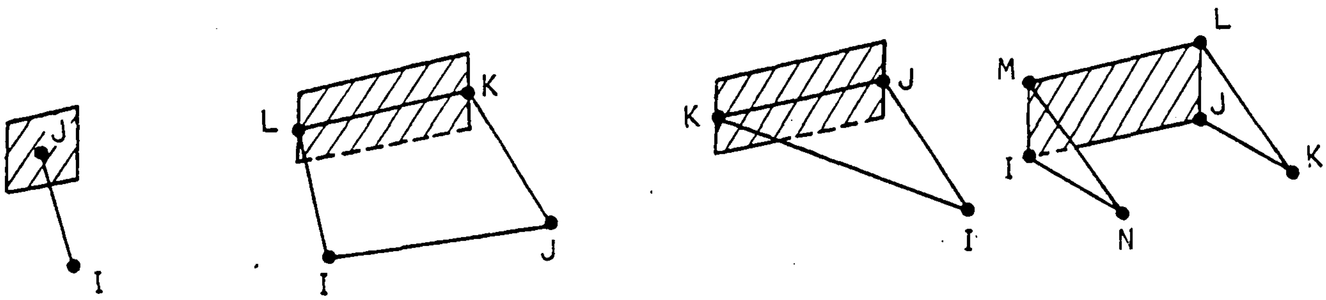
(a) Conduction/convection rod element.



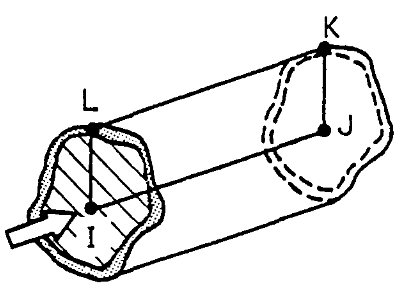
(b) Conduction/convection quadrilateral element.



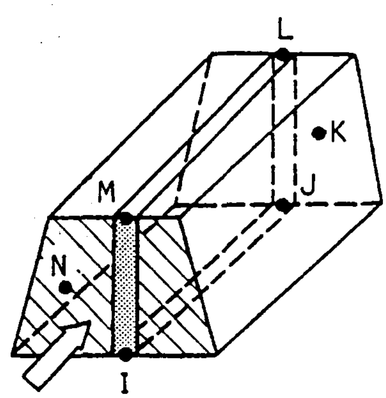
(c) Mass transport convection element.



(d) Surface convection elements.



(e) Tube/fluid element.



(f) Plate-fin/fluid element.

Figure 6. Element library.

matrices are available on all elements as an option. Conventional and upwind formulations (see refs. 1 to 3) are optional for all convection elements except the plate-fin/fluid integrated element.

Conduction/Convection Rod Element

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 (ref. 5). Isoparameteric means the same interpolation functions define the element shape and the element temperature distribution. The temperature within the element is given by

$$T\ (\xi,\eta) = \sum_{i=1}^{4} N_i\ T_i \tag{3}$$

where N_i are the interpolation functions,

$$N_1 = \frac{1}{4}\ (1 - \xi)\ (1 - \eta)$$

$$N_2 = \frac{1}{4}\ (1 + \xi)\ (1 - \eta)$$

$$N_3 = \frac{1}{4}\ (1 + \xi)\ (1 + \eta)$$

$$N_4 = \frac{1}{4}\ (1 - \xi)\ (1 + \eta) \tag{4}$$

and T_i are the nodal temperatures. The quantities ξ,η denote the isoparametric coordinates for a unit square. Matrices are computed for the element by integration in the ξ,η plane; in TAP 2 the integrals are evaluated by the four-point Gaussian 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 fluid conduction and energy transport downstream due to fluid flow. The element represents the first, second, and last terms in equation (1) and is based on the following assumptions (ref. 1): the thermal energy state of the fluid is characterized by the fluid bulk temperature which varies only in the flow direction, and the fluid velocity is represented by a mean velocity V which varies only in the flow direction. Conventional and upwind formulations are available as an option (refs. 1-3). The upwind formulation can be useful in some applications to eliminate spurious spatial fluid temperature oscillations, but it can have the adverse effect of introducing artifical diffusion with an attendant loss of accuracy.

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.

Surface Convection Elements

Surface convection elements (for surfaces with one to four nodes and a fluid with one or two nodes) represent 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 from the wall nodes and an area factor supplied as input data. The fluid nodal coordinates are arbitrary and are used only in plots. Conventional and upwind formulations are available as an option.

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 a user option the upwind formulation is available, and 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 6; 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 trapezodial for convenience), which may vary linearly along the element. The element has six nodes: two nodes to represent the fluid bulk temperature (nodes N and K) and four wall/fin nodes (I, J, L, and M). 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 fin convective heat transfer by an efficiency factor η which accounts for deviations in the fin temperature variation from the assumed linear profile, and (2) compute fluid pressure drops (see Heat Flux Calculations).

NONLINEAR ALGORITHM

For temperature-dependent thermal properties in steady-state analyses the finite element formulation employed in TAP 2 leads to a set of nonlinear algebraic equations of the form

$$[K(T)]\ \{T\} = \{Q\} \tag{5}$$

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, equations (5) reduces to a linear set of equations which may be solved directly. If the thermal parameters are a function of temperature, the Newton-Raphson (N-R) iteration algorithm is used

$$[J]_n\ \{\Delta T\}_{n+1} = \{R\}_n \tag{6}$$

$$\{T\}_{n+1} = \{T\}_n + \{\Delta T\}_{n+1} \tag{7}$$

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

A key assumption employed in TAP 2 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

$$[K] = \sum_m TP_m * [\bar{K}]_m \tag{8}$$

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

$$T_a = \frac{1}{N} \sum_{\ell=1}^{N} T_\ell \tag{9}$$

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

$$J_{ij} = TP*\bar{K}_{ij} \tag{10}$$

$$R_i = Q_i - TP*\sum_{\ell=1}^{N} \bar{K}_{i\ell}\, T_\ell \tag{11}$$

The algorithm indicated by equations (6), (7), (10), and (11) is known as a modified N-R iteration scheme (ref. 5). The Jacobian matrix is formed once and is held constant during the iterations (see fig. 3). At each iteration the unbalanced nodal loads are computed from equation (11), and the temperature increment is computed from equation (6). In the full N-R iteration scheme (ref. 7), the Jacobian matrix, equation (10), contains an additional term, and the Jacobian matrix is completely reformed at each iteration. The modified N-R scheme can require more iterations, but each iteration is less expensive than the full N-R scheme. Hence, in many cases, the modified N-R scheme has a net gain in efficiency.

TAP 2 automatically uses input nodal temperatures to initiate the nonlinear solution process. The iteration process is terminated when either a specified number of iterations has been performed or 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 five iterations (i.e. two to six analyses) using a convergence criteria of 0.1 percent.

TRANSIENT ALGORITHM

For linear transient analysis the finite element formulation employed in TAP 2 leads to a set of ordinary differential equations of the form

$$[C]\ \{\dot{T}\} + [K]\ \{T\} = \{Q\} \tag{12}$$

where $[C]$ is the system capacitance matrix. The capacitance matrix in TAP 2 as an option may be used in two forms: (1) a consistent formulation or (2) a lumped formulation. The capacitance matrices produced directly in the finite element formulation are called consistent capacitance matrices because their derivation is consistent with the mathematical formulation of the conductance matrices. The consistent capacitance formulation requires an implicit time-integration scheme because the time derivatives in equation (12) are coupled through off-diagonal terms in the capacitance matrix. TAP 2 employs the implicit Crank-Nicolson time integration scheme (ref. 8).

To find the transient solution to equation (12) a step-by-step procedure is used with the solution at each step computed at the middle of the time interval (t_i, t_{i+1}), where i denotes the time step. Defining $\{T_a\}$ as the temperature vector at the middle of the time step Δt, then the algorithm is

$$[K + \frac{2}{\Delta t} C] \{T_a\} = \frac{1}{2} \{Q_i + Q_{i+1}\} + \frac{2}{\Delta t} [C] \{T\}_i \tag{13}$$

$$\{T\}_{i+1} = 2\{T_a\} - \{T\}_i \tag{14}$$

The square matrix on the left-hand side of equation (13) is an equivalent conductance matrix. For a linear analysis, within a time interval having a constant time step, the equivalent conductance matrix can be formed and factored once at the beginning of the time interval (see fig. 4). The right-hand side of equation (13) is an equivalent load vector which must be reformed at each step since it depends on current heat loads and temperatures.

Although the Crank-Nicolson method is unconditionally stable, a method of estimating the time step is desirable because: (1) too small a time step may be excessively expensive; (2) too large a time step can introduce temporal oscillations which obliterate the true solution; and (3) too large a time step can introduce errors in the spatial temperature distribution. In TAP 2 the time step is estimated on an element basis. The time step is computed from

$$\Delta t = \frac{FDT}{\lambda_{max}} \tag{15}$$

where FDT is an arbitrary time step computation factor, and λ_{max} is computed by a method (ref. 9) developed for symmetric conductance matrices. Since the method gives an approximation to λ_{max} for the asymmetric matrices encountered in TAP 2, the time computation factor, FDT, has been adjusted by experience to give a reasonably reliable value of an estimated ΔT; FDT = 5 is currently used.

PLOTTING PROGRAM

A companion program (ref. 10) is used to plot the finite element model and calculated temperature distributions. 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.

CONCLUDING REMARKS

A finite element computer program (TAP 2) for steady-state and transient thermal analyses 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. Transient analyses are performed using an implicit Crank-Nicolson time integration scheme with consistent or lumped capacitance matrices as an option. Program output includes nodal temperatures and element heat fluxes. Pressure drops in fluid passages may be computed as an option.

APPENDIX A: PROGRAM DETAILS

Computer and System Requirements

TAP 2 was written using standard FORTRAN IV and was developed on the CDC computer system at NASA/LaRC. TAP 2 is almost system independent; the program is also operational on the DEC 10 computer system at Old Dominion University.

Storage Allocation

Dynamic storage allocation is used; all large arrays are stored in blank common designated as A. On the CDC system, TAP 2 computes the blank common available from the job card field length and attempts to process the input data and perform a solution. On the DEC 10 computer system the length of the blank common is set by a FORTRAN statement within the program. The program terminates execution with an error stating the additional storage required if insufficient storage is available.

Auxiliary Storage Files

TAP 2 uses 8 auxiliary storage files in a normal execution. The auxiliary storage files are identified in the table below.

TAP 2 Auxiliary Storage Files

File	Function
1	Element flux and pressure drop calculation data
2	Element conductance and capacitance matrices
3	Capacitance matrices and heat load vectors
5	Input data
6	Printer output
8	Node and element data for plots
10	Restart temperatures
20	Temperature for plots

APPENDIX B: INPUT DATA

General Setup of Input Deck

The general setup of a typical input data deck (or a data file for input via a terminal) is shown schematically in figure 7. A deck requires four basic data groups and three optional groups 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) For nonlinear analyses, a single control card containing control values for the iterative solution;

(4) A node input deck containing nodal coordinates, the boundary condition codes, and specified nodal temperatures;

(5) An element input deck containing element data organized by group. 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;

(6) For nonlinear or transient analysis, thermal data 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 data table; and

(7) For a transient analysis, one or more control cards specifying control values for the transient response.

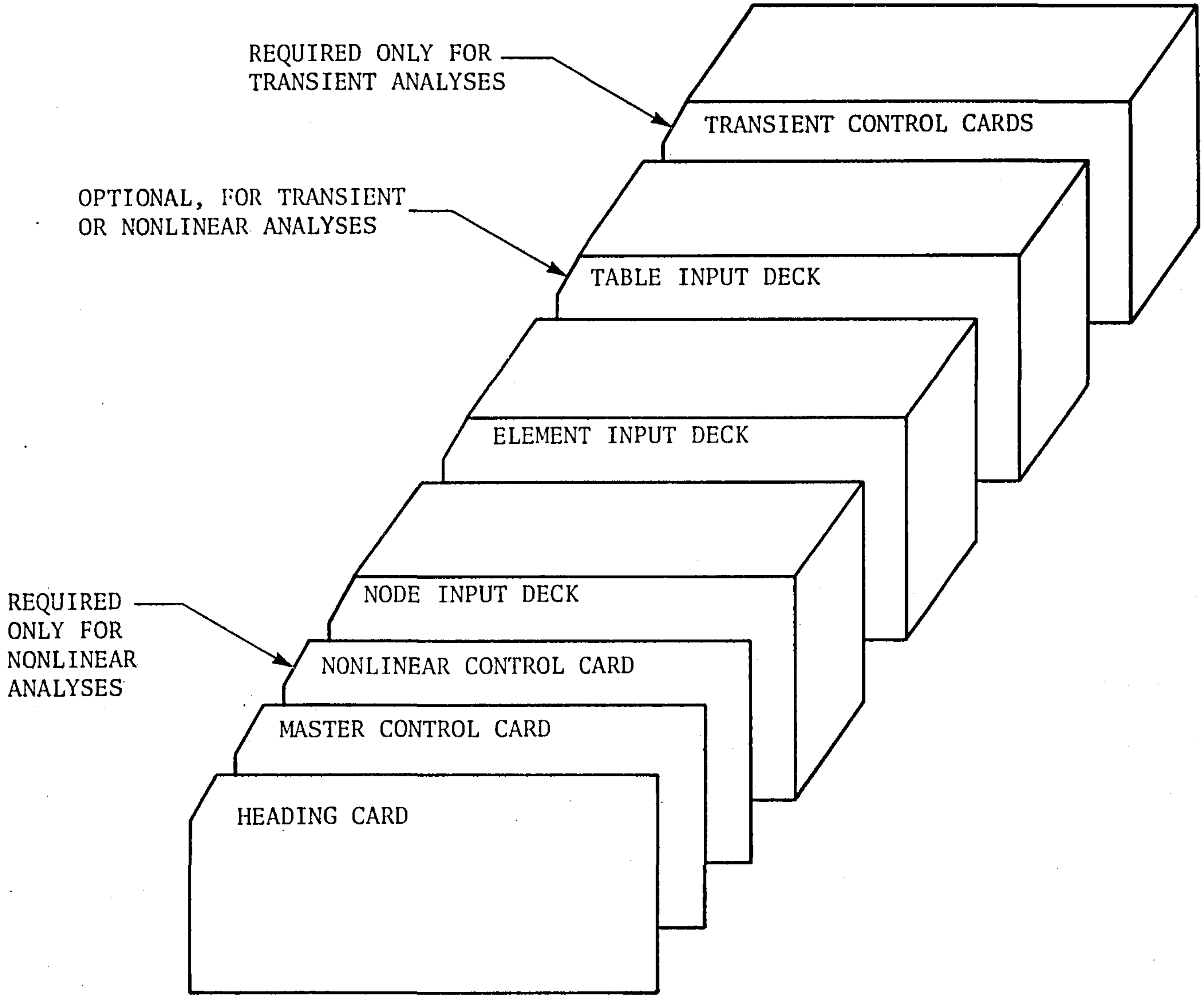


Figure 7. Input data sequence.

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 read using list-directed READ statements. Input data is, therefore, free-field and may be entered in any column on a card (or card image) separated by blanks or commas. All parameters specified on a data card must be entered; a blank cannot be used for a zero.

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 (18A4)

Note	Columns	Variable	Entry
(1)	1 - 72	HED(18)	Enter the heading information to be printed with the output

NOTE

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

II. MASTER CONTROL

Card 1 (8 parameters)

Note	Variable	Entry
(1)	NUMNP	Total number of nodal points in the model
(2)	NELTYP	Number of element groups
(3)	NUMTB	Number of tables for transient head loads or temperature-dependent thermal parameters
(4)	NANA	Analysis type .EQ.0 Data check only .EQ.1 Linear static .EQ.2 Linear transient .EQ.3 Nonlinear static .EQ.4 Nonlinear transient

II. MASTER CONTROL (Continued)

Card 1 (8 parameters)

Note	Variable	Entry
(5)	NDIAG	Flag for diagnostic printing .EQ.0 No diagnostic output .EQ.1 Diagnostic output .GT.1 Diagnostic output without element matrices
(6)	NFILE	File control code .EQ.0 No files are created .GE.0 Plot files are created .EQ.2 Restart file written .EQ.3 Read old restart file
(7)	NINT	Number of time intervals for transient analysis (default .EQ.1)
(8)	NOPT	Option for transient time step, DT .EQ.0 DT computed .EQ.1 DT input

Card 2 (required only for NANA = 3 or 4—2 parameters)

Note	Variable	Entry
(9)	NITER	Maximum number of Newton-Raphson iterations (default .EQ. 6)
(10)	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.

(3) For a nonlinear thermal analysis or a transient analysis with time-dependent heat loads, thermal data may be entered by tables. If tabular thermal data is to be input, the number of tables should be entered. Otherwise, a value of zero should be entered.

II. MASTER CONTROL (Continued)

(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 Gaussian elimination.

For NANA .EQ.2 a linear transient analysis is performed. Time-dependent heat loads may be entered as tables. The optional transient control card is required (see fig. 7). The equations are solved step-by-step using the Crank-Nicolson time integration algorithm.

For NANA .EQ.3 the thermal parameters vary with temperature and are entered in tabular form. The optional nonlinear control card is required (see fig. 7). The equations are solved by modified Newton-Raphson iteration.

For NANA .EQ.4 a nonlinear transient analysis is performed. Time-dependent heat loads and temperature-dependent thermal parameters are entered as tables. The optional nonlinear and transient control cards are required. The equations are solved step-by-step using the Crank-Nicolson time integration algorithm with modified Newton-Raphson iteration at each time step.

(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) For the NFILE .GE.0 node, element and temperature data are written on files 8 and 20 for subsequent use in plotting. See reference 10 for the source listings of the subroutines which generate the plot data files in an unformatted binary format. For NFILE .EQ.2 a time value and a single temperature vector are written on file 10 at the end of the program execution (see fig. 2). For NFILE .EQ.3 a time and temperature vector are read from file 10 during the input data phase and are used as the initial conditions for the analysis.

(7) The total time for which the transient thermal response is to be computed may be divided into NINT intervals. In each interval the time step is held constant. Thus, this program option permits utilization of variable time steps during the

transient response. System matrices are reformed at the beginning of each new time interval (see fig. 4). A new transient control card is required for each time interval.

(8) For NOPT.EQ.0 the program automatically computes the time step needed or if NOPT.EQ.1 the user supplies the time step. The selection of a time step is discussed in the Transient Algorithm section in the main body of the report. NOPT.EQ.0 should be used with caution since a very large amount of output could be generated if the program selects a small time step.

(9) The Newton-Raphson iterative solution process will terminate when the number of iterations reaches the value NITER. For NANA.EQ.3 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. For NANA.EQ.4 nodal temperatures are printed only at the completion of the iterations.

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

III. NODAL POINT DATA (7 parameters)

Note	Variable	Entry
(1)	N	Node number
(2)	ID(N)	Boundary condition code .EQ.0 Temperature unknown .EQ.1 Temperature specified
(3)	X(N) Y(N) Z(N)	X-coordinate Y-coordinate Z-coordinate
(4)	KN	Node number increment
(5)	T(N)	Nodal temperature

III. NODAL POINT DATA (Continued)

NOTES

(1) 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 4 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.

(2) 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) arrary.

(3) The coordinates of all nodes are entered in a common global coordinate system.

(4) 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

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

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

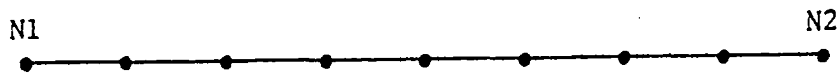
CARD 1 / N_1, ID(N_1), X(N_1), . . ., KN_1, T(N_1) /

CARD 2 / N_2, ID(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 $N_2 - KN_2$ is established. Note that the difference $N_2 - N_1$ must be evenly divisible by KN_2. Intermediate nodes between $N_1 - N_2$ 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). No generation is performed if KN_2 is zero.

III. NODAL POINT DATA (Concluded)

(4) (Concluded)



(5) Nodal temperatures entered for nodes with a boundary condition code ID(N) .EQ.1 are fixed in the solution process. For a nonlinear steady-state analysis the first iteration is performed with the thermal parameters evaluated for the input nodal temperatures. For transient analyses the input nodal temperatures are used as the initial conditions.

IV. ELEMENT DATA

Type 1 - Conduction/Convection Rod Element

Rod elements (fig. 8) are identified by the number 1. A linear temperature variation is assumed between nodes. Internal heat generation, prescribed surface heating, or convective surface heating is incorporated into the element formulation.

A. Control Card (4 parameters)

1	The number 1
NUME	Total number of rod elements in this element group
NUMAT	Number of material property cards
0	Zero

B. Material Property Cards (7 parameters)

Note	Variable	Entry
	MID	Material identification number
(1)	TK	Thermal conductivity (k) (required for linear analysis only)
	ITABK	Table number for thermal conductivity (nonlinear analysis only)
	CP	Specific heat (c_p)
	ITABC	Table number for specific heat
	ICONS	ICONS: .EQ.0 Lumped formulation .EQ.1 Consistent formulation
	RHO	Density

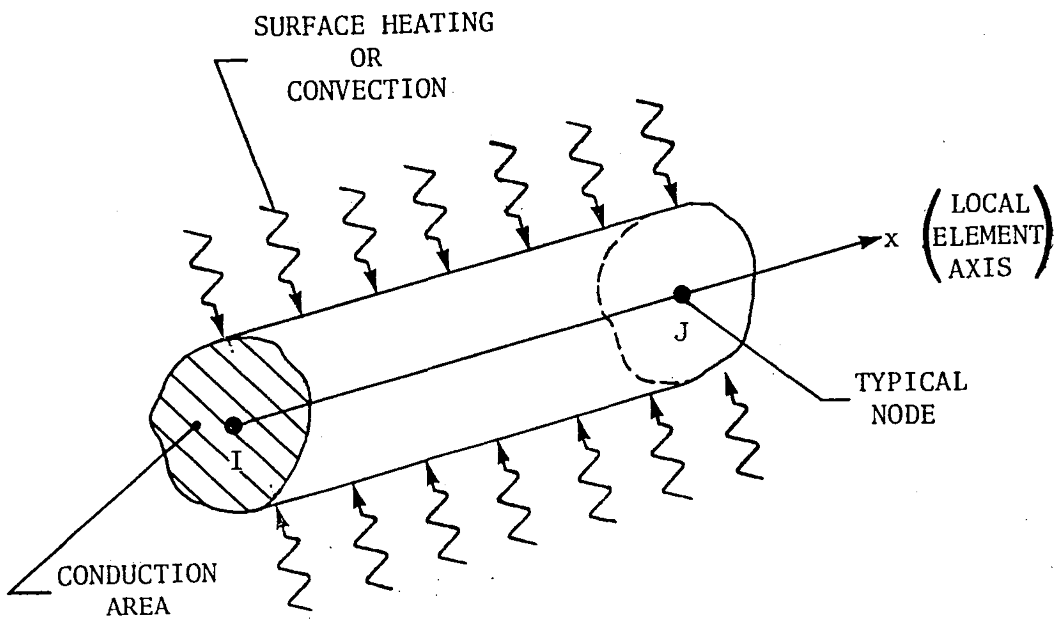
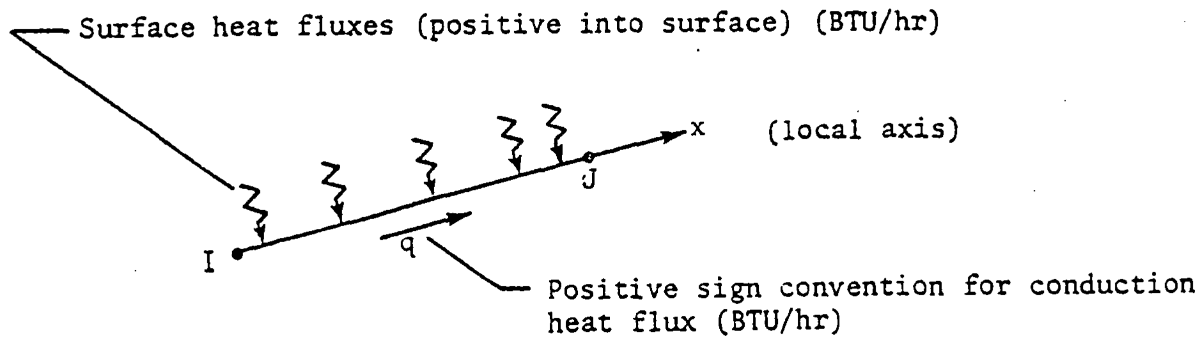


Figure 8. Conduction/convection rod element.

IV. ELEMENT DATA (Continued)

B. Material Property Cards (Concluded)



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.

Card 1 (required—9 parameters)

Note	Variable	Entry
	ID	Element number
(2)	I	Node number I
	J	Node number J
	MTYPE	Material identification number
(3)	KK	Optional element generation parameter for automatic generation of element data
	A	Cross-sectional area for conduction
	VOLQ	Heat generation per unit volume (e.g., BTU/HR-FT**3)
(4)	ITAB	Table number for heating time history
(5)	AF	Area factor for surface heating or convection

Card 2 (Optional—required only if the area factor is greater than zero)

Note	Variable	Entry
	SURFQ	Specified surface heat transfer rate (e.g., BTU/HR-FT**2) (positive into element)
(6)	HI	Convective medium heat transfer coefficient H_I at node I

IV. ELEMENT DATA (Continued)

Note	Variable	Entry
(6)	TI	Convective medium temperature T_I at node I
(Concl'd)	HJ	Convective medium heat transfer coefficient H_J at node J
	TJ	Convective medium temperature T_J at node J

NOTES

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

(2) The order of I and J determines the direction of the local x-axis (see fig. 8). 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

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

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

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 KK (given on the last card) is input as zero, it is set to one by the program.

(4) Only one time-dependent thermal load per element may be specified in a table. The table number ITAB may be used to define the time history of the heat generation per unit volume, or a specified surface heating, or the convective medium temperatures.

(5) 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.

(6) Convection heat transfer is based on an average convection coefficient, H = (HI + HJ)/2.

Type 3 - Conduction/Convection Quadrilateral Element

Quadrilateral elements (fig. 9) 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 is included in the element.

A. Control Card (4 parameters)

3	The number 3
NUME	Total number of quadrilateral elements in this group
NUMAT	Number of material property card sets
0	Zero

B. Material Property Card Sets (NUMAT sets required)

Card 1 (5 parameters per card)

Note	Variable	Entry
	MID	Material identification number
(1)	ITABK	Table number for thermal conductivity tensor temperature variation (nonlinear analyses only)
	ITABC	Table number for specific heat temperature variation
	ICONS	.EQ.0 Lumped capacitance formulation .EQ.1 Consistent formulation
	LAYERS	Number of laminae

(2) Card Set 2 (Number of cards required equal to LAYERS; 7 parameters per card)

	TH	Lamina thickness
(3)	KXX	Conductivity tensor component, K_{xx} (Real)
	KXY	Conductivity tensor component, K_{xy} (Real)
	KYY	Conductivity tensor component, K_{yy} (Real)

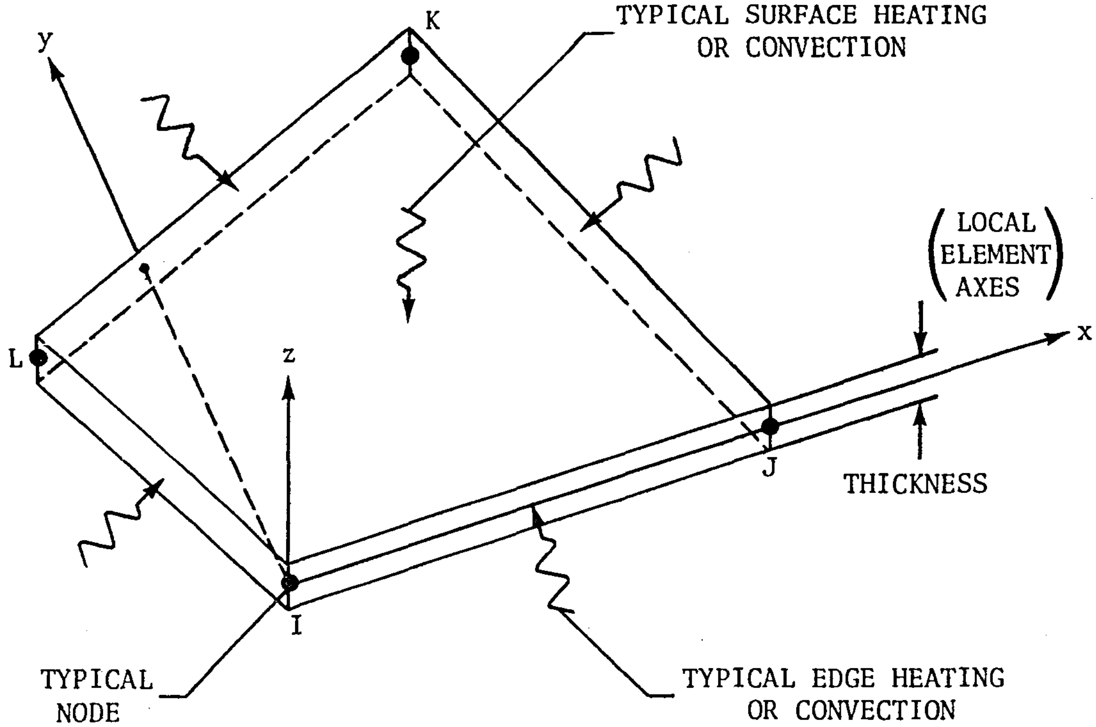
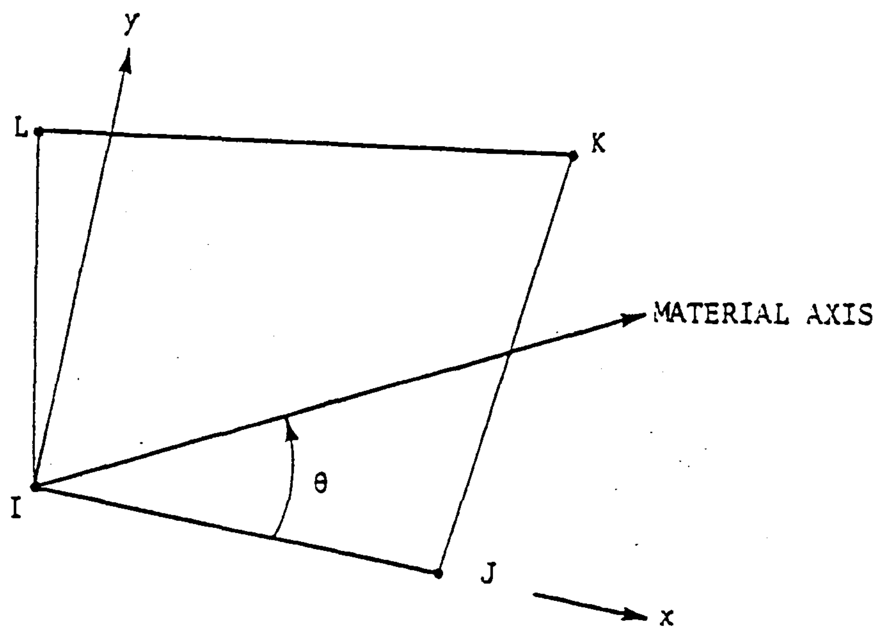


Figure 9. Conduction/convection quadrilateral element.

IV. ELEMENT DATA (Continued)

Note	Variable	Entry
(4)	THETA	Material axis angle, Θ (degrees)
	CP	Specific heat
	RHO	Density

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



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 (11 parameters)

Note	Variable	Entry	
(5)	M	Element number	
	I	Node I	
	J	Node J	
	K	Node K	
	L	Node L	
	MAT	Material identification number	
(6)	KG	Element generation parameter	
	IEDGE	IEDGE .EQ.0	No edge heating or edge convection
		.EQ.1,2,3,4	Number of edges for which there is edge heating or convection
	ISURF	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
	Q	Volumetric heat generation rate (e.g., BTU/HR-FT^3)	
(7)	ITABQ	Table number for time dependent heat load	

Card Set 2 (IEDGE cards) (7 parameters per card)

Note	Variable	Entry
(8)	N1	Edge node
	N2	Edge node
	QS	Edge heat loading, q (e.g., BTU/HR FT^2) (heat flux is positive into element)
	H1	Convection coefficient at node N1
	T1	Convective medium temperature at node N1
	H2	Convection coefficient at node N2
	T2	Convective medium temperature at node N2

Card Set 3 (ISURF cards) (8 parameters per card)

Note	Variable	Entry
(9)	HI or QSURF	Convection coefficient at node I, or convective surface heating, $q\left(\frac{BTU}{HR\text{-}FT^2}\right)$

IV. ELEMENT DATA (Continued)

Note	Variable	Entry
(10)	TI	Convective medium temperature at node I
	HJ	Convection coefficient at node J
	TJ	Convective medium temperature at node J
	HK	Convection coefficient at node K
	TK	Convective medium temperature at node K
	HL	Convection coefficient at node L
	TL	Convective medium temperature 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 matrices are formed on the first iteration using the input values of the conductivity tensor and specific heat. On subsequent iterations the values entered in the thermal conductivity and specific heat tables are used as multipliers of the matrices. Thus for a single isotropic layer the user should either: (1) input KXY, KYY, and CP as one (1.0) and enter the actual conductivity and specific heat values in the tables, or (2) enter conductivity and specific heat values and use normalized conductivity and specific heat values in the tables.

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

(3) For an isotropic material the conductivity value k should be entered for K_{xx} and K_{yy}, and K_{xy} should be entered as zero. If K_{yy} is entered as zero the program will set $K_{yy} = K_{xx}$.

(4) The orientation of the local x-axis is from I to J (see fig. 9). 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:

IV. ELEMENT DATA (Continued)

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

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

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

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

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

(6) Only one time-dependent thermal load per element may be specified in a table. The table number ITABQ may be used to define the time history of the heat generation per unit volume, or a specified surface heating, or the convective medium temperatures.

(7) If H_2 and T_2 are entered as zero, the program will set $H_2 = H_1$ and $T_2 = T_1$. The convective exchange is based on the average convection coefficient, $(H_1 + H_2)/2$.

(8) For specified surface heating enter QSURF followed by seven zero values for TI, HJ, . . .TL.

(9) The convective exchange is based on the average convection coefficient, (HI + HJ + HK + HL)/4.

Type 8 - Mass-Transport Element

Mass transport elements (fig. 10) are identified by the number 8. The element is used to represent combined conduction and convective energy transport due to a mass flow rate $\dot{m}$.

A. <u>Control Card (4 parameters)</u>

8	The number 8
NUME	Total number of elements in this group
NUMAT	Number of thermal-fluid property card sets
0	Zero

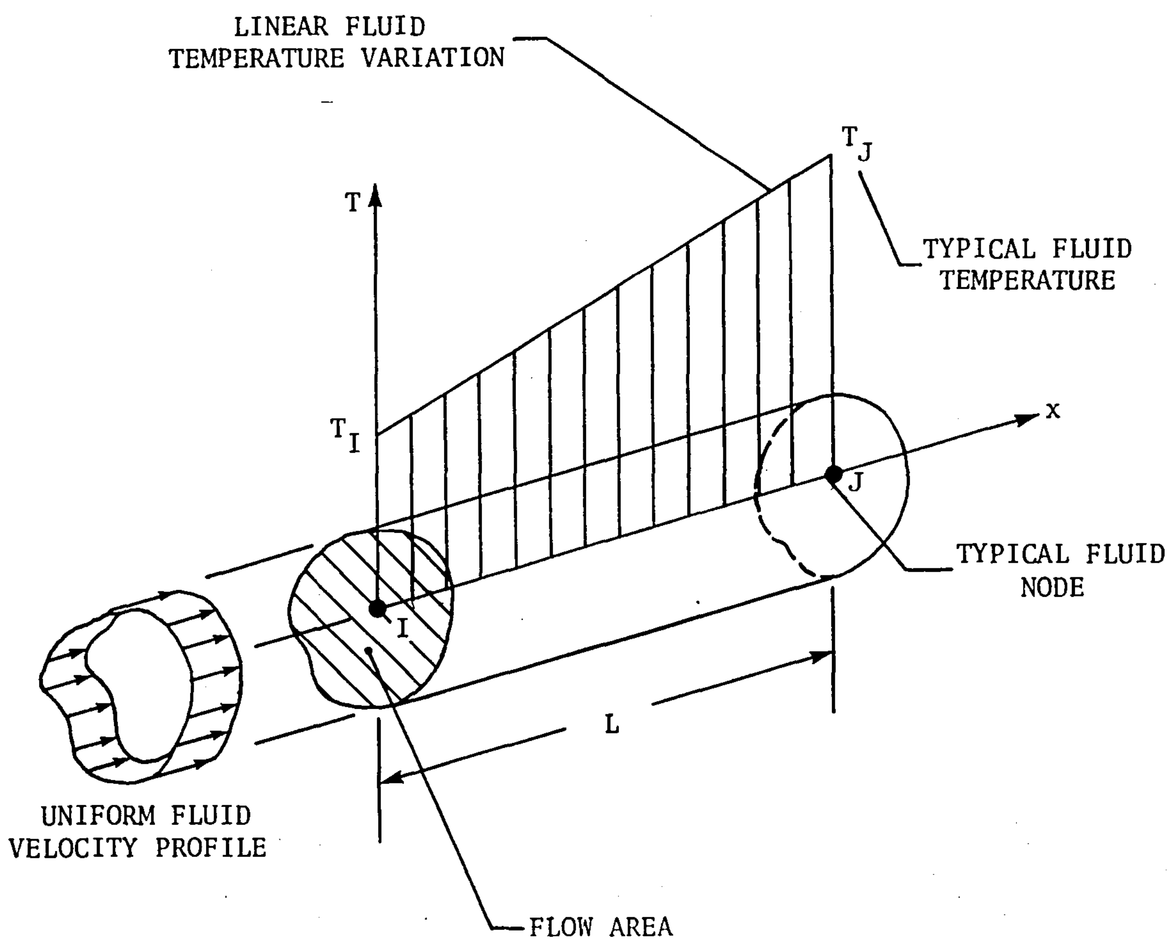


Figure 10. Mass transport element.

IV. ELEMENT DATA (Continued)

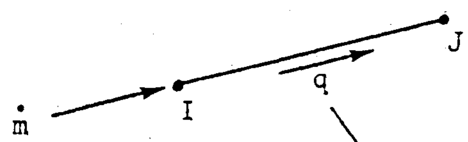
B. Fluid Properties (7 Parameters)

Note	Variable	Entry
	N	Property identification number
(1)	TK	Fluid thermal conductivity
	ITABK	Table number for fluid thermal conductivity
	C	Fluid specific heat, C_p
	ITABC	Table number for fluid specific heat
(2)	ICONS	ICONS .EQ.0 Lumped capacitance conventional formulation .EQ.1 Consistent capacitance conventional formulation .EQ.2 Upwind conductance and capacitance matrices, $\alpha = 1$ .EQ.3 Optimum conductance and capacitance matrices, $\alpha = \alpha_{opt}$
	RHO	Fluid density

C. Element Data Cards (7 parameters)

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

Note	Variable	Entry
	M	Element number
(3)	II	Node number, I
	JJ	Node number, J
	MATID	Property identification number
(4)	KG	Element generation parameter
	$\dot{m}$	Fluid mass flow rate (e.g., lbm/hr)
	A	Flow area



Heat flux, $q = \dot{m}\, C_p \left(\frac{T_I + T_J}{2}\right)\left(\frac{BTU}{hr}\right)$

IV. ELEMENT DATA (Continued)

NOTES

(1) For linear analyses the thermal conductivity TK and specific heat C are used to compute the thermal conductance matrix, capacitance matrix, and the heat flux recovery matrix for an element. For a nonlinear analysis and table numbers greater than zero, the matrices are initially computed using the thermal parameters as unity. Later, during the solution process, the matrices are multiplied by appropriate values determined from the parameter tables. The look-up temperature used in the table is the average element temperature, (TI + TJ)/2.

(2) For ICONS .LE.1 a conventional element formulation is used, and for ICONS .EQ.2 or 3 an upwind formulation is used. See references 1 and 5 for further details of the upwind formulation. For ICONS .EQ.2 the element uses full upwinding, i.e. the upwind parameter $\alpha = 1$. For ICONS .EQ.3 the "optimum" upwind value of α is computed from

$$\alpha_{opt} = \frac{1 + e^{-Pe}}{1 - e^{-Pe}} - \frac{2}{Pe}$$

where the Peclet number $Pe = C\,\dot{m}\,XL/(TK\ A)$ and XL is the element length. For a nonlinear analysis, or if TK or A equals zero, the "optimum" upwind value is used as one. Note that the upwind parameter is used for computation of both the conductance and capacitance matrices.

(3) The order of the element nodes determines the direction of fluid flow; the fluid flow is from node I to J.

(4) 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:

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

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

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

IV. ELEMENT DATA (Continued)

Type 9 - Surface-Convection Elements

Surface-convection elements (fig. 11) are identified by the number 9. The elements are used to represent convective heat transfer between a surface and a fluid with unknown temperature. Four elements, a line, a quadrilateral, a triangle, and a three-dimensional surface, are available.

A. Control Card (4 parameters)

Note	Variable	Entry
	9	The number 9
	NUME	The number of surface convection elements in this group
	NUMAT	Number of thermal-fluic property card sets
	ND	Number of element nodes

B. Fluid Properties (4 parameters)

Note	Variable	Entry
	N	Property identification number
(1)	H	Convection coefficient, h
	ITABH	Table number for convection coefficient
(2)	ICONS	.LE.1 Conventional formulation .EQ.2 Upwind formulation

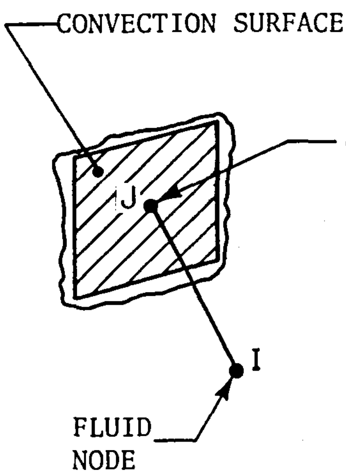
C. Element Parameter Data Cards (4 + ND parameters)

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

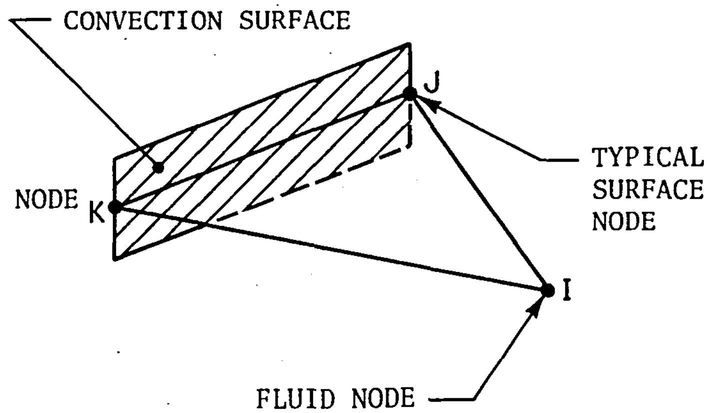
Note	Variable	Entry
	EID	Element number
(3)	IE(I)	ND node numbers I, J, K, L, M, N
	MATID	Property identification number
(4)	KG	Element generation parameter
(5)	AFACT	Area factor for convection

NOTES

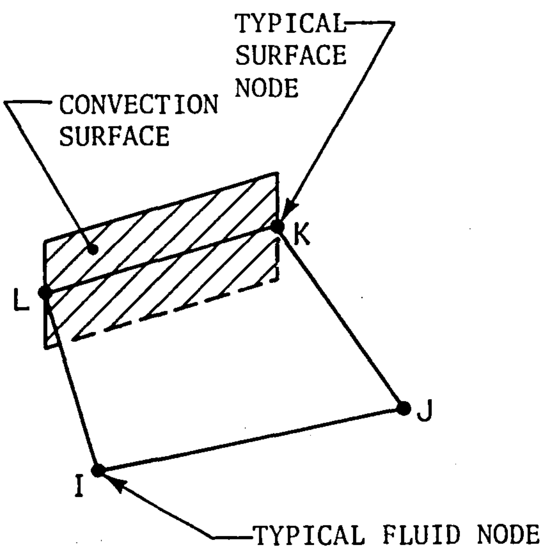
(1) For a linear analysis, the fluid convection coefficient read-in on the fluid property card is used in element computations. For a nonlinear analysis, values from a convection coefficient table are used if the table number is greater than zero.



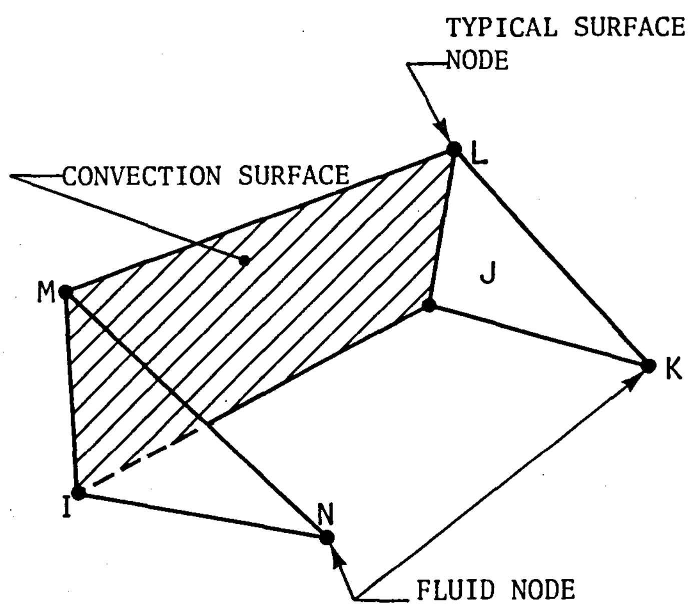
(a) Line element.



(b) Triangular element.



(c) Quadrilateral element.



(d) Plate (3-D) element.

Figure 11. Surface convection elements with unknown fluid temperatures.

IV. ELEMENT DATA (Continued)

(2) The upwind formulation is available as an option only on the quadrilateral element, i.e. when ND = 4. If ICONS .EQ.2, when ND = 4, the upwind element conductance matrix is computed based upon full upwinding, i.e. the upwind parameter $\alpha = 1$. The conventional formulation is used for all other elements regardless of the value of ICONS.

(3) ND node numbers should be entered. For the line element (fig. 11a) and triangular element (fig. 11b), node I denotes the fluid node. For the quadrilateral element (fig. 11c) nodes I and J denote the fluid nodes. For the plate (or 3-D) element nodes K and N denote the fluid nodes.

(4) Missing elements are generated using the 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 convective surface area, (fig. 11). For the line element the area factor equals the convective surface area. For the triangle and quadrilateral the surface area is the product of the area factor and distance between surface nodes. For the plate (3-D) element the surface area is equal to the area of the quadrilateral surface IJLM times the area factor.

Type 10 - Tube/Fluid Integrated Element

Tube/fluid integrated elements (fig. 12) are identified by the number 10. The element represents conduction/convection heat transfer in a thin tube of constant thickness and flow area

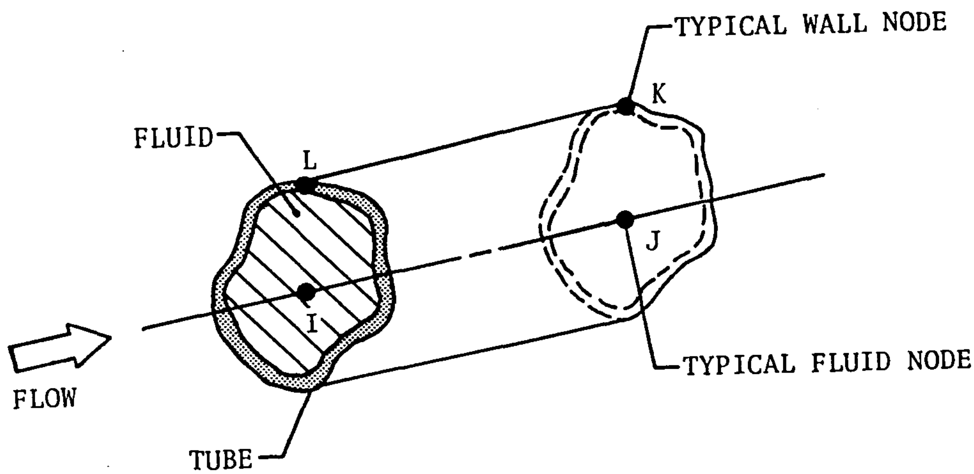


Figure 12. Integrated tube/fluid element.

enclosing a fluid with mass flow rate of $\dot{m}$. Heat loading on the tube external surface due to a specified heating or a convective exchange with a surrounding medium is included. Pressure drop computations are performed as an option.

A. Control Card (4 parameters)

Variable	Entry
10	The number 10
NUME	Total number of tube/fluid elements in this group
NPROP	Number of thermal-fluid property card sets
NPRES	Flag for pressure drop calculations .EQ.0 Pressures are not calculated .GT.0 Pressures are calculated

B. Thermal-Fluid Property Card Sets

Card 1 - Tube Properties (7 parameters)

Note	Variable	Entry
	MATID	Property identification number
(1)	TK	Thermal conductivity, k
	ITAB	Table number for tube thermal conductivity
(2)	CP	Specific heat
	ITAB	Table number for tube specific heat
(3)	ICONS	.EQ.0 Lumped conventional formulation .EQ.1 Consistent conventional formulation .EQ.2 Upwind fluid formulation, $\alpha = 1$
	RHO	Tube Density

Card 2 - Fluid Properties (5 parameters)

Note	Variable	Entry
(4)	H	Fluid convection coefficient, h
	ITAB	Table number for convection coefficient
(5)	CP	Fluid specific heat, C_p
	ITAB	Table number for fluid specific heat
	RHO	Fluid Density

IV. ELEMENT DATA (Continued)

(Optional) Card 3 - Tube-Fluid Properties for Pressure Recovery (6 paramaters)

Note	Variable	Entry
(6)	DH	Tube hydraulic diameter, D_H
(7)	F	Fluid friction factor, f
	ITABF	Table number for fluid friction factor
(8)	ITAB	Table number for fluid density
(9)	R	Gas constant, R
	GC	Proportionality 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 (13 parameters)

Note	Variable	Entry
	EID	Element number
(10)	I	Node number, I } Fluid nodes
	J	Node number, J } Fluid nodes
	K	Node number, K } Tube nodes
	L	Node number, L } Tube nodes
	MATID	Property identification number
(11)	KG	Element generation parameter
(12)	ISURF	ISURF .EQ.0; No surface heating or convection .GT.0; Surface heating or convection
	A	Tube cross-sectional conduction area
(13)	P	Perimeter of tube for internal convective heat transfer to fluid
	G	Fluid mass flow rate (e.g., lbm/hr)
	AFLOW	Flow area
(14)	PI	Element inlet pressure

IV. ELEMENT DATA (Continued)

Card 2- External Tube Heating or Convection Data (7 parameters)

Note	Variable	Entry
(15)	AS	Area factor for surface heating or convection
	SURFQ	Specified surface heating rate (e.g., BTU/HR-FT**2) (positive into surface)
	HL	Convective heat transfer coefficient, h_L, at node L
	TL	Surrounding medium temperature, T_L, at node L
	HK	Convective heat transfer coefficient, h_K, at node K
	TK	Surrounding medium temperature, T_K, at node K
	ITAB	Table number for time history of surface heating or medium temperature

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 tube specific heat is used for the tube capacitance matrix and may be entered as a constant or as a tabular function of temperature.

(3) If ICONS .EQ.0 a lumped conventional formulation is used for both tube and fluid capacitance matrices. If ICONS .EQ.1 a consistent formulation is used for both tube and fluid capacitance matrices. If ICONS .EQ.2 a consistent capacitance matrix is used for the tube but upwind conductance and capacitance matrices are formed for the fluid with the upwind parameter, $\alpha = 1$.

(4) 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 $(T_I + T_J)/2$.

(5) The fluid specific heat is used for the fluid mass transport conductance matrix and the fluid capacitance matrix. The fluid specific heat may be entered as a constant or a tabular function of temperature.

IV. ELEMENT DATA (Continued)

(6) The tube hydraulic diameter is defined by

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

(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 temperature of the fluid at nodes I, J

g_c = proportionality constant in Newton's second law

$$\left(\text{e.g., } g_c = \frac{32.17 \text{ ft - lbm}}{lb_f \text{ - sec}^2}\right)$$

(8) 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.

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

IV. ELEMENT DATA (Continued)

(10) The direction of fluid flow is determined by the node numbering sequence. Flow is from node I to node J (see fig. 12).

(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.

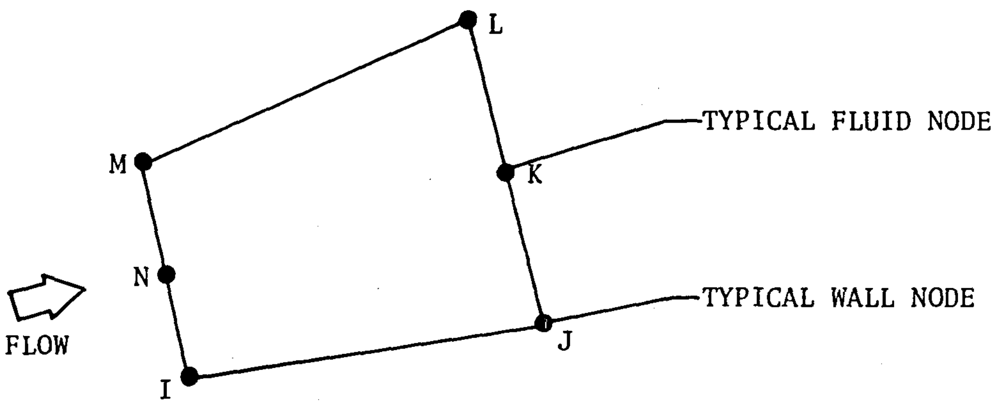
(13) The perimeter of the tube is used to compute the wetted area for convective heat transfer to the internal fluid by multiplying it by the element length.

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

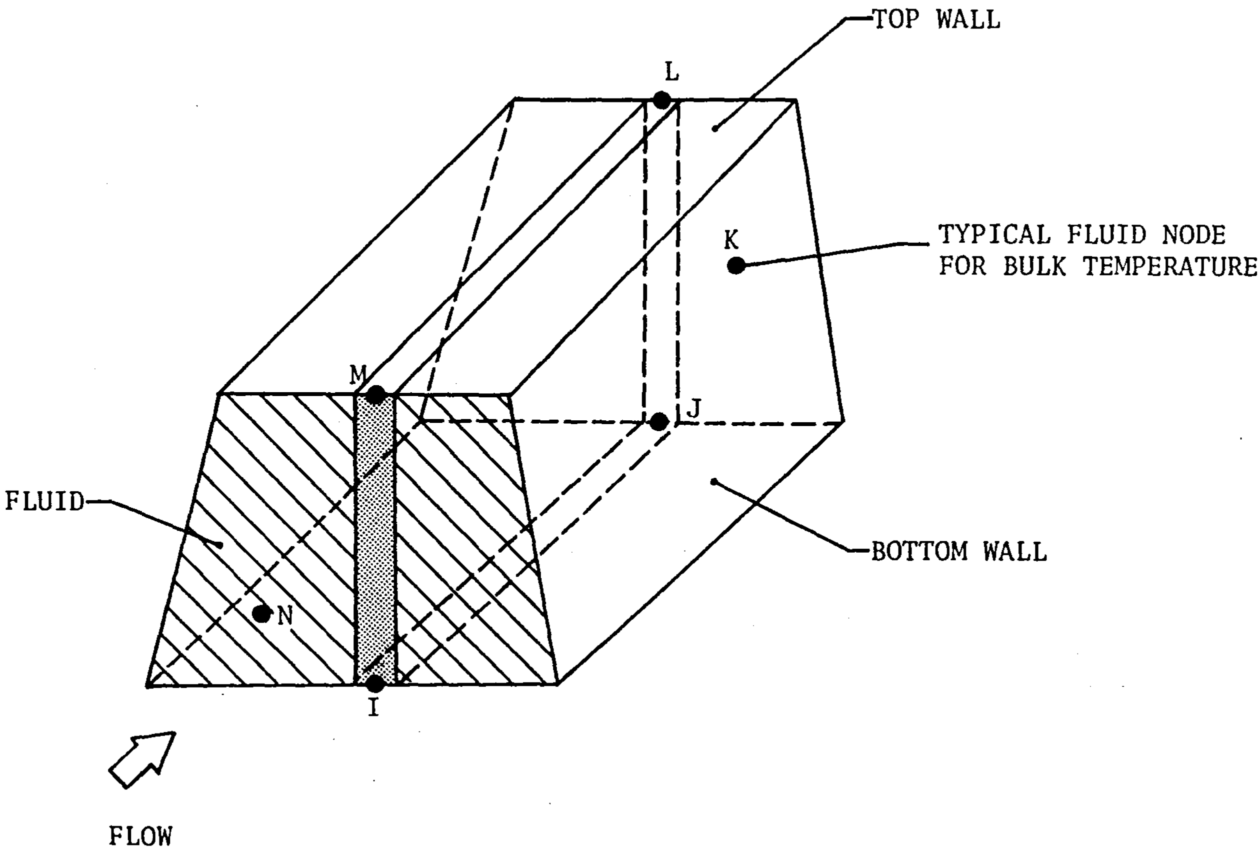
(15) The surface area for external heating is computed as the product of the area factor times the perimeter times the element length.

Type 11 - Plate-Fin/Fluid Integrated Element

Plate-fin/fluid integrated elements (fig. 13) 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) Side view.



(b) Oblique view.

Figure 13. Integrated plate-fin/fluid element.

IV. ELEMENT DATA (Continued)

A. Control Card (4 parameters)

Variable	Entry
11	The number 11
NUME	Total number of plate-fin/fluid elements in this group
NUMAT	Number of thermal-fluid property card sets
NPRES	Flag for pressure calculations .EQ.0; Pressures are not calculated .GT.0; Pressures are calculated

B. Thermal-Fluid Property Card Sets

Card 1 - Fin Properties (7 parameters)

Note	Variable	Entry
	N	Property identification number (fin and fluid properties)
(1)	TK	Thermal conductivity
	ITABK	Table number for fin thermal conductivity
	CP	Specific heat
	ITABCP	Table number for fin specific heat
(2)	ICONS	.EQ.0; Lumped capacitance formulation .EQ.1; Consistent formulation
	DENS	Fin density

Card 2 - Fluid Properties (5 parameters)

Note	Variable	Entry
(3)	H	Fluid convection coefficient
	ITABH	Table number for convection coefficient
	C	Fluid specific heat
	ITABC	Table number for fluid specific heat
	RHO	Fluid density

(Optional) Card 3 - Properties for Pressure Calculations (6 parameters)

Note	Variable	Entry
(4)	DH	Hydraulic diameter, D_H
(5)	F	Fluid friction factor, f
	ITABF	Table number for fluid friction factor
(6)	ITABR	Table number for fluid density

IV. ELEMENT DATA (Continued)

Note	Variable	Entry
(7)	R	Gas constant R
	GC	Proportionality constant in Newton's second law, g_c

C. Element Parameter Data Cards

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

Element Parameters

Card 1 (12 parameters)

Note	Variable	Entry
	M	Element number
	II	Node number, I
	JJ	Node number, J
(8)	KK	Node number, K (Fluid node)
	LL	Node number, L
	MM	Node number, M
	NN	Node number, N (Fluid node, inlet)
	MATID	Property identification number
(9)	KG	Element generation parameter
(10)	IFIN	Flag for fin efficiency .EQ.0 Fin efficiency computed .NE.0 Fin efficiency set equal to one
	GM	Fluid mass flow rate, $\dot{m}$ (e.g., lbm/hr)
(11)	PI	Element inlet pressure, P_N

Card 2 (4 parameters)

Note	Variable	Entry
(12)	FTHICK	Effective fin thickness
(13)	WTOP	Effective width of top wall for convection
	WBOT	Effective width of bottom wall for convection
(14)	AFACT	Fin area factor

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) Capacitance matrices are formed for the fin and the fluid. Only the conventional element formulation is used; no upwinding is available.

(3) 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 $(T_N + T_K)/2$.

(4) The passage hydraulic diameter is defined by

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

(5) 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

$$\left(\text{e.g., } g_c = \frac{32.17 \text{ ft - lbm}}{lb_f \text{ - sec}^2}\right)$$

(6) 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.

(7) 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 $P = \rho RT$.

(8) The direction of fluid flow is determined by the node numbering sequence. Flow is from node N to node K (see fig. 13).

(9) 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.

(10) The fin efficiency is available only for a linear analysis. IFIN.EQ.1 should be used for nonlinear analyses. If INFIN.EQ.0 is used with a nonlinear analysis an incorrect fin efficiency value will be used. For linear analyses with IFIN.EQ.0 the fin efficiency η is computed from

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

where

$$m = a\sqrt{\frac{h}{k}}$$

$$a = \text{YLNTH}\sqrt{\frac{\text{PERIM}}{\text{ACOND}}}$$

YLNTH = average height of the fin, e.g. $y_M - y_I$ (fig. 13)

PERIM = perimeter of the fin = 2*AFACT*AREA/YLNTH

AREA = surface area of one side of the quadrilateral IJLM (fig. 13)

ACOND = conduction area of fin = XLNTH*FTHICK

XLNTH = average length of the fin, e.g. $x_J - x_I$ (fig. 13)

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 14 below).

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

(12) 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.

(13) The top and bottom widths are used to compute the convection areas from the walls to the fluid (see note 12). The average of these widths is also used in the computation of the flow area of the element.

IV. ELEMENT DATA (Concluded)

(14) 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

$$q = \eta h \ (2*AREA*AFACT) \left[\frac{T_I + T_J + T_L + T_M}{4} - T_{BULK}\right]$$

where

η = fin efficiency (see note 10)

h = convection coefficient

AREA = surface area of fin

AFACT = fin area factor

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

V. THERMAL DATA TABLES

Thermal parameter tables are required for nonlinear and/or transient 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 data tables are described by the following sequence of data cards:

A. Control Card (one card for each table)

TABNO	Table number	
NPOINT	Number of data points given in table	
ITYPE	.EQ.1	Temp.-thermal parameter table
	.EQ.2	Time-heat load table

B. Table Identification (18A4)

Any desired heading information

C. Thermal Parameter Table (4 points per card, as many cards as required) (typical card)

$$\left.\begin{array}{l}\text{Temperature for point 1}\\ \text{Thermal parameter for point 1}\end{array}\right\}\text{Point 1}$$

V. THERMAL DATA TABLES (Concluded)

Temperature for point 2 Thermal parameter for point 2	Point 2
Temperature for point 3 Thermal parameter for point 3	Point 3
Temperature for point 4 Thermal parameter for point 4	Point 4

VI. TRANSIENT CONTROL CARDS

NOTE: NINT cards are required, see Section II, Master Control.

<u>NOPT.EQ.1</u> (User selects time step.)

NSTEPS	Number of time steps for temperature computation
DELTA	Time increment between temperature computations
NOUT	Temperature data to be printed at every NOUT step

<u>NOPT.EQ.0</u> (Program computes time step.)

TFINL	Final time for interval
FDT	Factor for computing time step (If FDT is entered as zero, FDT is set equal to 5.)

$$DT = \frac{FDT}{\lambda}$$

where λ is computed for each element considering conductance-capacity ratio

NOUT	Temperature data to be printed at every NOUT steps

APPENDIX C: INPUT DATA AND PROGRAM OUTPUT FOR SAMPLE PROBLEMS

Three sample problems are presented: (1) a linear steady-state conduction analysis of a rod, (2) a linear transient analysis of conduction in a wall, and (3) a one-dimensional forced convection analysis of a river flow. The problems are relatively simple and were selected to illustrate program input and output for the basic analyses options. Four additional sample problems illustrative of the TAP 2 steady-state analysis capability are presented in the TAP 1 user's manual (ref. 4). Sample plots are presented in reference 10. The sample problems are presented in figures 14 to 16.

SAMPLE PROBLEM 1

Linear Steady-State Conduction Analysis of a Rod

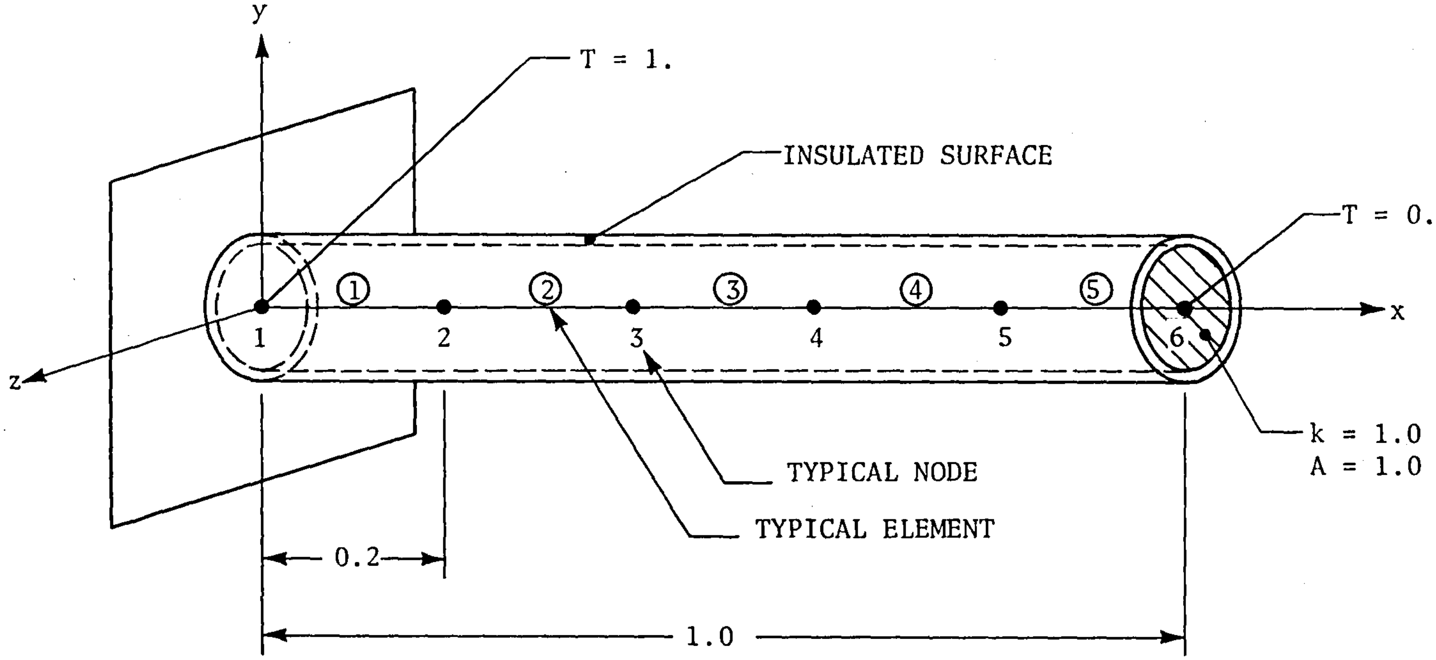


Figure 14. Linear steady-state conduction analysis of a rod.

```
PRINT INPUT DATA CARD IMAGES WITH CARD COLUMNS INDICATED EVERY 10TH CARD--
CARD
  NO./COL. 1.......10........20........30........40........50........60........70........80
     1      1-D STEADY-STATE, PURE CONDUCTION, ROD ELEMENT, CONSISTENT FORMULATION.
     2      6   1   0   1   0   1   1   1
     3      1   1   0.0   0.0   0.0   1   1.0
     4      2   0   0.2   0.0   0.0   1   0.0
     5      5   0   0.8   0.0   0.0   1   0.0
     6      6   1   1.0   0.0   0.0   1   0.0
     7        1   5   1   0
     8      1   1.0   0   0.0   0   1   0.0
     9      1   1   2   1   1   1.0   0.0   0   0.0
    10      5   5   6   1   1   1.0   0.0   0   0.0
```

```
1-D STEADY-STATE, PURE CONDUCTION, ROD ELEMENT, CONSISTENT FORMULATION.

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

    NUMBER OF NODAL POINTS    =     6
    NUMBER OF ELEMENT TYPES   =     1
    NUMBER OF TABLES          =     0
    ANALYSIS CODE(NANA)       =     1
      EQ.0, DATA CHECK ONLY,
      EQ.1, LINEAR STATIC
      EQ.2, LINEAR TRANSIENT
      EQ.3, NONLINEAR STATIC
      EQ.4, NONLINEAR TRANSIENT
    NUMBER OF TIME INTERVALS=       1
    TIME STEP CODE(NOPT)      =     1
       .EQ.0 DT COMPUTED
       .EQ.1 DT INPUT
    FILE CODE(NFILE)          =     1
      EQ.0, NO PLOT FILES
      GE.1, PLOT FILES CREATED
      EQ.2, RESTART FILE CREATED
      EQ.3, RESTART FILE READ
            NEW RESTART FILE
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	TEMPERATURE
1	1	0.00000E+00	0.00000E+00	0.00000E+00	0.10000E+01
2	0	0.20000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3	0	0.40000E+00	0.00000E+00	0.00000E+00	0.00000E+00
4	0	0.60000E+00	0.00000E+00	0.00000E+00	0.00000E+00
5	0	0.80000E+00	0.00000E+00	0.00000E+00	0.00000E+00
6	1	0.10000E+01	0.00000E+00	0.00000E+00	0.00000E+00

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 = 5
NUMBER OF MATERIALS = 1

MATERIAL	CONDUCTIVITY TABLE	CONDUCTIVITY K	SPECIFIC HEAT TABLE	SPECIFIC HEAT CSURP	CONSISTENT CAP. .EQ.1 YES	DENSITY RHO
1	0	0.1000E+01	0	0.0000E+00	1	0.0000E+00

N	I	J	MAT	CONDUCTION AREA	VOLUME Q	SURFACE Q	CONVECTION AREA	HI	CONVECTION DATA TI	HJ	TJ	LOAD HISTORY TABLES VOLQ	SURFACE
1	1	2	1	0.1000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0	0
2	2	3	1	0.1000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0	0
3	3	4	1	0.1000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0	0
4	4	5	1	0.1000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0	0
5	5	6	1	0.1000E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0	0

MAXIMUM CONDUCTANCE/CAPACITANCE RATIO, 0.00000000E+00 ELEMENT NUMBER 5

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


      TOTAL NUMBER OF EQUATIONS        =     6
      SEMI BANDWIDTH                   =     2

         INPUT NODAL TEMPERATURES
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           0.100000E+01   0.000000E+00   0.000000E+00   0.000000E+00   0.000000E+00
    6           0.000000E+00
```

```
T R A N S I E N T   C O N T R O L   D A T A

    NUMBER OF STEPS      =     1
    OUTPUT STEPS         =     1
    TIME INCREMENT USED= 0.00000E+00
    DT COMPUTED          = 0.00000E+00


         LINEAR ANALYSIS

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           0.100000E+01   0.800000E+00   0.600000E+00   0.400000E+00   0.200000E+00
    6           0.000000E+00
```

```
      O N E - D I M E N S I O N A L   R O D   E L E M E N T S,

         ELEMENT      CONDUCTION       SURFACE CONVECTION
                         FLUX                FLUX


               1        0.10000E+01        0.00000E+00
               2        0.10000E+01        0.00000E+00
               3        0.10000E+01        0.00000E+00
               4        0.10000E+01        0.00000E+00
               5        0.10000E+01        0.00000E+00
STOP

END OF EXECUTION
CPU TIME: 0.96  ELAPSED TIME: 3:52.18
EXIT
```

SAMPLE PROBLEM 2

Linear Transient Analysis of Conduction in a Wall

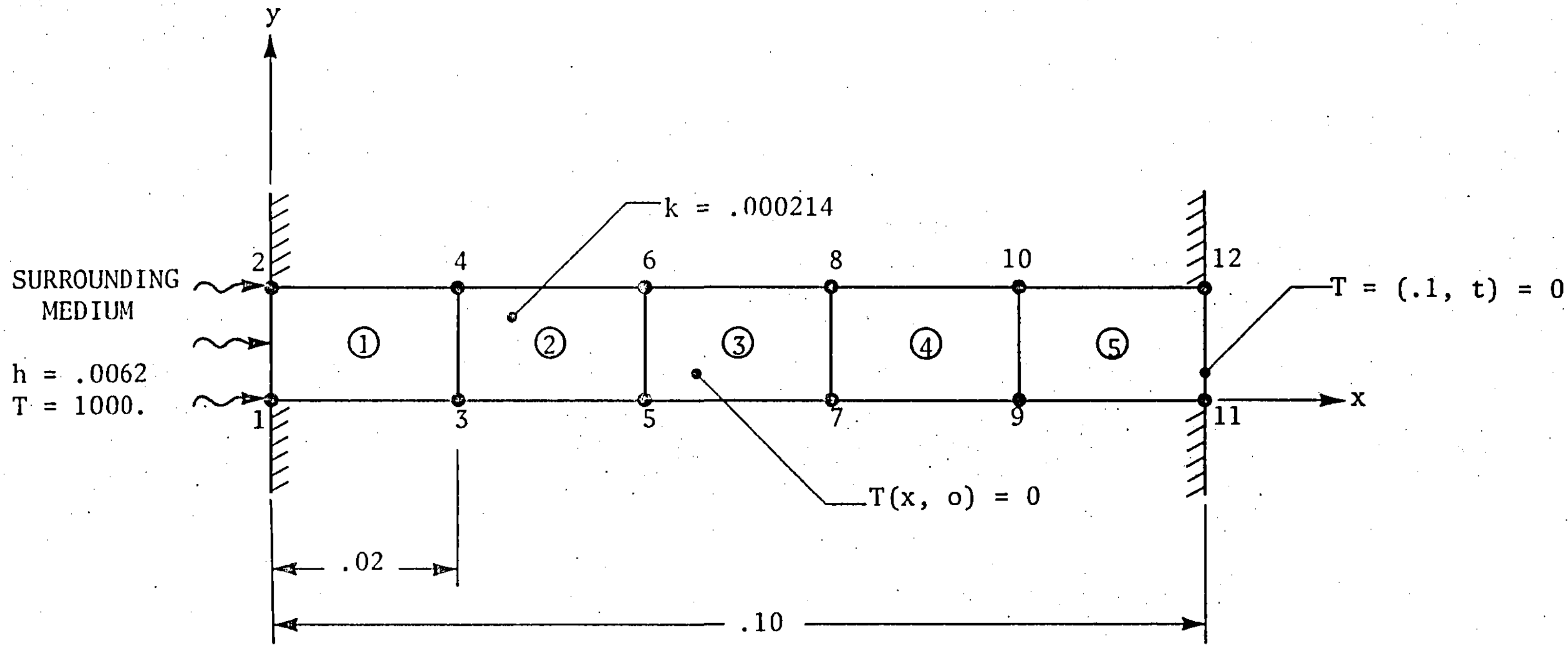


Figure 15. Linear transient analysis of conduction in a wall.

```
PRINT INPUT DATA CARD IMAGES WITH CARD COLUMNS INDICATED EVERY 10TH CARD--
CARD
  NO./COL. 1.......10........20........30........40........50........60........70........80
     1      1-D TRANSIENT, QUAD. ELEMENT, COND.+EDGE CONV., CONSISTENT FORMULATION.
     2      12   1   0   2   0   1   1   1
     3       1   0   0.00   0.00   0.0   2   0.0
     4       9   0   0.08   0.00   0.0   2   0.0
     5      11   1   0.10   0.00   0.0   2   0.0
     6       2   0   0.00   0.01   0.0   2   0.0
     7      10   0   0.08   0.01   0.0   2   0.0
     8      12   1   0.10   0.01   0.0   2   0.0
     9           3   5   1   0
    10      1   0   0   1   1
  NO./COL. 1.......10........20........30........40........50........60........70........80
    11      1.    .214E-3   0.0   .214E-3   0.0   .104   .296
    12      1   1   3   4   2   1   2   1   0   0.0   0
    13        2   1   0.0   .62E-2   1000.   .62E-2   1000.
    14      2   3   5   6   4   1   2   0   0   0.0   0
    15      5   9  11  12  10   1   2   0   0   0.0   0
    16      50   .01   10
```

```
1-D TRANSIENT, QUAD. ELEMENT, COND.+EDGE CONV., CONSISTENT FORMULATION.

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

    NUMBER OF NODAL POINTS    =   12
    NUMBER OF ELEMENT TYPES   =    1
    NUMBER OF TABLES          =    0
    ANALYSIS CODE(NANA)       =    2
      EQ.0,  DATA CHECK ONLY,
      EQ.1,  LINEAR STATIC
      EQ.2,  LINEAR TRANSIENT
      EQ.3,  NONLINEAR STATIC
      EQ.4,  NONLINEAR TRANSIENT
    NUMBER OF TIME INTERVALS=      1
    TIME STEP CODE(NOPT)     =      1
       .EQ.0 DT COMPUTED
       .EQ.1 DT INPUT
    FILE CODE(NFILE)         =      1
      EQ.0, NO PLOT FILES
      GE.1, PLOT FILES CREATED
      EQ.2, RESTART FILE CREATED
      EQ.3, RESTART FILE READ
            NEW RESTART FILE
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	TEMPERATURE
1	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
2	0	0.00000E+00	0.10000E-01	0.00000E+00	0.00000E+00
3	0	0.20000E-01	0.00000E+00	0.00000E+00	0.00000E+00
4	0	0.20000E-01	0.10000E-01	0.00000E+00	0.00000E+00
5	0	0.40000E-01	0.00000E+00	0.00000E+00	0.00000E+00
6	0	0.40000E-01	0.10000E-01	0.00000E+00	0.00000E+00
7	0	0.60000E-01	0.00000E+00	0.00000E+00	0.00000E+00
8	0	0.60000E-01	0.10000E-01	0.00000E+00	0.00000E+00
9	0	0.80000E-01	0.00000E+00	0.00000E+00	0.00000E+00
10	0	0.80000E-01	0.10000E-01	0.00000E+00	0.00000E+00
11	1	0.10000E+00	0.00000E+00	0.00000E+00	0.00000E+00
12	1	0.10000E+00	0.10000E-01	0.00000E+00	0.00000E+00

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 = 5
NUMBER OF DIFFERENT MATERIALS = 1

MATERIAL	CONDUCTIVITY TABLE	SPECIFIC HEAT TABLE	CONSISTENT CAP. .EQ.1 YES	LAYERS
1	0	0	1	1

MATERIAL	THICKNESS	CONDUCTIVITY TENSOR KXX	KXY	KYY	SPECIFIC HEAT	DENSITY RHO
1	0.1000E+01	0.2140E-03	0.0000E+00	0.2140E-03	0.1040E+00	0.2960E+00

ELEMENT INPUT DATA

N	I	J	K	L	MATID	KG	IEDGE	ISURF	Q	HISTORY TABLE
1	1	3	4	2	1	2	1	0	0.0000E+00	0

EDGE 2 . 1 QS= 0.0000E+00 H1= 0.6200E-02 T1= 0.1000E+04 H2= 0.6200E-02 T2= 0.1000E+04

N	I	J	K	L	MATID	KG	IEDGE	ISURF	Q	HISTORY TABLE
2	3	5	6	4	1	2	0	0	0.0000E+00	0
3	5	7	8	6	1	2	0	0	0.0000E+00	0
4	7	9	10	8	1	2	0	0	0.0000E+00	0
5	9	11	12	10	1	2	0	0	0.0000E+00	0

MAXIMUM CONDUCTANCE/CAPACITANCE RATIO, 0.64075494E+03 ELEMENT NUMBER 1

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

TOTAL NUMBER OF EQUATIONS = 12
SEMI BANDWIDTH = 4

INPUT NODAL TEMPERATURES

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	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
11	0.000000E+00	0.000000E+00			

TRANSIENT CONTROL DATA

```
NUMBER OF STEPS      =   50
OUTPUT STEPS         =   10
TIME INCREMENT USED= 0.10000E-01
DT COMPUTED          = 0.78033E-02
```

STEP= 10 TIME = 0.10000000E+00

TEMPERATURE VECTOR

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	0.498172E+03	0.498172E+03	0.251184E+03	0.251184E+03	0.100037E+03
6	0.100037E+03	0.291439E+02	0.291439E+02	0.531769E+01	0.531769E+01
11	0.000000E+00	0.000000E+00			

STEP= 20 TIME = 0.20000000E+00

TEMPERATURE VECTOR

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	0.593760E+03	0.593760E+03	0.380400E+03	0.380400E+03	0.219059E+03
6	0.219059E+03	0.110753E+03	0.110753E+03	0.441223E+02	0.441223E+02
11	0.000000E+00	0.000000E+00			

STEP= 30 TIME = 0.30000000E+00

TEMPERATURE VECTOR

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	0.646710E+03	0.646710E+03	0.455629E+03	0.455629E+03	0.297299E+03
6	0.297299E+03	0.173735E+03	0.173735E+03	0.788237E+02	0.788237E+02
11	0.000000E+00	0.000000E+00			

STEP= 40 TIME = 0.40000002E+00

TEMPERATURE VECTOR

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	0.680216E+03	0.680216E+03	0.503750E+03	0.503750E+03	0.348578E+03
6	0.348578E+03	0.216187E+03	0.216187E+03	0.102739E+03	0.102739E+03
11	0.000000E+00	0.000000E+00			

STEP= 50 TIME = 0.50000004E+00

TEMPERATURE VECTOR

NODE NO.	NO VALUE	NO+1 VALUE	NO+2 VALUE	NO+3 VALUE	NO+4 VALUE,
1	0.702022E+03	0.702022E+03	0.535135E+03	0.535135E+03	0.382179E+03
6	0.382179E+03	0.244151E+03	0.244151E+03	0.118557E+03	0.118557E+03
11	0.000000E+00	0.000000E+00			

ISOPARAMETRIC QUADRILATERAL ELEMENTS

	CONDUCTION FLUXES (LOCAL AXES)		SURFACE FLUXES (POSITIVE INTO SURFACE)		EDGE FLUXES (POSITIVE INTO EDGE)			
ELEMENT	QX	QY	TOP	BOTTOM	IJ	JK	KL	LI
1	0.1786E+01	0.5960E-07	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	-0.4353E-01
2	0.1637E+01	0.5960E-07	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3	0.1477E+01	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4	0.1344E+01	-0.2980E-07	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
5	0.1269E+01	-0.2980E-07	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

STOP

END OF EXECUTION
CPU TIME: 3.24 ELAPSED TIME: 5:46.92
EXIT

SAMPLE PROBLEM 3

Forced Convection Analysis of a River Flow

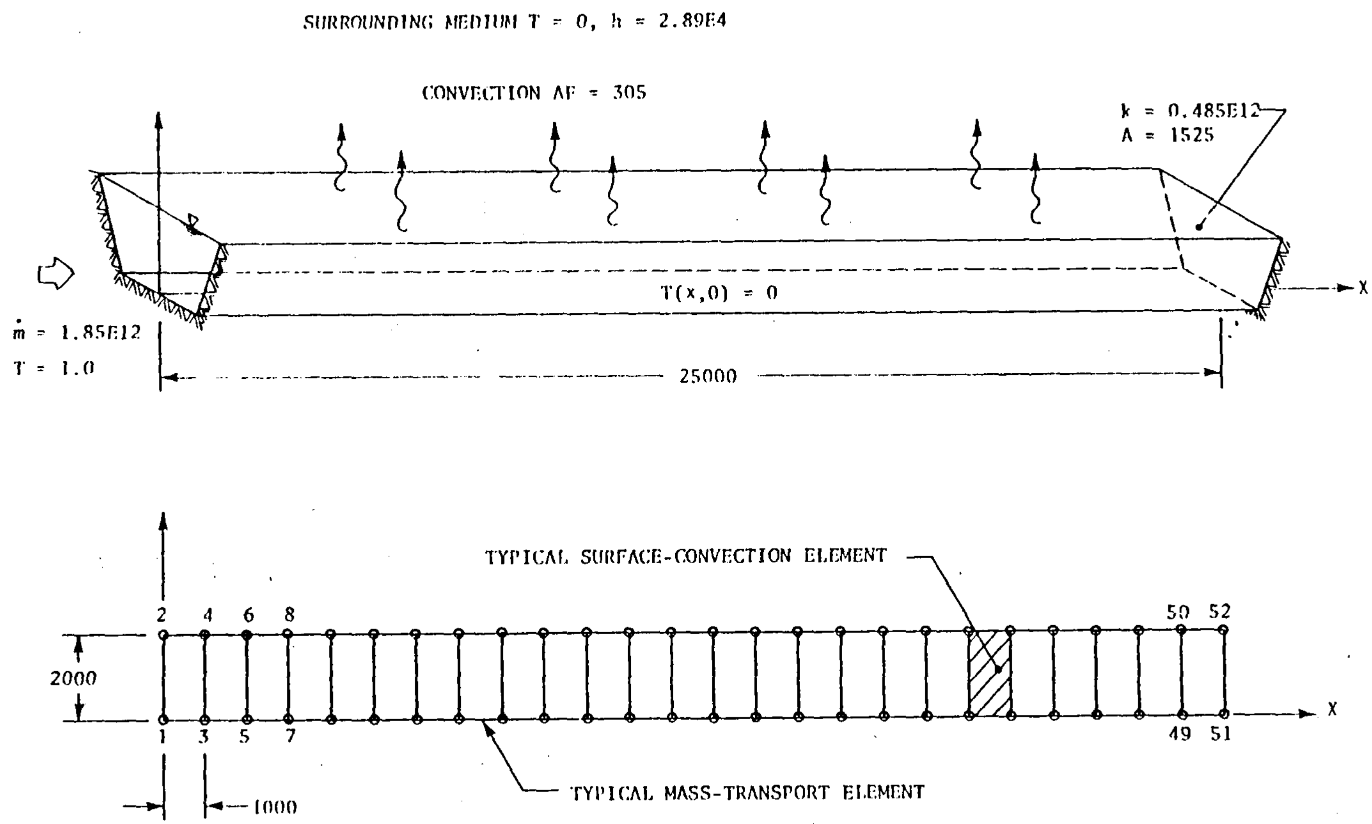


Figure 16. One-dimensional forced convection analysis of a river flow.

```
PRINT INPUT DATA CARD IMAGES WITH CARD COLUMNS INDICATED EVERY 10TH CARD--
CARD
  NO./COL. 1.......10........20........30........40........50........60........70........80
     1       RIVER FLOW, TRANSIENT, MASS TRANS.+SURFACE CONV. ELEMENTS, UPWIND.
     2       52   2   0   2   0   1   1   1
     3        1   1        0.   0.        0.   2   1.
     4        3   0     1000.   0.        0.   2   0.
     5       49   0    24000.   0.        0.   2   0.
     6       51   0    25000.   0.        0.   2   0.
     7        2   1        0.   0.     2000.   2   0.
     8       52   1    25000.   0.     2000.   2   0.
     9            8   25   1   0
    10       1   .485E+12   0   1.   0   2   1.E+6
  NO./COL. 1.......10........20........30........40........50........60........70........80
    11        1   1   3   1   2   1.85E+12   1525.
    12       25  49  51   1   2   1.85E+12   1525.
    13            9  25   1   4
    14       1   2.89E+4   0   2
    15        1   1   3   4   2   1   2   305.
    16       25  49  51  52  50   1   2   305.
    17       20   1.   5
```

RIVER FLOW, TRANSIENT, MASS TRANS.+SURFACE CONV. ELEMENTS, UPWIND.

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  =     2
    NUMBER OF TABLES         =     0
    ANALYSIS CODE(NANA)      =     2
      EQ.0, DATA CHECK ONLY,
      EQ.1, LINEAR STATIC
      EQ.2, LINEAR TRANSIENT
      EQ.3, NONLINEAR STATIC
      EQ.4, NONLINEAR TRANSIENT
    NUMBER OF TIME INTERVALS=      1
    TIME STEP CODE(NOPT)     =     1
       .EQ.0 DT COMPUTED
       .EQ.1 DT INPUT
    FILE CODE(NFILE)         =     1
      EQ.0, NO PLOT FILES
      GE.1, PLOT FILES CREATED
      EQ.2, RESTART FILE CREATED
      EQ.3, RESTART FILE READ
            NEW RESTART FILE
```

NODAL POINT INPUT DATA

NODE NUMBER	BOUNDARY CONDITION CODE	NODAL POINT COORDINATES X	Y	Z	TEMPERATURE
1	1	0.00000E+00	0.00000E+00	0.00000E+00	0.10000E+01
2	1	0.00000E+00	0.00000E+00	0.20000E+04	0.00000E+00
3	0	0.10000E+04	0.00000E+00	0.00000E+00	0.00000E+00
4	1	0.10000E+04	0.00000E+00	0.20000E+04	0.00000E+00
5	0	0.20000E+04	0.00000E+00	0.00000E+00	0.00000E+00
6	1	0.20000E+04	0.00000E+00	0.20000E+04	0.00000E+00
7	0	0.30000E+04	0.00000E+00	0.00000E+00	0.00000E+00
8	1	0.30000E+04	0.00000E+00	0.20000E+04	0.00000E+00
9	0	0.40000E+04	0.00000E+00	0.00000E+00	0.00000E+00
10	1	0.40000E+04	0.00000E+00	0.20000E+04	0.00000E+00
11	0	0.50000E+04	0.00000E+00	0.00000E+00	0.00000E+00
12	1	0.50000E+04	0.00000E+00	0.20000E+04	0.00000E+00
13	0	0.60000E+04	0.00000E+00	0.00000E+00	0.00000E+00
14	1	0.60000E+04	0.00000E+00	0.20000E+04	0.00000E+00
15	0	0.70000E+04	0.00000E+00	0.00000E+00	0.00000E+00
16	1	0.70000E+04	0.00000E+00	0.20000E+04	0.00000E+00
17	0	0.80000E+04	0.00000E+00	0.00000E+00	0.00000E+00
18	1	0.80000E+04	0.00000E+00	0.20000E+04	0.00000E+00
19	0	0.90000E+04	0.00000E+00	0.00000E+00	0.00000E+00
20	1	0.90000E+04	0.00000E+00	0.20000E+04	0.00000E+00
21	0	0.10000E+05	0.00000E+00	0.00000E+00	0.00000E+00
22	1	0.10000E+05	0.00000E+00	0.20000E+04	0.00000E+00
23	0	0.11000E+05	0.00000E+00	0.00000E+00	0.00000E+00
24	1	0.11000E+05	0.00000E+00	0.20000E+04	0.00000E+00
25	0	0.12000E+05	0.00000E+00	0.00000E+00	0.00000E+00
26	1	0.12000E+05	0.00000E+00	0.20000E+04	0.00000E+00
27	0	0.13000E+05	0.00000E+00	0.00000E+00	0.00000E+00
28	1	0.13000E+05	0.00000E+00	0.20000E+04	0.00000E+00
29	0	0.14000E+05	0.00000E+00	0.00000E+00	0.00000E+00
30	1	0.14000E+05	0.00000E+00	0.20000E+04	0.00000E+00
31	0	0.15000E+05	0.00000E+00	0.00000E+00	0.00000E+00
32	1	0.15000E+05	0.00000E+00	0.20000E+04	0.00000E+00
33	0	0.16000E+05	0.00000E+00	0.00000E+00	0.00000E+00
34	1	0.16000E+05	0.00000E+00	0.20000E+04	0.00000E+00
35	0	0.17000E+05	0.00000E+00	0.00000E+00	0.00000E+00
36	1	0.17000E+05	0.00000E+00	0.20000E+04	0.00000E+00
37	0	0.18000E+05	0.00000E+00	0.00000E+00	0.00000E+00
38	1	0.18000E+05	0.00000E+00	0.20000E+04	0.00000E+00
39	0	0.19000E+05	0.00000E+00	0.00000E+00	0.00000E+00
40	1	0.19000E+05	0.00000E+00	0.20000E+04	0.00000E+00
41	0	0.20000E+05	0.00000E+00	0.00000E+00	0.00000E+00
42	1	0.20000E+05	0.00000E+00	0.20000E+04	0.00000E+00
43	0	0.21000E+05	0.00000E+00	0.00000E+00	0.00000E+00
44	1	0.21000E+05	0.00000E+00	0.20000E+04	0.00000E+00
45	0	0.22000E+05	0.00000E+00	0.00000E+00	0.00000E+00
46	1	0.22000E+05	0.00000E+00	0.20000E+04	0.00000E+00
47	0	0.23000E+05	0.00000E+00	0.00000E+00	0.00000E+00
48	1	0.23000E+05	0.00000E+00	0.20000E+04	0.00000E+00
49	0	0.24000E+05	0.00000E+00	0.00000E+00	0.00000E+00
50	1	0.24000E+05	0.00000E+00	0.20000E+04	0.00000E+00
51	0	0.25000E+05	0.00000E+00	0.00000E+00	0.00000E+00
52	1	0.25000E+05	0.00000E+00	0.20000E+04	0.00000E+00

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

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

THERMAL-FLUID PROPERTIES

MATERIAL	CONDUCTIVITY TABLE	CONDUCTIVITY K	SPECIFIC HEAT TABLE	SPECIFIC HEAT CSUBP	CONSISTENT CAP. UPWIND CONTROL	DENSITY RHO
1	0	0.4850E+12	0	0.1000E+01	2	0.1000E+07

ELEMENT INPUT DATA

N	I	J	PID	KG	MASS FLOW RATE	FLOW AREA	UPWIND PARAMETER
1	1	3	1	2	0.1850E+13	0.1525E+04	0.1000E+01
2	3	5	1	2	0.1850E+13	0.1525E+04	0.1000E+01
3	5	7	1	2	0.1850E+13	0.1525E+04	0.1000E+01
4	7	9	1	2	0.1850E+13	0.1525E+04	0.1000E+01
5	9	11	1	2	0.1850E+13	0.1525E+04	0.1000E+01
6	11	13	1	2	0.1850E+13	0.1525E+04	0.1000E+01
7	13	15	1	2	0.1850E+13	0.1525E+04	0.1000E+01
8	15	17	1	2	0.1850E+13	0.1525E+04	0.1000E+01
9	17	19	1	2	0.1850E+13	0.1525E+04	0.1000E+01
10	19	21	1	2	0.1850E+13	0.1525E+04	0.1000E+01
11	21	23	1	2	0.1850E+13	0.1525E+04	0.1000E+01
12	23	25	1	2	0.1850E+13	0.1525E+04	0.1000E+01
13	25	27	1	2	0.1850E+13	0.1525E+04	0.1000E+01
14	27	29	1	2	0.1850E+13	0.1525E+04	0.1000E+01
15	29	31	1	2	0.1850E+13	0.1525E+04	0.1000E+01
16	31	33	1	2	0.1850E+13	0.1525E+04	0.1000E+01
17	33	35	1	2	0.1850E+13	0.1525E+04	0.1000E+01
18	35	37	1	2	0.1850E+13	0.1525E+04	0.1000E+01
19	37	39	1	2	0.1850E+13	0.1525E+04	0.1000E+01
20	39	41	1	2	0.1850E+13	0.1525E+04	0.1000E+01
21	41	43	1	2	0.1850E+13	0.1525E+04	0.1000E+01
22	43	45	1	2	0.1850E+13	0.1525E+04	0.1000E+01
23	45	47	1	2	0.1850E+13	0.1525E+04	0.1000E+01
24	47	49	1	2	0.1850E+13	0.1525E+04	0.1000E+01
25	49	51	1	2	0.1850E+13	0.1525E+04	0.1000E+01

MAXIMUM CONDUCTANCE/CAPACITANCE RATIO, 0.11640000E+02   ELEMENT NUMBER   25

S U R F A C E   C O N V E C T I O N   E L E M E N T S

NUMBER OF CONVECTION ELEMENTS = 25
NUMBER OF CONVECTION PROPERTIES = 1
NUMBER OF ELEMENT NODES = 4

CONVECTION PROPERTIES

PROPERTY	CONVECTION H	CONVECTION H TABLE	ICONS
1	0.2890E+05	0	2

ELEMENT INPUT DATA

N	I	J	K	L	M	N	MATID	KG	AREA FACTOR
1	1	3	4	2	0	0	1	2	0.3050E+03
2	3	5	6	4	0	0	1	2	0.3050E+03
3	5	7	8	6	0	0	1	2	0.3050E+03
4	7	9	10	8	0	0	1	2	0.3050E+03
5	9	11	12	10	0	0	1	2	0.3050E+03
6	11	13	14	12	0	0	1	2	0.3050E+03
7	13	15	16	14	0	0	1	2	0.3050E+03
8	15	17	18	16	0	0	1	2	0.3050E+03
9	17	19	20	18	0	0	1	2	0.3050E+03
10	19	21	22	20	0	0	1	2	0.3050E+03
11	21	23	24	22	0	0	1	2	0.3050E+03
12	23	25	26	24	0	0	1	2	0.3050E+03
13	25	27	28	26	0	0	1	2	0.3050E+03
14	27	29	30	28	0	0	1	2	0.3050E+03
15	29	31	32	30	0	0	1	2	0.3050E+03
16	31	33	34	32	0	0	1	2	0.3050E+03
17	33	35	36	34	0	0	1	2	0.3050E+03
18	35	37	38	36	0	0	1	2	0.3050E+03
19	37	39	40	38	0	0	1	2	0.3050E+03
20	39	41	42	40	0	0	1	2	0.3050E+03
21	41	43	44	42	0	0	1	2	0.3050E+03
22	43	45	46	44	0	0	1	2	0.3050E+03
23	45	47	48	46	0	0	1	2	0.3050E+03
24	47	49	50	48	0	0	1	2	0.3050E+03
25	49	51	52	50	0	0	1	2	0.3050E+03

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

INPUT NODAL TEMPERATURES

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	0.100000E+01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
6	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
11	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
16	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
21	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
26	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
31	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
36	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
41	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
46	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
51	0.000000E+00	0.000000E+00			

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

NUMBER OF STEPS = 20
OUTPUT STEPS = 5
TIME INCREMENT USED= 0.10000E+01
DT COMPUTED = 0.42955E+00

STEP= 5 TIME = 0.50000000E+01

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	0.100000E+01	0.000000E+00	0.993685E+00	0.000000E+00	0.971704E+00
6	0.000000E+00	0.975810E+00	0.000000E+00	0.860581E+00	0.000000E+00
11	0.852299E+00	0.000000E+00	0.673930E+00	0.000000E+00	0.429359E+00
16	0.000000E+00	0.233705E+00	0.000000E+00	0.113523E+00	0.000000E+00
21	0.506617E-01	0.000000E+00	0.211821E-01	0.000000E+00	0.841176E-02
26	0.000000E+00	0.320409E-02	0.000000E+00	0.117921E-02	0.000000E+00
31	0.421653E-03	0.000000E+00	0.147120E-03	0.000000E+00	0.502604E-04
36	0.000000E+00	0.168582E-04	0.000000E+00	0.556422E-05	0.000000E+00
41	0.181056E-05	0.000000E+00	0.581722E-06	0.000000E+00	0.184797E-06
46	0.000000E+00	0.581402E-07	0.000000E+00	0.182925E-07	0.000000E+00
51	0.656081E-08	0.000000E+00			

STEP= 10 TIME = 0.10000000E+02

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	0.100000E+01	0.000000E+00	0.995187E+00	0.000000E+00	0.990302E+00
6	0.000000E+00	0.984598E+00	0.000000E+00	0.979641E+00	0.000000E+00
11	0.968098E+00	0.000000E+00	0.963915E+00	0.000000E+00	0.934692E+00
16	0.000000E+00	0.919845E+00	0.000000E+00	0.869618E+00	0.000000E+00
21	0.804378E+00	0.000000E+00	0.722288E+00	0.000000E+00	0.607926E+00
26	0.000000E+00	0.468542E+00	0.000000E+00	0.329207E+00	0.000000E+00
31	0.212138E+00	0.000000E+00	0.126569E+00	0.000000E+00	0.706059E-01
36	0.000000E+00	0.371519E-01	0.000000E+00	0.185797E-01	0.000000E+00
41	0.888779E-02	0.000000E+00	0.408864E-02	0.000000E+00	0.181716E-02
46	0.000000E+00	0.783942E-03	0.000000E+00	0.332776E-03	0.000000E+00
51	0.155803E-03	0.000000E+00			

STEP= 15 TIME = 0.15000000E+02

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	0.100000E+01	0.000000E+00	0.995275E+00	0.000000E+00	0.990564E+00
6	0.000000E+00	0.985863E+00	0.000000E+00	0.981124E+00	0.000000E+00
11	0.976402E+00	0.000000E+00	0.971282E+00	0.000000E+00	0.966481E+00
16	0.000000E+00	0.959661E+00	0.000000E+00	0.954273E+00	0.000000E+00
21	0.943124E+00	0.000000E+00	0.933243E+00	0.000000E+00	0.914719E+00
26	0.000000E+00	0.890385E+00	0.000000E+00	0.856800E+00	0.000000E+00
31	0.808826E+00	0.000000E+00	0.745651E+00	0.000000E+00	0.667257E+00
36	0.000000E+00	0.573934E+00	0.000000E+00	0.469728E+00	0.000000E+00
41	0.363329E+00	0.000000E+00	0.264930E+00	0.000000E+00	0.182298E+00
46	0.000000E+00	0.118891E+00	0.000000E+00	0.746004E-01	0.000000E+00
51	0.489005E-01	0.000000E+00			

STEP= 20 TIME = 0.20000000E+02

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	0.100000E+01	0.000000E+00	0.995278E+00	0.000000E+00	0.990578E+00
6	0.000000E+00	0.985899E+00	0.000000E+00	0.981241E+00	0.000000E+00
11	0.976599E+00	0.000000E+00	0.971975E+00	0.000000E+00	0.967341E+00
16	0.000000E+00	0.962728E+00	0.000000E+00	0.957978E+00	0.000000E+00
21	0.953312E+00	0.000000E+00	0.948073E+00	0.000000E+00	0.943020E+00
26	0.000000E+00	0.936523E+00	0.000000E+00	0.929764E+00	0.000000E+00
31	0.920565E+00	0.000000E+00	0.909019E+00	0.000000E+00	0.893672E+00
36	0.000000E+00	0.872675E+00	0.000000E+00	0.844640E+00	0.000000E+00
41	0.807766E+00	0.000000E+00	0.760320E+00	0.000000E+00	0.701726E+00
46	0.000000E+00	0.633310E+00	0.000000E+00	0.560300E+00	0.000000E+00
51	0.499091E+00	0.000000E+00			

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

H E A T F L U X E S

ELEMENT	FLUID HEAT FLUX
1	0.1846E+13
2	0.1837E+13
3	0.1828E+13
4	0.1820E+13
5	0.1811E+13
6	0.1802E+13
7	0.1794E+13
8	0.1785E+13
9	0.1777E+13
10	0.1768E+13
11	0.1759E+13
12	0.1749E+13
13	0.1739E+13
14	0.1726E+13
15	0.1712E+13
16	0.1692E+13
17	0.1667E+13
18	0.1634E+13
19	0.1589E+13
20	0.1528E+13
21	0.1450E+13
22	0.1352E+13
23	0.1235E+13
24	0.1104E+13
25	0.9799E+12

S U R F A C E C O N V E C T I O N E L E M E N T

H E A T F L U X E S

ELEMENT	SURFACE HEAT FLUX(POSITIVE INTO SURFACE)
1	0.8794E+10
2	0.8752E+10
3	0.8711E+10
4	0.8670E+10
5	0.8629E+10
6	0.8588E+10
7	0.8547E+10
8	0.8506E+10
9	0.8465E+10
10	0.8424E+10
11	0.8380E+10
12	0.8335E+10
13	0.8284E+10
14	0.8225E+10
15	0.8155E+10
16	0.8063E+10
17	0.7945E+10
18	0.7785E+10
19	0.7569E+10
20	0.7283E+10
21	0.6911E+10
22	0.6444E+10
23	0.5884E+10
24	0.5261E+10
25	0.4669E+10

STOP

END OF EXECUTION
CPU TIME: 4.93 ELAPSED TIME: 13:10.02
EXIT

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15. Supplementary Notes

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16. Abstract

A finite element computer program (TAP 2) for steady-state and transient thermal analyses 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. Transient analyses are performed using an implicit Crank-Nicolson time integration scheme with consistent or lumped capacitance matrices as an option. Program output includes nodal temperatures and element heat fluxes. Pressure drops in fluid passages may be computed as an option. User instructions and sample problems are presented in appendixes.

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