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TACO - A FINITE ELEMENT HEAT TRANSFER CODE

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TACO - A FINITE ELEMENT HEAT TRANSFER CODE

1. INTRODUCTION

TACO is a two-dimensional implicit finite element code for heat transfer analysis. It can perform both linear and nonlinear analyses and can be used to solve either transient or steady state problems. Either plane or axisymmetric geometries can be analyzed.

TACO has the capability to handle time or temperature dependent material properties and materials may be either isotropic or orthotropic. A variety of time and temperature dependent loadings and boundary conditions are available including temperature, flux, convection, and radiation boundary conditions and internal heat generation.

Additionally, TACO has some specialized features such as internal surface conditions (e.g., contact resistance), bulk nodes, enclosure radiation with view factor calculations, and chemical reactive kinetics. A user subprogram feature allows for any type of functional representation of any independent variable. A bandwidth and profile minimization option is also available in the code.

Graphical representation of data generated by TACO is provided by a companion post-processor named POSTACO (1).

The following sections outline the basic theory on which TACO is based, explain the capabilities of the code, and describe the input data required to perform an analysis with TACO. Some simple examples are provided to illustrate the use of the code.

2. GENERAL DESCRIPTION

2.1 BASIC EQUATIONS

The basic heat transfer problem for which TACO is designed is that of transient nonlinear conduction which can be described by the differential equation

$$\rho c_p \dot{\theta} = (k_{ij} \theta_{,j})_{,i} + Q \quad \text{in } R \quad (1)$$

with boundary conditions

$$\theta = \theta_s \quad \text{on } S_1 \quad (2)$$

and

$$k_{ij} \theta_{,j} n_i + q = 0 \quad \text{on } S_2 \quad (3)$$

and with the initial condition

$$\theta = \theta_0 \quad \text{at } t=t_0 \quad (4)$$

where R is the region of interest contained within boundary surface $S = S_1 + S_2$. In these equations, commas are used to denote spatial derivatives and a dot denotes a partial derivative with respect to time. Index notation is used with the summation convention (repeated indices imply summation). The various quantities in these equations are defined as follows:

θ	$= \theta(x_i, t)$	= temperature
x_i		= spatial coordinates
t		= time
ρ	$= \rho(x_i)$	= density
c_p	$= c_p(x_i, \theta, t)$	= specific heat
k_{ij}	$= k_{ij}(x_i, \theta, t)$	= thermal conductivity
Q	$= Q(x_i, \theta, t)$	= internal heat generation rate per unit volume

$\theta_s = \theta(s,t)$	= specified temperature on boundary S_1
$q = q(s,\theta,t)$	= specified heat flow across boundary S_2
n_i	= components of the unit normal vector on boundary S (the direction cosines)
$\theta_0 = \theta_0(x_i)$	= initial temperature
t_0	= initial time

The boundary heat flow q can be expressed in the general nonlinear form

$$q = \sum f(\theta,t) (\theta^a - \theta_q^a)^b \quad (5)$$

where f , a , b and θ_q depend on the type of boundary condition being specified. The summation sign indicates that more than one type of condition may be specified at a point on the boundary (e.g., radiation and convection). Equation (5) may be "linearized" into the form

$$q = f_0(\theta,t) + h(\theta,t)(\theta - \theta_q) \quad (6)$$

where the f_0 term allows for the case where $a=b=0$ in Eq. (5) (i.e., a flux boundary condition).

2.2 FINITE ELEMENT FORMULATION

In order to formulate the above problem in terms of the finite element method (2), one can proceed as follows: First the region R is subdivided into a series of sub-regions or elements within which the temperature is approximated by

$$\theta(x_i,t) \approx \sum_j N_j(x_i) \theta_j(t) \quad (7)$$

where $\theta_j(t)$ are the element nodal point temperatures and $N_j(x_i)$ are the element interpolation functions.

Next, the Galerkin principle (2) is utilized to obtain the element heat capacity and conductivity matrices and element thermal load vector which can be represented respectively by

$$C_{ij} = \int_V N_i \rho c_p N_j dV \quad (8)$$

$$K_{ij} = \int_V N_{i,\alpha} k_{\alpha\beta} N_{j,\beta} dV + \int_{S_2} N_i h N_j dS \quad (9)$$

$$F_i = \int_V N_i Q dV + \int_{S_2} N_i (h\theta_q - f_0) dS \quad (10)$$

where the volume and surface integrals are over each element.

Appropriate combination of the element matrices yields the system equation

$$C \dot{\theta} + K \theta = F \quad (11)$$

where

C = system heat capacity matrix

K = system conductivity matrix

F = thermal load vector

θ = vector of nodal point temperatures

$\dot{\theta}$ = vector of time derivatives of nodal point temperatures

2.3 TIME INTEGRATION SCHEME

The time integration of Equation (11) is carried out in TACG using a generalized midpoint method (3) which is formulated as follows:

$$C_{t+\alpha\Delta t} \dot{\theta}_{t+\alpha\Delta t} + K_{t+\alpha\Delta t} \theta_{t+\alpha\Delta t} = F_{t+\alpha\Delta t} \quad (12)$$

where

$$\theta_{t+\alpha\Delta t} = (1-\alpha)\theta_t + \alpha\theta_{t+\Delta t} \quad (13)$$

$$\theta_{t+\Delta t} = \theta_t + \Delta\theta_t \quad (14)$$

$$\dot{\theta}_{t+\alpha\Delta t} = (\theta_{t+\Delta t} - \theta_t)/\Delta t \quad (15)$$

$$C_{t+\alpha\Delta t} = C(\theta_{t+\alpha\Delta t}) \quad (16)$$

$$K_{t+\alpha\Delta t} = K(\theta_{t+\alpha\Delta t}) \quad (17)$$

$$F_{t+\alpha\Delta t} = (1-\alpha) F_t + \alpha F_{t+\Delta t} \quad (18)$$

Substituting Equations (12-18) into Equation (11) and rearranging gives the following equation for $\Delta\theta_t$:

$$K_{t+\alpha\Delta t}^* \Delta\theta_t = F_{t+\alpha\Delta t}^* \quad (19)$$

where

$$K_{t+\alpha\Delta t}^* = \frac{C_{t+\alpha\Delta t}}{\Delta t} + \alpha K_{t+\alpha\Delta t} \quad (20)$$

$$F_{t+\alpha\Delta t}^* = F_{t+\alpha\Delta t} - K_{t+\alpha\Delta t} \theta_t \quad (21)$$

The parameter α in the above equations must be limited to $0 \leq \alpha \leq 1$. In terms of classical procedures, $\alpha = 0$ gives the forward explicit method, $\alpha = \frac{1}{2}$ results in the Crank-Nicholson method, and $\alpha = 1$ gives the backward implicit method. For $\frac{1}{2} \leq \alpha \leq 1$, the procedure is unconditionally stable. For $0 \leq \alpha < \frac{1}{2}$, the procedure can be unstable if the time step is too large. It is, therefore, recommended that α be selected in the range $\frac{1}{2} \leq \alpha \leq 1$. The code uses $\alpha = \frac{1}{2}$ as the default value.

For steady state analysis, Equation (11) reduces to

$$K\theta = F \quad (22)$$

which requires only a one step solution.

2.4 LINEAR SOLUTION SCHEME

In a linear problem, the solution procedure is to simply march along in time solving Equation (19) for $\Delta\theta_t$ at each time step. This $\Delta\theta_t$ is then added to the previous θ_t to update the nodal temperatures. A new F^* vector must be formed at each time step. However, the effective conductivity matrix K^* need only be reformed if the time step size Δt changes.

Equation (19) represents a system of linear algebraic equations which is symmetric and in band or profile form. The equations are solved in TACO by an efficient, out-of-core, direct, block profile solver (6).

2.5 NONLINEAR SOLUTION SCHEME

In a nonlinear problem, both K^* and F^* may be functions of θ and thus iteration must be used to solve Equation (19). Two iteration methods are available in TACO to solve such equations. The first is the direct iteration method wherein K^* is reformed and, thus, necessarily reduced for each iteration. The second, a modified direct iteration method does not reform K^* for each iterate but uses the initial K^* calculated at the first iteration within the time step. The direct iteration method converges more rapidly than the modified method but each iteration requires more computation. TACO also allows combinations of the two methods to be used. The decision as to which method or combination of methods is best to use on a particular problem must be made based on user

experience or a trial-and-error process. In addition, for problems where K^* changes slowly with temperature and where Δt does not change, TACO has the option to use the same K^* over several time steps.

2.6 ELEMENT DESCRIPTION

Presently TACO utilizes a four node isoparametric element for interior regions. This element degenerates to a three node triangle when two node numbers of the four node element are identical (see figure).

2.7 MATERIAL PROPERTIES

The density, specific heat, and thermal conductivity are assumed to be spatially constant within each element. While density must also be constant in time, the specific heat and conductivity may be functions of either time or temperature. In addition, the thermal conductivity may be either isotropic or orthotropic. TACO allows an arbitrary number of different materials to be specified. Carried to the extreme, each element could be composed of a different material.

2.8 INTERNAL HEAT GENERATION

Internal heat generation rates can be functions of time or temperature. Spatially, they are assumed constant within an element. Heat generation may be specified by element, by material, or both (in which case the effect is additive).

2.9 INITIAL CONDITIONS

Initial temperatures may be specified in TACO by either a single constant value over the entire body or by different values assigned to each nodal point. In cases where it is desired to specify initial temperatures which are discontinuous across element interfaces, the user must average the temperatures at the interfaces for specification at the nodal points defining the interfaces.

2.10 BOUNDARY CONDITIONS

As indicated in Section 2.1, boundary conditions can be specified as either temperature (Eq. 2) or heat flow (Eq. 3). Temperature "boundary conditions" can be specified as functions of time at any node whether on the physical boundary or not.

Heat flow boundary conditions can, as explained earlier, take the general form

$$q = f(\theta, t) (\theta^a - \theta_q^a) \quad (23)$$

and can be specified more than once over the same surface such as in a case of, say, combined radiation and convection. Heat flow boundary conditions can be specified on any "surface" (element boundary).

Equation (23) can be specialized to several standard types of boundary conditions. The following examples help to illustrate this.

1. Flux: $q = q_f$

Set $f = q_f$, $a=1$, and $h=\theta_q=0$.

2. Forced Convection: $q = h(\theta, t) (\theta - \theta_\infty)$

Set $f=h$, $a=b=1$, and $\theta_q = \theta_\infty$ where h is the convection heat transfer coefficient and θ_∞ is the equilibrium temperature.

3. Radiation: $q = \sigma \epsilon (\theta^4 - \theta_\infty^4)$

Set $f = \sigma \epsilon$, $a=4$, $b=1$, and $\theta_q = \theta_\infty$ where σ is the Stefan-Boltzmann constant, ϵ is the surface emissivity, and θ_∞ is the equilibrium temperature.

In addition to boundary conditions of the general form of Eq. (23), TACO allows for direct specification of the flux and forced convection boundary conditions (see Sections 5.9 and 5.10).

For situations where it is desired to specify adiabatic ($q=0$) conditions such as at an insulated surface or on a line of symmetry, no boundary condition need be specified. This is the default condition in TACO; i.e., if no boundary condition is specified on a surface, it is assumed to be $q=0$.

2.11 INTERNAL SURFACE CONDITIONS

It is possible in TACO to specify conditions between internal surfaces which are of the same form as the general external boundary conditions described in the previous section. In this case the general form is

$$q = f(\theta, t) (\theta_A^a - \theta_B^a)^b \quad (24)$$

where subscripts A and B refer to the "element" segments as indicated in the following figure

and θ_A and θ_B are the respective temperatures of these surfaces.

This type of "internal surface condition" is suitable for specifying contact resistances between surfaces and for describing certain types of "gap" elements.

While four node numbers are required to define this type of "surface condition", opposed nodal coordinates may coincide. That is, an "element" may have zero thickness.

2.12 BULK NODES

The bulk node concept is best described with the aid of the following figure:

Here a bulk node "B" is used to represent the entire volume of a particular material such as a gas in a cavity. The heat flow between the bulk node (material) "B" and an adjoining surface "S" is given, in general, by

$$q = f(\theta, t) (\theta_S^a - \theta_B^a)^b \quad (25)$$

where θ_S and θ_B represent the temperatures of the surface "S" and the bulk node "B" respectively. In addition, the density, specific heat and volume of the bulk material are specified.

Equation (25) is of the same general form as Equation (23) and (24) in the preceding two sections and can be specialized to specific cases in the same manner as described in Section 2.10.

TACO requires that a bulk node be given a node number as well as coordinates. However, these coordinates in general are arbitrary.

The bulk node concept can also be used in the case where it is desired to specify a lumped heat capacity at a node. In such a case, no segments "S" are associated with the bulk node and only the density, heat capacity and volume associated with the bulk node are specified.

2.13 ENCLOSURE RADIATION

TACO has the capability of solving problems of diffuse gray body radiation in an enclosure coupled with conduction in the material surrounding the enclosure. For convenience, TACO calculates the necessary view factors internally so that data preparation and input are minimized. However, the option to input view factors is available should the user desire.

A detailed discussion of the enclosure radiation capabilities of TACO is contained in Appendix B.

2.14 FUNCTION DEFINITIONS

Any specified function of time or temperature (i.e., material properties, thermal loadings, boundary conditions) can be described by either piecewise linear curve or by a functional relationship defined in a user subprogram.

A typical piecewise linear curve is shown below.

Values of a function at intermediate points on a curve are obtained by linear interpolation. Functional values outside the range of a curve are extrapolated as constants (dashed lines).

Except for the case of specific heat and conductivity a single curve may be used for several functions if their ordinates differ by only a constant. This is accomplished by the use of curve multipliers which are applied to the ordinate of the curve.

In order to differentiate between a function of time and a function of temperature, the sign on the number assigned to the curve describing the function is used. For a time variation, the curve number is positive and for a temperature variation, the curve number is preceded by a negative sign. A curve number of zero indicates that a function is constant.

If it is desired to use a functional representation other than a piecewise linear curve, the user subprogram option can be used. This option is described in the next section.

2.15 USER SUBPROGRAM

A user subprogram option is available in TACO whereby any type of functional relationship(s) may be defined. In this case, the user provides a subprogram which can contain any number of its own subroutines. The user subprogram is compiled separately and loaded with the appropriate TACO binary files to create a separate controllee.

User subprogram functions are handled in the same way as the piecewise linear functions of the preceding section. That is, positive curve numbers indicate time variations while negative signs on curve numbers designate temperature variations. In order to distinguish a function provided by a user subprogram, a curve number greater than 999 (in absolute value) is assigned.

The details necessary for implementation of the user subprogram option are contained in Appendix A.

2.16 PHASE CHANGES

A phase change can be approximated in TACO by defining a heat capacity curve with a discontinuity such as illustrated in the figure below.

The cross-hatched rectangular area under the curve is equal to $\rho\lambda$ where ρ is the density and λ is the latent heat of the material. The width of the rectangular is given by $\theta_L - \theta_S$ where θ_L is the liquidus temperature and θ_S is the solidus temperature. Thus, the height of the rectangular is $\rho\lambda/(\theta_L - \theta_S)$.

For a material, such as a pure metal, where a phase change occurs at a unique temperature θ_M instead of over a temperature range bounded by θ_S and θ_L , it is necessary to define fictitious values of θ_S and θ_L by

$$\theta_S = \theta_M - \Delta\theta$$

$$\theta_L = \theta_M + \Delta\theta$$

where $\Delta\theta$ is some small temperature interval.

In TACO density ρ and specific heat c_p are specified separately so that the ordinate of the ρc_p versus θ curve must be divided by ρ to obtain the specific heat curve.

Care must be exercised in choosing the time step Δt for problems involving phase transformations. Several trials may be required to determine a time step small enough to avoid missing the latent heat effect associated with the phase change (rectangular part of ρc_p curve above). The variable time step option may be found useful in such problems.

2.17 CHEMICAL KINETICS

Calculations involving chemical reactive kinetics are handled in TACO through the user subprogram option. Subprograms have been developed for several types of reactive kinetics. These subprograms and instructions on their use may be obtained from the author.

2.18 UNITS

Any set of units may be used in TACO. However, all units must be consistent with the governing equations. An example of a consistent set of units is given in the table below.

<u>QUANTITY</u>	<u>SYMBOL</u>	<u>Units</u>
Temperature	θ	$^{\circ}\text{C}$
Spatial coordinate	x_i	m
Time	t	s
Density	ρ	kg/m^3
Specific heat	c_p	$\text{J}/\text{kg} \cdot ^{\circ}\text{C}$
Thermal conductivity	k	$\text{W}/\text{m} \cdot ^{\circ}\text{C}$
Heat generation rate per unit volume	Q	W/m^3
Heat flux per unit area	q	W/m^2

(Note: The kg in the density represents kilogram mass).

2.19 TRANSIENT ANALYSIS

TACO has both fixed and variable time step capabilities. In addition, any number of fixed time step blocks may be specified allowing for variation of time step size in a stepwise fashion.

In order to insure accuracy, it is often necessary to make more than one run using different time step parameters. For example, if a fixed time step of Δt were used, it may be advisable to make a second run with a time step of $\frac{1}{2} \Delta t$ and the solutions compared to see if the time step is small enough.

2.20 STEADY STATE ANALYSIS

As an implicit code, TACO can obtain a steady-state solution in one step. However, if the time to reach steady state is required, then a transient analysis must be performed.

Initial estimates for nodal temperatures in nonlinear steady state problems may be input in place of initial conditions for transient problems.

2.21 MESH GENERATION

TACO has no general mesh generation of capability. Rows of evenly spaced nodes and rows of sequential elements may be generated. However, TACO relies on separate two-dimensional mesh generation codes (e.g., (4) and (5)) for complex zoning. The output from the mesh generation code is used to provide the nodal point and element data for TACO (see Sections 5.3 and 5.4). This data is then combined with the necessary additional data (Section 5) to construct the input deck or file for TACO. To avoid possible difficulties, the user is cautioned to request a complete ("long") list of nodal and element data when using a mesh generation code.

2.22 BANDWIDTH AND PROFILE MINIMIZATION

The Gibbs-Poole-Stockmeyer algorithm (8) for determining a nodal numbering scheme to minimize the bandwidth and profile of the K^* matrix is available as an option in TACO. The result of the selection of this option is essentially transparent to the user. The original and minimized bandwidth and profile data is printed. However, all nodal temperature data is written in terms of the user's original nodal numbering scheme.

2.23 POST PROCESSING

A companion post processor, POSTACO (1), is available for producing graphical output for data generated by TACO. POSTACO reads the binary plot files produced by TACO and can generate several types of plots. These include contour plots, nodal time history plots, and plots of temperature vs. distance along arbitrary cut lines.

2.24 THERMAL STRESS ANALYSIS

The temperatures calculated by TACO can be used in performing uncoupled thermal stress analyses with mechanical codes (e.g., (7)) These codes can read the temperature states from the binary plot files generated by TACO.

3. AVAILABILITY

At Lawrence Livermore Laboratory TACO is available as a controllee on the OCTOPUS system. On the CDC 7600 computers, it resides in GLGLIB and can be obtained as follows:

EXE GLGLIB TACO DR. / t v

On the CRAY computer, TACO is in MDGLIB and can be extracted with

LIB MDGLIB!X TACO!END / t v

4. EXECUTION

TACO may be executed directly from the teletype or indirectly through a batch processor.

The execution line is as follows:

TACO I=infile,O=printfile,P=plotfile,BOX=(ann id) / t v

Here infile denotes the name given to the input file described in the User's Guide which follows. The name printfile is given to the BCD print file and plotfile denotes the root name of the familled binary plot files produced by TACO. The entries ann and id are the user's box number and output identifier. Entries infile, printfile, and plotfile are limited to six characters or less. The entries are order independent.

File name dropouts are permitted on the execution line. Some examples follow:

TACO I=infile,P=plotfile,BOX=(ann id) / t v

TACO P=plotfile,I=infile,O=printfile / t v

TACO P=plotfile / t v

TACO I=infile,BOX=(ann id) / t v

If infile is omitted, the name "TACOIN" is assumed. If printfile is omitted, the print file name "PRINT" is used. Omission of plotfile results in the name "TPLOT" being assigned as the plot file root name. The "BOX=(ann id)" information may be omitted unless execution is through a batch processor.

4. EXECUTION (cont'd.)

Plot files created by TACO are famlied by appending a numeral starting with "01" to the root name plotfile. For example, if plotfile is "PLOT", the files will be famlied as

PLOT, PLOT01, PLOT02, PLOT03,...

Appendix C describes the plot file data base.

5. TACO USER'S GUIDE

The following pages contain the instructions necessary to enable the user to construct the input file (data deck) required by TACO. In addition, a section (5.18) describes some interactive controls available to the user during interactive execution from a terminal.

5.1. TITLE CARD

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-64	8A8	Heading to appear on output	1

NOTE: 1. Any number of additional heading cards may be included. However, these additional cards must have the character "&" in column 1.

Cards with the character "&" in column 1 can be placed anywhere in the data deck for use as comment cards or as spacers. All such cards are ignored by TACO.

If the word "STOP" is encountered in the first four columns, execution is terminated. Therefore, to be safe, the last card in the data should be a "STOP" card.

5.2 CONTROL CARDS

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Number of nodal points.	
6-10	I5	Number of elements.	
11-15	I5	Number of materials.	
16-20	I5	Number of elements with internal heat generation.	1
21-25	I5	Number of nodes at which nonzero initial temperatures are specified.	2
26-30	I5	Number of nodes at which temperature boundary conditions are specified.	3
31-35	I5	Number of boundary segments on which flux boundary conditions are specified.	4
36-40	I5	Number of boundary segments on which convection boundary conditions are specified.	
41-45	I5	Number of boundary segments on which nonlinear boundary conditions are specified.	
46-50	I5	Number of special internal boundary elements.	
51-55	I5	Number of bulk nodes. (See Section 5.13.)	
56-60	I5	Number of boundary segments associated with bulk nodes. (See Section 5.13.)	
61-65	I5	Number of segments involved with radiation in enclosures. (See Section 5.14.)	
66-70	I5	Number of piecewise linear curves used to describe time and/or temperature variations of material properties, thermal loadings or boundary conditions.	
71-75	I5	Data Check Code (IDATA) IDATA = -1: normal execution without printout of nodal point and element input data IDATA = 0: normal execution with complete data printout IDATA = 1: data check only	
76-80	I5	Bandwidth and Profile Minimization Code (IBAND) IBAND = 0: no minimization IBAND = 1: minimization	

CONTROL CARDS (cont'd.)

- NOTES:
1. Heat generation rates may be specified by element or by material (see Sections 5.5-5.6). However, the total number of elements must be given here.
 2. Initial nodal temperatures may be specified either on nodal coordinate cards or on separate cards (see Sections 5.3 and 5.7) or both. Two values given for the same node will be added. The number given here refers to those values input separately (Section 5.7).
 3. While referred to as temperature "boundary conditions", any nodal temperature may be specified whether on a boundary or not.
 4. While referred to as "boundary segments", fluxes may be specified on any element boundary whether it is interior to the region or is, in fact, on the region boundary.

CONTROL CARDS (cont'd.)

Card 2

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Type of geometry (IGEOM) IGEOM = 0: axisymmetric IGEOM = 1: plane (DEFAULT : IGEOM = 0)	
6-10	I5	Spatial Gaussian integration order (NGIO) $1 \leq \text{NGIO} \leq 4$ (DEFAULT: NGIO = 2)	
11-20	E10.0	Scale factor for geometry XLENG (DEFAULT: XLENG = 1.0)	

CONTROL CARDS (cont'd.)

Card 3

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Transient analysis code (ITRAN) ITRAN = 0: steady state ITRAN = 1: transient Skip the remaining entries if ITRAN = 0	
6-10	I5	Time step code (ISTEP) ISTEP = 0: fixed time step ISTEP = 1: variable time step	
11-15	I5	Output print interval (IPRNT) (DEFAULT: IPRNT = 1)	2
16-20	I5	Output plot interval (IPLOT) (DEFAULT: IPLOT = 1)	2
21-30	E10.0	Initial time (TIMEIN) (DEFAULT: TIMEIN = 0.0)	
31-40	E10.0	Initial temperature of entire body (TEMPIN) (DEFAULT: TEMPIN = 0.0)	1
41-50	E10.0	Time integration parameter (ALPHA) (DEFAULT: ALPHA = 0.5)	

- NOTES: 1. Initial temperatures may also be input as individual nodal values (see Sections 5.3 and 5.7). In such cases, the value given here (TEMPIN) will be assigned to all nodes except those whose initial temperatures are prescribed elsewhere. In nonlinear steady state problems TEMPIN may be used as an initial temperature estimate for the iterative solution process.
2. The initial temperatures and the temperatures at the last time step will always be printed and plotted unless printing or plotting is suppressed. Printing or plotting can be suppressed by setting either IPRNT or IPLOT respectively equal to a negative number.
3. The default of ALPHA=0.5 does not allow the time integration parameter to be set to exactly zero. If it is desired to set ALPHA=0.0, use a very small value (e.g., 1.0E-10) instead.

Card 4

Skip if steady state solution (ITRAN = 0)

Fixed Time Step (ISTEP=0)

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	E10.0	Time step size (DT)	
11-20	E10.0	Maximum time (TMAX)	1

Variable Time Step (ISTEP=1)

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	E10.0	Initial time step (DT)	
11-20	E10.0	Maximum Time (TMAX)	
21-30	E10.0	Minimum time step (DTMIN) (DEFAULT: DTMIN = 1.E-10)	2
31-40	E10.0	Maximum time step (DTMAX) (DEFAULT: DTMAX = 1.E+10)	2
41-50	E10.0	Maximum nodal temperature change below which time step will be increased (DELMIN) (DEFAULT: DELMIN = 1.0)	3
51-60	E10.0	Maximum nodal temperature change above which time step will be decreased (DELMAX) (DEFAULT: DELMAX = 10.0)	3
61-70	E10.0	Modification factor for decreasing time step (DTDEC) ($DT = DT/DTDEC$) (DEFAULT: DTDEC = 2.0)	
71-80	E10.0	Modification factor for increasing time step (DTINC) ($DT = DT*DTINC$) (DEFAULT: DTINC = 2.0)	

CONTROL CARDS (cont'd.)

- NOTES:
1. A fixed time step size may be changed during execution with the NEWSTEP option described in Section 5.16.
 2. A calculated time step of less than the minimum step size (DTMIN) will result in a termination of execution. A calculated time step of greater than the maximum step size (DTMAX) will be replaced by DTMAX.
 3. At each time step, the node at which the maximum temperature change (in absolute value) occurs will be determined. If the maximum temperature change is less than DELMIN, the time step will be increased. If the maximum temperature change is greater than DELMAX, the step size will be decreased and the time step started over.

CONTROL CARDS (cont'd.)

Card 5

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Nonlinear Solution Code (INON) INON = 0: linear analysis INON = 1: nonlinear analysis Skip remaining entries if INON = 0	
6-10	I5	Number of time steps between effective conductivity matrix reformations (NTREF) (DEFAULT: NTREF = 1)	1
11-15	I5	Number of time steps between equilibrium iterations (NITER) (DEFAULT: NITER = 1)	
16-20	I5	Maximum number of equilibrium iterations permitted per reformation (ITMAX) (DEFAULT: ITMAX = 15)	2
21-25	I5	Maximum number of effective conductivity matrix reformations per time step (NREFMAX) (DEFAULT: NREFMAX = 5)	
26-40	E15.0	Convergence tolerance for equilibrium iterations (TOL) (DEFAULT: TOL = 0.001)	

NOTES: 1. If the time step changes, a reformation is made regardless of the value of NTREF.

2. If no reformation is made within a time step, ITMAX is the maximum number of iterations permitted within the time step. For nonlinear, steady-state problems, the default value is ITMAX = 1.

CONTROL CARDS (cont'd.)

Card 6

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	15	Temperature unit code (IUNITS) IUNITS = 0: dimensionless IUNITS = 1: Centigrade IUNITS = 2: Kelvin IUNITS = 3: Fahrenheit IUNITS = 4: Rankine	

5.3 NODAL POINT DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node point number	1
6-10	5X	Skip	
11-20	E10.0	x- or r-coordinate	1
21-30	E10.0	y- or z-coordinate	1
31-40	E10.0	Initial temperature	2
41-45	I5	Generation increment (INC)	1
		(DEFAULT: INC = 0)	

NOTES: 1. Node point cards need not be in order. However, the highest node number must terminate the data. When data is missing, node numbers are generated according to the sequence

$$N_i, N_i+INC, N_i+2*INC, \dots, N_j$$

where N_i and N_j are the node numbers on two consecutive cards and INC is read from the N_j card. Linear interpolation is used to calculate the coordinates of the generated nodes. If INC is zero or blank, no nodes are generated.

2. Any non-zero values read here will replace those nodal temperatures assigned the value TEMPIN in Section 5.2 (Card 3). Initial nodal temperatures may also be input separately in Section 5.7. Initial temperatures may be used as initial estimates for iterative solutions of nonlinear steady state problems.

5.4 ELEMENT DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Element number	1
6-10	I5	Node N_1	1
11-15	I5	Node N_2	1
16-20	I5	Node N_3	1
21-25	I5	Node N_4	1
26-30	I5	Element material number	1
31-35	I5	Number of elements to be generated following this one	1
36-40	I5	Generation increment (INC) (DEFAULT: INC = 1)	1
41-50	E10.0	Angle ψ (in degrees) as defined in Section 5.5	

NOTE: 1. Element cards need not be in order. However, the number of cards plus the number of elements generated must equal the total number of elements specified on the first control card. When elements are generated, the element numbers are incremented by one following the first number in the sequence and the node numbers are incremented according to

$$N_j^{i+1} = N_j^i + \text{INC} \quad (i=1,2,3,4)$$

Element node numbers N_1 - N_4 can begin at any one of the four nodes but must be numbered counterclockwise around an element.

5.5 MATERIAL PROPERTY DATA

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	A10	Material identification	
11-15	I5	Material identification number	1
16-20	I5	Material type (MTYPE)	2,3
		MTYPE = 0: null material	
		MTYPE = 1: isotropic	
		MTYPE = 2: globally orthotropic	
		MTYPE = 3: locally orthotropic	
21-30	E10.0	Density ρ	
31-35	I5	Curve number for specific heat c_p	4
36-50	E15.0	Specific heat if curve number is zero	
51-55	I5	Curve number for heat generation rate Q	4
56-70	E15.0	Curve multiplier for heat generation rate Q	

Card 2

Material Type 1 (Isotropic)

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Curve number for thermal conductivity k	4
6-20	E15.0	Thermal conductivity k if curve number is zero	

Card 2 (cont'd.)

Material Types 2 and 3 (Orthotropic)

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Curve number for thermal conductivity k_1	4
6-20	E15.0	Thermal conductivity k_1 if curve number is zero	
21-25	I5	Curve number for thermal conductivity k_2	4
26-40	E15.0	Thermal conductivity k_2 if curve number is zero	
41-50	E10.0	Global material angle ψ_G (in degrees) if material type 2	3

- NOTES: 1. The material identification numbers must be less than or equal to the number (NUMMAT) given on the first control card (Section 5.2). The total number of materials identified must equal NUMMAT.
2. If MTYPE = 0, any elements with the corresponding material identification number will be deleted.
3. Material orthotropy may be specified either globally or locally. In the case of a global definition, a global material angle is defined as in the following figure where x_1 and x_2 denote the material axes:

Card 2 (cont'd.)

For the case of locally specified material orthotropy, an angle ψ is defined for each element as follows

The individual angles ψ are input in the element definitions Section 5.4).

4. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative, and zero curve numbers respectively.

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

5.6. HEAT GENERATION DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Element number	1,2
6-10	I5	Curve number for heat generation rate Q	3
11-20	E10.0	Curve multiplier for Q	4
21-25	I5	Number of elements to be generated following this one	1
26-30	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

- NOTES:
1. Heat generation cards need not be in order. When elements are generated, the element numbers are incremented by INC as in the case of element cards (Section 5.4). The number of cards plus the number generated must equal the total number specified on the first control card. Curve numbers and multipliers are set to the the same value for each element in the sequence.
 2. Heat generation may also be specified by material (see Section 5.5). If an element has heat generation specified both by element and by material, the effect will be additive.
 3. A curve number with a positive sign indicates time dependent heat generation. A curve number with a negative sign indicates that the heat generation is temperature dependent. A curve number of zero indicates constant heat generation rate.

A curve number of greater than 999 indicates a user subroutine is used to provide heat generation rates. The positive and negative signs is used, as above, to indicate time or temperature variation.
 4. If a curve number of zero is given, the curve multiplier then becomes the constant heat generation rate.

5.7 INITIAL TEMPERATURE DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node number	1
6-20	E15.0	Initial temperature	2
21-25	I5	Number of nodes to be generated following this one (NMISS)	1
26-30	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

- NOTES: 1. Initial temperature cards need not be in order. When data is generated, node numbers are incremented according to the sequence

$$N_i, N_i+INC, N_i+2*INC, \dots, N_i+NMISS*INC$$

The number of cards in this section plus the number generated must equal the number indicated on the first control card (Section 5.2).

2. Initial nodal temperatures may also be input in Section 5.3. Values of initial nodal temperature given in this section will replace any previously specified values.

5.8 NODAL TEMPERATURE SPECIFICATION

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node number	1
6-10	I5	Time function curve number	2
11-20	E10.0	Curve multiplier	2
21-25	I5	Number of nodes to be generated following this one (NMISS)	1
26-30	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

NOTES: 1. Nodal temperature specification cards need not be in order. When data is generated, node numbers are incremented according to the sequence

$$N_i, N_i+INC, N_i+2*INC, \dots, N_i+NMISS*INC$$

The number of cards in this section plus the number generated must equal the number indicated on the first control card (Section 5.2).

2. In order to specify a constant value of nodal temperature, set the curve number to zero and the multiplier to the desired value.

5.9 FLUX BOUNDARY CONDITION DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node N_1	1
6-10	I5	Node N_2	1
11-15	5X	Skip	
16-20	I5	Curve number for flux	3
21-30	E10.0	Curve multiplier at node N_1	2,4
31-40	E10.0	Curve multiplier at node N_2	2,4
41-45	I5	Number of segments to be generated following this one	1
46-50	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

NOTES: 1. Flux boundary condition segment cards need not be any numerical order. When segments are generated, the node numbers will be incremented according to

$$N_j^{i+1} = N_j^i + \text{INC} \quad (j=1,2)$$

The number of cards in this section plus the number of segments generated must equal the number given on the first control card (Section 5.2).

2. Flux on a boundary segment is allowed to vary in a linear fashion as shown below.

FLUX BOUNDARY CONDITION DATA (cont'd.)

NOTES: 3. A positive curve number indicates a time dependent flux. A curve number preceded by a negative sign indicates a temperature dependent flux. A curve number of zero indicates a constant flux.

A curve number of greater than 999 indicates a user subroutine is provided for flux values. The positive and negative sign is used, as above, to indicate time or temperature variation.

4. If a curve number is zero, the curve multipliers then become the constant segment end point flux values.

5.10 CONVECTION BOUNDARY CONDITION DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node N_1	1
6-10	I5	Node N_2	1
11-15	5X	Skip	
16-20	I5	Function curve number for heat transfer coefficient h	2
21-30	E10.0	Curve multiplier for h	3
31-35	5X	Skip	
36-40	I5	Time function curve number for convective equilibrium temperature θ_∞	2
41-50	E10.0	Curve multiplier for θ_∞ at node N_1	3.4
51-60	E10.0	Curve multiplier for θ_∞ at node N_2	3.4
61-65	I5	Number of segments to be generated following this one	1
66-70	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

NOTES: 1. Convection boundary condition segment cards need not be in any numerical order. When segments are generated, the node numbers will be incremented according to

$$N_j^{i+1} = N_j^i + \text{INC} \quad (j=1,2) .$$

The number of cards in this section must equal the number given on the first control card (Section 5.2).

2. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative and zero curve numbers respectively.

CONVECTION BOUNDARY CONDITION DATA (cont'd.)

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

Convective equilibrium temperatures should be either functions of time or constants (i.e., curve numbers should not be negative).

3. If a curve number is zero, the curve multipliers then become the constant values being specified for the function.
4. Convective equilibrium temperatures are allowed to vary in a linear fashion along a segment by specifying separate values at each end of the segment.

5.11 GENERAL NONLINEAR BOUNDARY CONDITION DATA

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node N_1	2
6-10	I5	Node N_2	2
11-15	5X	Skip	
16-20	I5	Function curve number for coefficient f	3
21-30	E10.0	Curve multiplier for f	4
31-35	5X	Skip	
36-40	I5	Time function curve number for equilibrium temperature θ_∞	3
41-50	E10.0	Curve multiplier for θ_∞ at node N_1	4
51-60	E10.0	Curve multiplier for θ_∞ at node N_2	4
61-70	E10.0	Exponent "a"	1
71-80	E10.0	Exponent "b"	1

Card 2

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Number of segments to be generated following this one	2
6-10	I5	Generation increment (INC) (DEFAULT: INC = 1)	2

NOTES: 1. General nonlinear boundary conditions are of the form

$$q = f(\theta, t) \left[\theta^a - \theta_\infty^a(t) \right]^b$$

(See Section 2.10 for a detailed discussion.)

GENERAL NONLINEAR BOUNDARY CONDITION DATA (cont'd.)

2. Boundary segment cards need not be in any numerical order. When segments are generated, the node numbers will be incremented according to

$$N_j^{i+1} = N_j^i + INC(j-1,2) .$$

The number of segment cards read in this section plus the number generated must equal the number given on the first control card (Section 5.2).

3. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative and zero curve numbers respectively.

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

Equilibrium temperatures should be either functions of time or constants (curve numbers should not be negative).

4. If a curve number is zero, the curve multipliers then become the constant values being specified for the function.

Equilibrium temperatures are allowed to vary in a linear fashion along a segment by specifying separate values at each end of the segment.

5.12 INTERNAL SURFACE CONDITION DATA

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node N_1	1,2
6-10	I5	Node N_2	1,2
11-15	I5	Node N_3	1,2
16-20	I5	Node N_4	1,2
21-25	5X	Skip	
26-30	I5	Curve number for coefficient f	3
31-40	E10.0	Curve multiplier for f	4
41-50	E10.0	Exponent "a"	1
51-60	E10.0	Exponent "b"	1
61-65	I5	Number of segments to be generated following this one	2
66-70	I5	Generation increment (INC) (DEFAULT: INC = 1)	2

NOTES: 1. Internal surface conditions are of the form

$$q = f(\theta, t) \left[\theta_A^a - \theta_B^a \right]^b$$

Four nodes are required to define an internal surface condition. These nodes should be numbered as shown in the following figure:

INTERNAL BOUNDARY CONDITION DATA (cont'd.)

Surface "A" should be defined by nodes N_1 and N_2 and surface "B" by nodes N_3 and N_4 . No two node numbers may be the same. However, nodes N_1 and N_4 can have the same coordinates. Likewise for N_2 and N_3 .

2. These cards need not be in any numerical order. However, the number of cards plus the number of elements generated must equal the total number of elements specified on the first control card. When elements are generated, the element numbers are incremented by one following the first number in the sequence and the node numbers are incremented according to

$$N_j^{i+1} = N_j^i + INC \quad (j=1,2,3,4)$$

3. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative, and zero curve numbers respectively.

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

4. If a curve number is zero, the curve multipliers then become the constant values being specified for the function.

5.13 BULK NODE DATA

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Bulk node number	1
6-10	I5	Material number of bulk node	1
11-15	I5	Number of boundary segments associated with this bulk node (NBNSEG)	2
16-30	E15.0	Total volume associated with this bulk node	1

- NOTES: 1. The number of bulk nodes input must be equal to the number indicated on the first control card (Section 5.2). Each bulk node must be assigned a material number. This allows the density and specify heat for the material represented by a bulk node to be input in Section 5.5. The total volume of material represented by each bulk node is required to be input also.
2. The number of element boundary segments (NBNSEG), associated with each bulk node must be given. The total number of segments for all of the bulk nodes must equal the number indicated on the first control card (Section 5.2). A lumped heat capacity for a node may be specified by identifying a bulk node with no associated boundary segments (NBNSEG = 0).

Card 2

Omit if NBNSEG = 0.

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1- 5	I5	Node N_1	2
6-10	I5	Node N_2	2
11-15	5X	Skip	
16-20	I5	Curve number for coefficient f	3
21-30	E10.0	Curve multiplier for f	4
31-40	E10.0	Exponent "a"	1
41-50	E10.0	Exponent "b"	1
51-55	I5	Number of segments to be generated following this one	2
56-60	I5	Generation increment (INC) (DEFAULT: INC = 1)	2

NOTES: 1. The heat flow equation for a bulk node is of the form

$$q = f(\theta, t) \left[\theta_S^a - \theta_B^a \right]^b$$

(See Section 2.14 for a detailed discussion.)

2. These cards need not be in any numerical order. When segments are generated, the element numbers are incremented by one following the first number in the sequence and the node numbers are incremented according to

$$N_j^{i+1} = N_j^i + \text{INC} \quad (j=1,2)$$

3. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative, and zero curve numbers respectively.

BULK NODE DATA (cont'd.)

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

4. If a curve number is zero, the curve multipliers then become the constant values being specified for the function.

5.14 ENCLOSURE RADIATION DATA

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-5	I5	Segment number	1,2
6-10	I5	Node N_1	1,2
11-15	I5	Node N_2	1,2
16-20	I5	Curve number for emissivity	3
21-30	E10.0	Curve multiplier for emissivity	4
31-35	I5	KFLAG, flag indicating whether segment participates in conduction part of problem, KFLAG = 1, segment participates KFLAG = 1, no participation	5
36-40	I5	Number of segments to be generated following this one	1
41-45	I5	Generation increment (INC) (DEFAULT: INC = 1)	1

NOTES: 1. The number of segments participating in enclosure radiation which are input must be equal to the number indicated on the first control card. Segments must have a number assigned to them such as shown in the example below.

19	20	21	22	23
14	15	16	17	18
		11	12	13
6	7	8	9	1
1	2	3	4	5

Segment No.	Node N_1	Node N_2
1	7	6
2	8	7
3	11	8
4	16	11
5	15	16
6	14	15
7	6	14

5.14 ENCLOSURE RADIATION DATA (cont'd.)

2. Segment cards need not be in order. When segments are generated, the segment numbers are incremented by one following the first number in the sequence and the node numbers are incremented according to

$$N_j^{(1)} = N_j + \text{INC} \quad (j=1,2)$$

Segment code number must be ordered in the clockwise direction around the enclosure (see above figure).

3. Time dependent, temperature dependent, and constant functional relations are indicated by positive, negative, and zero curve numbers respectively.

Curve numbers greater than 999 in absolute value indicate that a user subroutine is being provided to evaluate particular functions.

4. If a curve number is zero, the curve multipliers then become the constant values being specified for the function.
5. It is often necessary to set the temperature of a segment θ_k equal to a fixed value and the emissivity $\epsilon_k = 1.0$. Such would be the case of Segment No. 7 in the figure for Note 1 where the segment is used to represent the opening of a cavity to an external radiative environment of a fixed temperature. In order to accomplish this within TACO, the curve multiplier for emissivity is given a value equal to the negative of the desired temperature.
6. Segments which only participate in the radiation part of the problem and not, directly, in the conduction part should be indicated by setting $KFLAG = 1$. Segment No. 7 illustrated in the figure with Note 1 is such a segment. Segments with $KFLAG = 1$ will be indicated in the printout by a "*" appended to the segment number.

5.14 ENCLOSURE RADIATION DATA (cont'd.)

Card 2

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-5	I5	Symmetry code (ISYM) ISYM=0: no symmetry ISYM=1: symmetry about x- or r-axis ISYM=2: symmetry about y-axis ISYM=3: symmetry about both axes	
6-10	I5	Code for view factors (NVIEW) NVIEW=0: view factors are calculated NVIEW≠0: NVIEW view factors are read	
11-20	E10.0	Stefan-Boltzmann constant	
21-25	I5	Number of divisions per segment in view factor calculations (NDIV), (DEFAULT: NDIV=10)	1
26-30	I5	View factor print flag (IVP) IVP=0: view factors not printed IVP=1: view factors printed	
31-35	I5	View factor file flag (IVFILE) IVFILE= 1: view factors written into BCD file named "VIEWS" IVFILE= 0: view factors not written IVFILE=-1: view factors are read from file named "VIEWS"	

NOTES: 1. The larger the value of NDIV, the more computer time will be required to calculate the view factors. If no segments are partially obstructed from the view of any other segments, NDIV = 1 will give accurate values for view factors. If partial obstructions exist, the larger the value of NDIV, the more accurate the calculated view factors will be.

5.14 ENCLOSURE RADIATION DATA (cont'd.)

Card 3

Skip if NVIEW=0 or IVFILE=-1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-5	I5	Number of segment k	1
6-10	I5	Number of segment j	1
11-20	E10.0	View factor F_{k-j}	1

NOTES: 1. Cards defining view factors for all surfaces to be included in the radiation calculations must be input (Total = NVIEW). Surfaces between which view factors are omitted are assumed to have view factors of zero.

5.15 PIECEWISE LINEAR CURVE DATA

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	A10	Curve identification	
11-15	I5	Curve number	1
16-20	I5	Number of points in curve (NPTS)	

Card 2

Repeat for NPTS Points

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	E10.0	Time or temperature	2
11-20	E10.0	Functional value	

- NOTES: 1. Curve numbers as described here must always be positive even if the curve was given a negative number to indicate a temperature dependent function in another section.
2. Curve point coordinates must be in order starting with the lowest time or temperature.

5.16 BLOCK TIME STEP OPTION

Card 1

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-7	A7	Word "NEWSTEP"	1

Card 2

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-10	E10.0	New time step size (DT)	2
11-20	E10.0	New maximum time (TMAX)	

- NOTES: 1. After execution with the fixed time step option (Control Card No. 4), TACO will read a new title card. If it finds this entry, it will read the next card and resume execution. This process may be repeated as many times as desired.
2. The printing and plotting intervals specified on Control Card No. 3 remain unchanged. Temperatures at the end of the first new time step and at the new maximum time will always be printed and plotted unless suppressed by giving negative intervals on Control Card No. 3.

5.17 "NEWFILE" OPTION

<u>Columns</u>	<u>Format</u>	<u>Entry</u>	<u>Note</u>
1-7	A7	Word "NEWFILE"	1

- NOTE: 1. After execution TACO will attempt to read a new title card. If it finds this entry, it will create a new input file named NEWFILE which is identical to the original input file except that the initial time and time step size are set to the current values and the initial temperatures on the nodal cards (Section 5.3) are replaced by the current temperatures. The user can then restart the solution with this input file.

5.18 INTERACTIVE CONTROLS

Several interactive controls are available to the user when executing TACO via teletype. These controls allow the user to query the status of the code execution, to change time step size, or to terminate execution. The controls are utilized by typing keywords in a left-justified alphanumeric (A7) format. A list of keywords and their corresponding teletype responses follows.

<u>Keyword</u>	<u>Response</u>
TIME	Current time, time step size, and step number
TIMES	Time, time step size, and step number at the present and each following step
NOTIMES	Turns off effect of "TIMES"
NODES	Same as "TIMES" except that user is initially prompted from one to five node numbers whose temperatures are also typed out at each time step
NONODES	Turns off effect of "NODES"
NEWSTEP	Same as "NEWSTEP" option in Section 5.15 except teletype prompts for new time step size and maximum time which are then utilized starting at the next time step
STOP	Execution is terminated immediately in normal mode as with "STOP" card in Section 5.1
ABORT	Execution is terminated immediately in error mode with drop file retained

6. EXAMPLES

In this section the solutions for two example problems are shown. These problems were purposely chosen to have small numbers of elements and yet illustrate several of the capabilities of TACO. Both examples have exact solutions with which the numerical results can be compared.

6.1 EXAMPLE NO. 1

This a nonlinear, one-dimensional, steady-state problem which can be stated mathematically as follows:

$$\frac{d}{dx} \left(k \frac{d\theta}{dx} \right) + Q = 0 \quad 0 \leq x \leq L$$

$$k = A + B\theta$$

$$-k \frac{d\theta}{dx} = C (\theta^4 - \theta_{\infty}^4) \quad \text{at } x = 0$$

$$\theta = \theta_L \quad \text{at } x = L$$

For the set of numerical values

$$L = 1$$

$$C = 0.0025$$

$$A = 1$$

$$\theta_{\infty} = 4$$

$$B = -0.2$$

$$\theta_L = 1$$

$$Q = 0.2$$

the exact solution is

$$\theta = 2-x$$

6. EXAMPLES (cont'd.)

A finite element mesh with only two elements was used in the analysis. This mesh and the TACO input data used to this problem are shown in Figures 6.1 and 6.2.

Note that TACO requires a single layer of two-dimensional elements to analyze this problem. The problem is made one-dimensional by making the sides parallel to the x -axis adiabatic. TACO defaults to the adiabatic boundary condition and, thus, such conditions need not be specified in the input data.

In order to illustrate the convergence of the solution, the temperatures at $x = 0.0$ and $x = 0.5$ for each iteration are shown in the following table:

ITERATION NUMBER	TEMPERATURE	
	$x = 0.0$	$x = 0.5$
0	0.0	0.0
1	1.500	1.275
2	1.853	1.446
3	1.955	1.484
4	1.986	1.495
5	1.996	1.499
6	1.999	1.500
7	2.000	1.500

FIGURE 6.1. MESH FOR EXAMPLE NO. 1

```

TACO EXAMPLE NO. 1
8 CONTROL CARDS
8 CARD 1
6 2 1 0 0 2 0 0 1 0 0 0 0 1 0 0
8 CARD 2
1 2 1.0
8 CARD 3
0
8 CARD 4 (NOT REQUIRED)
8 CARD 5
1
8 CARD 6
0
8 NODAL POINT DATA
1 0.0 0.0 0.0
5 1.0 0.0 0.0 2
2 0.0 0.5 0.0
6 1.0 0.5 0.0 2
8 ELEMENT DATA
1 1 3 4 2 1 1 2
8 MATERIAL DATA
PSEUDO 1 1 1.0 0 1.0 0 0.2
-1
8 TEMPERATURE BOUNDARY CONDITIONS
5 0 1.0 1 1
8 NONLINEAR BOUNDARY CONDITIONS
2 1 0 0.0025 0 4.0 4.0 4.0 1.0
0
8 PIECEWISE LINEAR CURVE DATA
K-CURVE 1 2
0.0 1.0
5.0 0.0
STOP

```

FIGURE 6.2. INPUT DATA FOR EXAMPLE NO. 1

6. EXAMPLES (cont'd.)

6.2 EXAMPLE NO. 2

This is a linear, one-dimensional, transient problem. It is stated mathematically as follows

$$\rho c_p \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial \theta}{\partial x} \right) \quad 0 < x < L$$

$$\theta(0, t) = \theta_0$$

$$-k \frac{\partial \theta}{\partial x} (L, t) = h[\theta(L, t) - \theta_\infty]$$

$$\theta(x, 0) = \theta_0$$

The exact solution is

$$\begin{aligned} \theta(x, t) = & \theta_0 - (\theta_0 - \theta_\infty) \left(\frac{H}{1+H} \right) \left(\frac{x}{L} \right) \\ & + 2H(\theta_0 - \theta_\infty) \sum_{n=1}^{\infty} \frac{\sin \lambda_n L \sin \lambda_n x}{(\lambda_n L)^2 + H \sin^2 \lambda_n L} e^{-\lambda_n^2 \alpha t} \end{aligned}$$

where

$$\alpha = \frac{k}{\rho c_p} = \text{thermal diffusivity}$$

$$H = \frac{hL}{k} = \text{Biot number}$$

6. EXAMPLES (cont'd.)

and λ_n is obtained from

$$(\lambda_n L) \cot (\lambda_n L) = -H$$

The following specific numerical values were chosen for the analysis:

$$\rho = c_p = k = L = \theta_0 = 1$$

$$\theta_\infty = 0$$

$$h = 0.6$$

A five element mesh was used to analyze this problem. This mesh and the input data for one solution case are shown in Figures 6.3 and 6.4.

Figures 6.5 and 6.6 are time history plots at $x = 1$ for $\Delta t = 0.10$ and $\Delta t = 0.05$. Each plot contains curves obtained using $\alpha = 0.5$ (Crank-Nicholson) and $\alpha = 1.0$ (backward implicit) in addition to the exact solution curve.

Figure 6.7 is a plot of temperature versus position at time $t = 0.1$ for the $\Delta t = 0.1$ solution. Both the $\alpha = 0.5$ and $\alpha = 1.0$ curves are plotted as is the exact solution.

FIGURE 6.3. MESH FOR EXAMPLE NO. 2

```

TACO EXAMPLE NO. 2
8 CONTROL CARD NO. 1
12 5 1 0 0 2 0 1 0 0 0 0 0 0 0
8 CONTROL CARD NO. 2
1 2 1.0
8 CONTROL CARD NO. 3
1 0 1 1 6.0 1.0 0.5
8 CONTROL CARD NO. 4
0.1 1.0
8 CONTROL CARD NO. 5
0
8 CONTROL CARD NO. 6
0
8 NODAL DATA
1 0.0 0.0 0.0
11 1.0 0.0 0.0 2
2 0.0 0.2 0.0
12 1.0 0.2 0.0 2
8 ELEMENT DATA
1 1 3 4 2 1 4 2
8 MATERIAL DATA
PSEUDO 1 1 1.0 0 1.0 0 0.0
0 1.0
8 TEMPERATURE BOUNDARY CONDITIONS
1 0 1.0 1 1
8 CONVECTION BOUNDARY CONDITIONS
11 12 0 0.6 0 0.0 0.0
STOP

```

FIGURE 6.4. INPUT DATA FOR EXAMPLE NO. 2

FIGURE 6.5. TIME HISTORY AT $x = 1$ FOR $\Delta t = 0.1$

FIGURE 6.6. TIME HISTORY AT $x = 1$ FOR $\Delta t = 0.05$

FIGURE 6.7. TEMPERATURE VERSUS POSITION AT TIME $t = 0.1$ FOR $\Delta t = 0.1$

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8. REFERENCES

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APPENDIX A

USER SUBPROGRAM

As mentioned in Section 2.15, a user subprogram option is available in TACO. This option allows the user to write a separate subprogram with which to calculate functional values of quantities such as material properties and boundary conditions. This may be necessary in cases where the use of piecewise linear curves or constants as described in Section 2.14 are not sufficient or too cumbersome for describing a particular function. The purpose of this appendix is to explain how this option is implemented in TACO.

Functions defined by a user subprogram are handled in the same way as piecewise linear curves in that "curve" numbers are used to indicate which function is being evaluated. Positive curve numbers indicate functions of time and negative curve numbers indicate functions of temperature. In order to distinguish a function provided by a user subprogram, the curve number must be greater than 999 (in absolute value).

The user subprogram must be named "USUB" and must have five entry points including the call to USUB. The entry point names and their purposes are as follows:

USUB :To initialize and read data.

USUB2 :To calculate functional values.

USUB3 :To update variables which may not be common to TACO. For example, in chemical kinetics calculations, the reactant concentrations may be calculated in the user subprogram whereas TACO only requires the heat generated by the reactive process.

USUB4 :To print results of user subprogram calculations at desired intervals.

USUB5 :To plot results of user subprogram calculations at desired intervals.

Any of the entry points may be dummy entries (i.e., enter subprogram and return).

A simple example of a user subprogram is shown in the following listing (Note: some compilers such as CFT on the CRAY computers require the argument list to appear with each entry statement, e.g., entry USUB2 (N,T,F)):

```

1      SUBROUTINE USUB (N,T,F)
2 C
3 C      EXAMPLE USER SUBPROGRAM
4 C
5 C      THIS SUBPROGRAM CALCULATES VALUES FOR F=F(T)
6 C      FROM THE FOLLOWING TWO FUNCTIONAL REPRESENTATIONS.
7 C          1. F(T)=A*SIN(6.2831853*T/TAU)
8 C          2. F(T)=B*EXP(-BETA*T)
9 C
10 C      READ DATA
11 C
12 C      READ(5,1000) A,TAU,B,BETA
13 1000 FORMAT(4E10.0)
14 C
15 C      PRINT DATA
16 C      ("HEADER" STARTS NEW PAGE WITH TITLE AT TOP)
17 C
18 C      CALL HEADER
19 C      WRITE(6,2000) A,TAU,B,BETA
20 2000 FORMAT(1H0,6HA = ,E16.5 // 6HTAU = ,E16.5 //
21         6HB = ,E16.5 // 6HBETA = ,E16.5 //)
22 C
23 C      ENTRY POINT TO CALCULATE FUNCTIONAL VALUES
24 C          ABS(N)=1001 -> FUNCTION NO. 1
25 C          ABS(N)=1002 -> FUNCTION NO. 2
26 C          OTHERWISE ERROR EXIT (CALL ADIOS(2))
27 C
28 C      ENTRY USUB2
29 C          IF(ABS(N).EQ.1002) GO TO 200
30 C          IF(ABS(N).NE.1001) CALL ADIOS(2)
31 C          F=A*SIN(6.2831853*T/TAU)
32 C          GO TO 300
33 200 F=B*EXP(-BETA*T)
34 300 RETURN
35 C
36 C      ENTRY POINT TO UPDATE VARIABLES
37 C      (JUST NEED A DUMMY ENTRY HERE)
38 C      ENTRY USUB3
39 C      RETURN
40 C
41 C      ENTRY POINT TO PRINT RESULTS OF CALCULATIONS WITHIN "USUB"
42 C      (AGAIN A DUMMY ENTRY IS USED HERE)
43 C      ENTRY USUB4
44 C      RETURN
45 C
46 C
47 C      ENTRY POINT TO PLOT RESULTS OF CALCULATIONS WITHIN "USUB"
48 C      (AGAIN A DUMMY ENTRY IS USED HERE)
49 C      ENTRY USUB5
50 C      RETURN
51 C
52 C      END

```


Once the source file for USUB has been created, it must be compiled and then loaded with the necessary TACO binary files to obtain a controllee. This can be accomplished as follows:

1. Obtain the file TACORUN from storage on the CDC7600 computers with

EXE GLGLIB TACORUN DR. / t v

and on the CRAY computers with

LIB MDGLIB!X TACORUN!END / t v

2. Compile USUB and create new TACO controllee on the CDC7600 computers with

TRIX AC!O(TACORUN)!RUN!END / t v

and on the CRAY computers with

TRIXGL!O(TACORUN)!RUN!END / t v

The above steps will result in the automatic execution of several routines. These routines read files from storage as they are needed and destroy them when they are no longer required. Upon the successful completion of Step 2, the following files will remain:

TACO : A new controllee incorporating the user's subprogram

TACOM: The load map for TACO

TACO*: The symbol table for TACO

USUB : The user subprogram source

BSUB : The binary file for USUB

LSUB : The list file for USUB

APPENDIX B

ENCLOSURE RADIATION

B.1. INTRODUCTION

TACO has the capability to solve problems of conduction in a solid coupled with radiation in enclosures within the solid. Presently, only enclosures bounded by diffuse-gray surfaces can be treated. Also, only two-dimensional geometries (planar or axisymmetric) can be analyzed. This appendix briefly describes the theoretical basis for enclosure radiation and explains how the theory is implemented in TACO.

B.2. BASIC THEORY

The basis for the analysis of enclosure radiation as performed by TACO is the net-radiation method. This method is described in detail by Siegel and Howell (1).

In TACO an enclosure is defined by the N discrete surfaces which are, in general, the boundaries of the elements which surround the enclosure as illustrated in the following figure.

ENCLOSURE RADIATION (cont'd.)

The basis functions for the elements surrounding an enclosure are such that the temperature on an element boundary varies linearly between nodal points. However, for purposes of the enclosure radiation analysis, it is convenient to assign a constant value of temperature to each discrete enclosure surface. This temperature is obtained by averaging the values at the two nodes defining each enclosure surface.

Assuming that the temperature of each enclosure surface is known, Siegel and Howell (1) derive the following equations:

$$\sum_{j=1}^N \left[\delta_{kj} - (1-\epsilon_k)F_{k-j} \right] q_{0,j} = \epsilon_k \sigma \theta_k^4 \quad (\text{B.1})$$

$$q_{i,k} = \sum_{j=1}^N F_{k-j} q_{0,j} \quad (\text{B.2})$$

$$q_k = q_{0,k} - q_{i,k} \quad (\text{B.3})$$

where

- θ_k = absolute temperature of surface k
- $q_{0,k}$ = outgoing radiant energy per unit area (radiosity) from surface k
- $q_{i,k}$ = incoming radiant energy per unit area to surface k
- q_k = net energy flux leaving surface k
- ϵ_k = emissivity of surface k
- F_{k-j} = view or configuration factor from surface k to surface j
- δ_{kj} = Kronecker delta
- σ = Stefan-Boltzmann constant.

ENCLOSURE RADIATION (cont'd.)

In order to obtain the net energy flux q_k for surface k , the series of linear algebraic equations represented by Eq. (B.1) must first be solved for the radiosities $q_{0,j}$ ($j=1,2,\dots,N$). Equations (B.2) and (B.3) then combine to give q_k .

The above procedure is used by TACO to solve the radiation part of the coupled problem. At each time step, Equations (B.1-B.3) are solved using the θ_k values estimated from the previous time step. The resulting fluxes q_k are then used as boundary conditions for the solution of the conduction problem. This solution then gives new estimates for the surface temperatures θ_k . The process is then repeated until convergence is achieved. The solution then proceeds to the next time step.

The series of equations represented by Eq. (B.1) is solved by Gauss-Seidel iteration rather than by a direct method. This method of solution appears to work well and has the advantage of saving considerable computer storage.

B.3. VIEW FACTORS

The view or configuration factors required in Eq. (B.1) are normally calculated by TACO. However, the option to input view factors is available should the user desire to do so. In order to properly calculate the view factors TACO requires that the nodes describing the enclosure surfaces be input in order as they appear when proceeding clockwise around the enclosure (see Section 5.14).

B.4 SYMMETRY

When planes of symmetry are used to reduce the size of a problem, the conduction "boundary conditions" become $q=0$ (i.e., adiabatic). However, in the case of enclosure radiation, a plane of symmetry does not imply that $q=0$. In this case the symmetry plane acts like a mirror reflecting radiant energy back to the mirror images of surfaces beyond the plane as illustrated below.

ENCLOSURE RADIATION (cont'd.)

TACO will account for this mirror effect of a symmetry plane. However, the user must describe the location of the symmetry planes in the input (Section 5.14).

B.5 INSULATED SURFACES

An insulated surface on an enclosure boundary can be defined by giving that surface an emissivity $\epsilon=0$. Otherwise, such a surface is treated the same as any other.

B.6 OPENINGS

When an enclosure has an opening to the exterior of a body, the opening acts like a nonreflective surface. Such a surface acts as a blackbody radiator ($\epsilon=1$) at the outer surrounding temperature. Therefore an opening may be specified in TACO by defining an enclosure boundary segment with $\epsilon=1$ and with a temperature equal to that of the outer surroundings.

B.7 REFERENCES

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APPENDIX C

PLOT FILE DATA BASE

As described in the section on execution, TACO creates a family of direct addressable binary plot files. The default length of each file is 1,000,000 octal (262,144 decimal) words. The format for these files is as follows:

CONTROL SECTION (64 words, 8 characters per word)

<u>Words</u>	<u>Description</u>
1-10	Title of problem
11	Time of day when run was begun
12	Date of run
13	Letter designator for computer on which run was made
14	Name of code ("TACO")
15	Compilation date of code
16	NDIM, number of dimensions (NDIM=2)
17	NUMNP, number of nodal points
18	ICODE, post-processor code (ICODE=1)
19	NGLBV, number of global variables written with each state (NGLBV=0)
20-23	Blank
24	NUMEL, number of elements
25	NUMATS, number of materials
26	NUMST, number of states
27-64	Blank

GEOMETRY SECTION (2*NUMNP+5*NUMEL Words)

<u>Words</u>	<u>Description</u>
2*NUMNP	Array of nodal coordinates: $x_1, y_1, x_2, y_2, \dots$ or $r_1, z_1, r_2, z_2, \dots$
5*NUMEL	Element connectivity arrays and material numbers (MATN): $N_1, N_2, N_3, N_4, \text{MATN})_1, (N_1, N_2, N_3, N_4, \text{MATN})_2, \dots$

PLOT FILE DATA BASE (cont'd.)

TIME STATE SECTION (NUMST*(NUMNP+1) Words)

NUMST states written as follows:

<u>Words</u>	<u>Description</u>
1	Time
NUMNP	Nodal point temperatures at this time: $\theta_1, \theta_2, \dots$