

ON MODELING AND THE USE OF THE NASTRAN THERMAL ANALYZER

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SUMMARY

Eight alternative modeling techniques to specify prescribed temperature at grid or scalar points for transient thermal analyses are presented. Four cases are for constant temperatures, and the others are time-varying temperature functions. Theoretical explications and detailed listing of input data cards used for illustrating different modelings are given. It is shown that the $\bar{N}TA$ can be exploited to extend beyond its normal capabilities through innovative modeling techniques.

In addition, the effect of node valency on the energy distribution to grid points is illustrated and discussed. Guidelines to delineate this effect are given.

INTRODUCTION

The NASTRAN Thermal Analyzer ($\bar{N}TA$) is a finite-element based general purpose heat transfer computer program integrated in the NASTRAN system (refs. 1 and 2). Its development was intended to provide analytical analysis capabilities in the multiple disciplinary areas. Special attention was directed to the interface problem which interferes with reliable predictions of the thermo-stresses or deflections, especially for very large sized structures and complex configurations. The $\bar{N}TA$ was developed by making an effective use of the functional modules available in NASTRAN to their fullest extent. In addition, new modules comprising new elements and solution algorithms to satisfy the unique requirements posed by thermal applications were added. The $\bar{N}TA$ is indeed very versatile and flexible. Analysis capabilities, however can be further exploited by innovative modeling techniques to compensate for some of the apparent restrictions of the program, which were not implemented solely for economic reasons. Working around such restrictions through intelligent modeling is an achievable practice in engineering applications.

This paper deals with two essential subjects relevant to the $\bar{N}TA$ modeling. The problems considered are:

- (1) Alternative modeling techniques for specifying the prescribed temperatures at grid or scalar points in transient thermal analyses

A total of eight distinct modeling techniques are presented. Four cases concern with a constant temperature value, and the others, a time-varying temperature function. For the ease of reference and comparison, all cases are illustrated using a single basic physical problem. Details of altering the input data cards from case to case are given. Theoretical explications which amplify the basis of modeling techniques are included as necessary. Accuracy of solutions along with individual merits and disadvantages is discussed. While not attempting to be exhaustive, these illustrations will provide general NTA users with a practical guide supplementing what has been documented and demonstrated in the two-volume set manuals (refs. 3 and 4).

- (2) The effect of the node valency on energy distribution to grid points

The energy distribution to grid points attributed to the effect of the node valency is exemplified by a unit surface of a rectangular area which is heated by an external heat flux. This rectangular surface is represented in six different models using two-dimensional triangular and quadrilateral elements. Users are reminded by facts to be cautious in a modeling process. Guidelines and suggestions to delineate this effect are given.

MODELING TECHNIQUES FOR PRESCRIBED TEMPERATURES

Unlike the steady-state linear and nonlinear cases (using the rigid formats APP HEAT, SOL 1 and SOL 3, respectively), for which the NTA permits direct modeling of the prescribed temperature at grid or scalar points via the provided single-point-constraint (SPC1*) and temperature (TEMP and TEMPD) cards directly, the modeling to specify the prescribed temperatures in both linear and nonlinear transient thermal analyses (using the rigid format APP HEAT, SOL 9) requires indirect and more intricate techniques. A well adopted method to simulate the effect of a prescribed temperature T_i (i denotes grid or scalar point identification) is to connect a good thermal conductor between the point i and a datum of temperature at zero degree. The thermal conductor has a very large thermal conductance, K_{i0} , where the subscripts i and 0 denote the terminals of connection. A power or rate of heat flow Q_i is then applied to that point to yield the desired value of a constrained temperature, according to

$$T_i = \frac{Q_i}{K_{i0}} \quad (1)$$

*The names of actual NTA cards are capitalized and underlined.

where $T_o = 0$ has been implied, and K_{i_o} is a thermal conductance defined by

$$K_{i_o} = \left(\frac{kA}{\ell} \right)_{i_o} \quad (2)$$

k , A and ℓ are thermal conductivity, cross-sectional area and length of the conductor, respectively. For instance, if a constant value of 512°C is prescribed at the point i , a conductor with a very large thermal conductance, say $K_{i_o} = 10^6 \text{ W}/^\circ\text{C}$ is chosen, and a power, $Q_i = 512 \times 10^6 \text{ W}$, is then applied to i , the desired value of the prescribed temperature is obtained from equation (1), i.e.

$$T_{i_o} = \frac{512 \times 10^6}{10^6} = 512^\circ\text{C} \quad (3)$$

This method is due directly to an analogy between the thermal and structural systems, which is depicted in figure 1. A train of the $\bar{N}TA$ Bulk Data cards consisting of CELAS2 (to enter K_{i_o} and link between i and o), DAREA (to enter Q_i) and TLOAD2 (to apply Q_i to i and specify the transient loading conditions) is generally employed.

Based on the same principle, the modeling technique for a constant prescribed temperature at a grid point can be extended to the case of time-varying temperatures. This can be accomplished by a substitution of a time-dependent thermal load $Q_i(t)$ for Q_i , a constant value, in equation (1), provided admissible quantities and connectable $\bar{N}TA$ Bulk Data cards are selected properly and referenced correctly. This approach is, by no means, the only modeling technique available to the $\bar{N}TA$ users. Eight options of modeling techniques to specify constant and time-varying temperatures at grid or scalar points will be systematically presented. All cases will be illustrated by a single simple physical problem which does not lose any generalities insofar as the thermal boundary conditions are concerned. Consequently, any alterations made to the input data cards for individual cases can be easily identified and compared, and the accuracy of solutions easily evaluated.

The physical problem is that of determining the transient temperature response of a composite slab of infinite extent during a 45-second period (see fig. 2). The rear surface of the insulation layer, having the value of $\epsilon = \alpha = 0.9$, dissipates heat radiatively to an environment of 0°C . The front surface of the metallic slab in contact with a hot flowing gas has a convective film coefficient of $h = 0.071 \text{ W}/\text{cm}^2\text{-}^\circ\text{C}$. The thermo-physical properties and dimensions are tabulated in table 1. A uniform initial temperature of 20°C throughout the composite slab is assumed. Temperatures of the flowing hot gas are specified as:

- (1) A constant prescribed value maintained at $T_f = 1927^\circ\text{C}$.
- (2) A time-varying temperature function $T_f(t)$ which is given in figure 3.

One-dimensional rod elements are sufficient to represent the described problem in a finite-element model. A sketch of the composite slab and its finite-element representation is shown in figure 2.

A listing of that portion of the input data deck, which describes the problem in the NTA model and is common to all eight cases is shown in figure 4. With comments appropriately added, functions of various sections of the Bulk Data Deck are self-explanatory. The blank space bounded by the two lines of dotted stars is reserved for inserting different packets of the NTA Bulk Data cards which model the prescribed temperatures for the hot flowing gas that is represented by GRID or SPOINT 200.* A description and discussion for each individual case is in order. Relevant Bulk Data cards will be listed.

For a Constant Prescribed Temperature

- (1) To specify a constant temperature via CELAS2, DAREA, and TLOAD2

As described previously, this method is a common modeling technique. The Bulk Data cards which fill the blank space reserved in the input data deck (fig. 4) are shown in figure 5, Case (1) of the attached listing of computer printout excerpts.

A fictitious large thermal conductance $K_{i_o} = 10^6$ W/cm- $^\circ\text{C}$ is entered in the 3rd field of CELAS2. Its 4th field identifies the point which is numbered 200 and is of the SPOINT type as indicated by the 0 in the 5th field. The two blanks in the following two fields imply that the other end of the thermal conductor is connected to a datum of 0°C . The quantity of power, $Q_{i_o} = 1927 \times 10^6$ W, is entered in the 5th field in the thermal load card DAREA, whose identification 501 appearing in its 2nd field is referenced by TLOAD2 in the latter's third field. The set identification 401 of the TLOAD2 must be referenced by a DLOAD card in the Case Control Deck to activate the selection of an applied thermal load in the transient solution algorithm. Other filled data in these Bulk Data cards are obvious when the NTA manual (ref. 3) is consulted. No repetition need be made.

- (2) To specify a constant temperature via CELAS2, SLOAD, and TLOAD2

To illustrate how a variety of other available thermal load cards may be substituted for DAREA in the preceding case, SLOAD is selected for its simplicity. The

*Unless otherwise noted to use GRID 200 as a restriction, GRID 200 and SPOINT 200 are interchangeable in all other cases where SPOINT 200 is explicitly indicated.

packet of Bulk Data cards for modeling a constant temperature at the SPOINT 200 is shown in figure 5, Case (2). Results are identical to that of the preceding case. Other thermal load cards such as QVECT, QBDY1, QBDY2, and QHBDY may also serve as the replacement for DAREA, but generally require the use of associated cards as an inherent requirement. Later cases will illustrate this point.

(3) To specify a constant temperature via CDAMP2

The apparent attractiveness of this modeling technique is attributed to its modeling simplicity. A CDAMP2 card loaded with an extremely large thermal mass would maintain a prescribed temperature at the applied point, as long as sufficient amount of thermal power is supplied. While achieving the intended boundary condition satisfactorily, the addition of a fictitious, very large thermal mass as a component in the corresponding matrix would produce an unstable solution. As a result, accuracy of the solution is questionable. Furthermore, there are restrictions associated with this technique: Only GRID is permitted to be referenced by CDAMP2 for adding a thermal mass. A restriction (defect) of the program code requires the presence of CELAS2, DAREA, and TLOAD2 in the input data deck even though they would not contribute to the result of solution. Although the use of this technique is not recommended, Bulk Data cards used in modeling are shown in figure 5, Case (3) for reference.

(4) To specify a constant temperature via EPOINT, DMIG, DAREA and TLOAD2

The demonstrated modeling techniques in the preceding cases are incapable of providing information on the amount of the heat of constraint required to sustain the prescribed temperature at a point. In each case, a very large fictitious thermal load or a thermal mass was applied to achieve the desired effect. The NTA permits a direct input to the conduction matrix through DMIG which can be utilized together with EPOINT, DAREA and TLOAD2 to enter a true value of the prescribed temperature and yet yield the value of the heat of constraint as a part of the solution. Some manipulations are required, however, to accommodate this scheme. It's theoretical basis will be discussed first.

In transient thermal analysis, the general differential equation in matrix form is

$$[C] \{\dot{T}\} + [K] \{T\} = \{Q_e\} + \{Q_r\} \quad (4)$$

where

[C] a symmetric matrix of heat capacitance

[K] a symmetric matrix of heat conduction

{Q_e} a vector of applied thermal loads that are allowed to be time-dependent

$\{Q_r\}$ a vector of non-linear thermal loads that depend on temperature

$\{T\}$ a vector of temperatures at grid points

Equation (4) can be abridged as

$$[L] \{T\} = \{Q\} \quad (5)$$

where $[L]$, a nonlinear differential operator, is obtained by a comparison of equation (4) with equation (5), that gives

$$[L] = \left[[C] \cdot \frac{d}{dt} + [K] \right] \quad (6)$$

and

$$\{Q\} = \{Q_\ell\} + \{Q_r\} \quad (7)$$

Constraining a point to a constant temperature, we need to create one new unknown and one new equation. The new unknown representing the heat of constraint required to sustain the temperature to a prescribed level is defined as

$$T_{2001} = \text{heat of constraint} \quad (8)$$

Adding the quantity T_{2001} into equation (5) yields the following modified form

$$[L] \{T\} = \{Q\} + \left\{ \begin{array}{c} 0 \\ 0 \\ \vdots \\ \vdots \\ T_{2001} \\ 0 \end{array} \right\} \leftarrow \text{row for the point 200} \quad (9)$$

The new equation is defined as

$$T_{200} = q_{2001} \quad (10)$$

This quantity q_{2001} is an additional component in the vector $\{Q\}$ to be arranged in a row corresponding to that of the point 2001. The above equations can be merged to become

$$\begin{bmatrix}
 & & & & 0 \\
 & & & & 0 \\
 & & & & \vdots \\
 & & & & 0 \\
 & & & & -1.0 \\
 \cdots & \cdots & \cdots & \cdots & 0 \\
 0 & 0 & \cdots & 0 & 1.0
 \end{bmatrix}
 \begin{Bmatrix}
 T \\
 T_{2001}
 \end{Bmatrix}
 =
 \begin{Bmatrix}
 Q \\
 q_{2001}
 \end{Bmatrix}
 \tag{11}$$

← row for the point 200
 ← row for the point 2001

↑ column for the point 2001
 ↑ column for the point 200

The Bulk Data cards used in modeling are given in figure 5, Case (4). An EPOINT is used to accommodate the new unknown T_{2001} . The two added quantities in the merged L-matrix are input through the DMIG cards. The prescribed temperature is entered by DAREA with its true value. As usual, a TLOAD2 again serves to reference the DAREA and provides an identification to be selected by the DLOAD card in the Case Control Deck to activate transient thermal loading conditions.

The use of DMIG for inputting components directly to the conduction matrix requires its function to be selected in the Case Control Deck by a K2PP card. Therefore, K2PP=FIXED, was added.

Since the modified L-matrix appearing on the left-hand side of equation (11) is asymmetric, an altering of the program code to the APP HEAT, SOL 9 is required. The DMAP-ALTER packet which was inserted in the Executive Control Deck is reproduced below for reference.

```

$ DMAP-ALTER FOR APP HEAT SOL 9 TO FACILITATE ASYMMETRIC CONDUCTION MATRIX
ALTER 53,53 $ FOR APP HEAT, SOL 9 TO ACCOMMODATE ASYMMETRIC MATRIX HKGG
MCE2 HUSET,HGM,HRGG,HBGG,,/HRNN,HBNN,, $
PARAM //C,N,PREC/V,N,PREC $
UPARTN HUSET,HKGG/HKNNB,HKMN,HKNM,HKMM/C,N,G/C,N,N/C,N,M $
MPYAD HKMM,HGM,HKMN /HKM /C,N,O/C,N,1/C,N,1/V,N,PREC $
MPYAD HKNM,HGM,HKNNB/HKN /C,N,O/C,N,1/C,N,1/V,N,PREC $
MPYAD HGM ,HKM,HKN /HKNN/C,N,1/C,N,1/C,N,1/V,N,PREC $
ENDALTER

```

Results of this method are identical to those of Case (1). In addition, the "Temperature Vector" output for the point 2001 should be interpreted as the heat of constraint (in the units of power, w) as defined by equation (10).

While the advantages of this modeling technique are self-evident, the disadvantages are: (A) An increase of the problem size, and (B) The nonstandard definition of output.

For a Time-Varying Temperature Function

- (5) To specify a time-varying temperature function via CELAS2, QVECT, TABLED1, TLOAD2, etc.

A prescribed temperature at a point varied as a time function can be modeled by an extension of the basic technique shown in Case (1). The technique used is to replace DAREA with other admissible thermal load cards which would provide with the time-varying thermal power capability. QVECT permits its vector components of the directional thermal flux to be referenced by the TABLED1 cards where tabulated values of temperature vs. time functions can be entered.

The CELAS2 and TLOAD2 serve the same functions as described in Case (1).

Since QVECT can only input a thermal flux to a point through a boundary surface element, CHBDY is therefore required. To define the surface area of the provided CHBDY element as well as to specify the surface absorptivity to absorb the radiant flux, PHBDY must be included. Moreover, CHBDY can only be referenced by a GRID, which, therefore, must replace the SPOINT 200 in the packet of the Bulk Data cards as shown in figure 6, Case (5).

- (6) To specify a time-varying temperature function via CELAS2, QVECT, TLOAD1, TABLED1, etc.

A variation of the modeling technique used in the last example is demonstrated. Although TLOAD2 is the only card that must be replaced, in this case by TLOAD1, the sequence of referencing from card to card to perform specific functions has altered substantially. The time-varying temperature function does not rely on the provision of the vector components of QVECT. Instead, QVECT serves only to facilitate a large fictitious thermal load, while tabulated values of a time-varying temperature function are entered in TABLED1 which, in turn, is referenced by TLOAD1. The packet of Bulk Data cards in figure 6, Case (6) shows the detail of inter-relationships among individual cards.

- (7) To specify a time-varying temperature function via CELAS2, QHBDY, TLOAD1, TABLED1, etc.

The preceding case has shown that a temperature vs. time function can be modeled via TLOAD1 and TABLED1, and that a thermal load card is used merely to accommodate a constant value of thermal flux. In the present case, QHBDY is substituted for QVECT. Nothing else is altered and the packet of Bulk Data cards is shown in figure 6, Case (7).

- (8) To specify a time-varying temperature function via EPOINT, DMIG, DAREA, TLOAD1 and TABLED1

As evidenced in Cases (6) and (7), a combination of TLOAD1 and TABLED1 is well suited to accommodate temperature vs. time functions.

Therefore, the modeling techniques previously devised for a constant prescribed temperature can be modified easily if TLOAD2, which was used originally in the constant prescribed temperature case, is replaced by a combination of TLOAD1 and TABLED1. An application of this substitution to Case (4) has successfully demonstrated another method available to the users. The uniqueness and features of this modeling technique are identical to that of Case (4). A packet of relevant Bulk Data cards is shown in figure 6, Case (8).

Details of the illustrated cases with emphasis on the inter-relationships of the cards in the Bulk Data Deck and those between the Case Control and the Bulk Data Decks together with results are documented separately (ref. 5).

EFFECT OF THE NODE VALENCY

A node valency is the pattern of element arrangement in an assembled model in relation to an associated grid point. Since a number of factors could influence the solution accuracy of a finite-element model (ref. 6), the effect of the node valency can be controlled by modeling and is, therefore, considered and discussed herewith.

The input energy to an element, whether from an external thermal flux to the surface of an element or from an internal volumetric heating source, is evenly distributed to the vertices of the element according to the solution algorithm currently implemented in the \bar{N} TA program. The effect of a node valency on the total energy distribution to grid points is essential to the eventual temperature results. As an illustration, without computation, six types of node valency available to model a constant area A of a rectangle are shown in figure 7. Each rectangular surface is assumed to be cut out from an assembled finite-element model along a boundary. The surface is heated by a constant uniform heat flux q . Then Q_i is the amount of energy being distributed to

that grid point i from all connected elements that define the node valency at i . For example, the rectangular surface is modeled by four equal quadrilateral elements as shown in figure 7(a). The distribution of energies at three noted grid points are $Q_1 = (1/4)Aq$, $Q_2 = (1/16)Aq$ and $Q_3 = (1/8)Aq$.

When the same rectangular surface is modeled differently by using triangular elements as shown in Cases (b) through (f) in figure 7, Q_i ($i = 1, 2, 3, 4$, wherever applicable) of each case shows that at the same location of the centers of these rectangles, Q_1 has varied from $1/3$ to $1/6$, Q_2 from $1/6$ to $1/24$, and Q_3 from $1/2$ to $1/8$ units. This is an indication of uneven distribution of a uniformly applied heat flux to a surface of the same area attributed to the node valency. In practice, a structure represented by a finite-element model usually employs sufficiently large number of elements arranged in a very regular pattern or patterns. This fact implies that those grid points, being fully surrounded by connected elements, would receive the same fraction of energy as long as the grid points have the node valency which would result in identical values of Q_i . It is also seen that the grid points that are isolated or located along boundary lines, where the grid points are not fully surrounded by adjacent elements, would be affected by the node valency more than their counterparts located on the interior of the surface. Therefore, to delineate temperature solution inaccuracy, when the existing software of the $\bar{N}TA$ is used, the selection of uniformly sized and the similar type of elements arranged in a regular pattern for interior points is recommended. Using finer discretization or smaller elements along the boundary lines is also desirable but the engineering practice must trade-off with other considerations.

As a last resort, application of thermal loads manually to those isolated grid points or those along the boundary lines is a practical method of compensating for uneven energy distribution. The Bulk Data card QHBDY is employable for such an application.

REFERENCES

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3. Lee, H. P.: NASTRAN Thermal Analyzer — Theory and Application Including a Guide to Modeling Engineering Problems, Volume 1: The NASTRAN Thermal Analyzer Manual, NASA Goddard Space Flight Center, X-322-76-16, December 1975.

4. Jackson, C. E., Jr.: NASTRAN Thermal Analyzer — Theory and Application Including a Guide to Modeling Engineering Problems, Volume 2: A Guide to the GSFC NASTRAN Thermal Analyzer Sample Problem Library, NASA Goddard Space Flight Center, X-322-76-17, December 1975.
5. Lee, H. P.: Alternative Techniques for Modeling the Prescribed Temperatures in a Transient Thermal Analysis Using the NASTRAN Thermal Analyzer, NASA Goddard Space Flight Center, System Division, Greenbelt, Md., Sept. 1976.
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TABLE 1. - THERMO-PHYSICAL PROPERTIES AND DIMENSIONS

Layer	Metallic Slab (a)	Insulation (b)
Thermal conductivity k (W/cm-°C)	2.25×10^{-3}	0.2×10^{-3}
Thermal capacitance ρC_p (Cal/cm ³ -°C)	1.44×10^{-1}	1.163
Thickness ΔX (cm)	0.30	0.40

STRUCTURAL SYSTEM

THERMAL SYSTEM

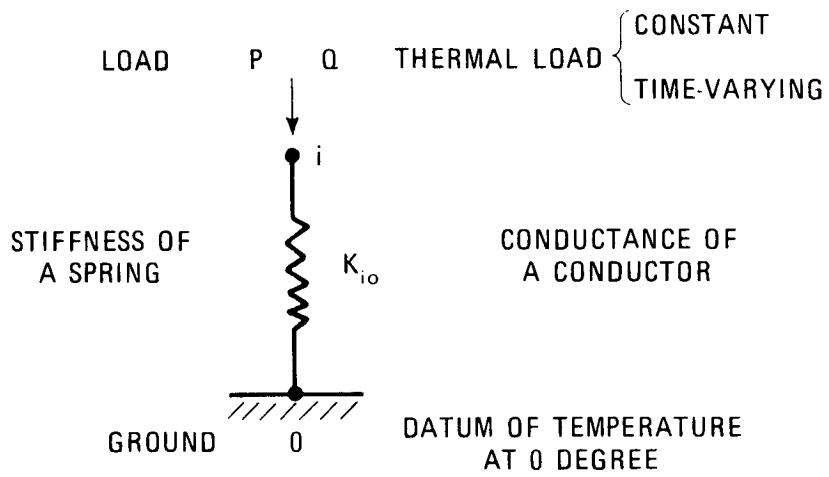


Figure 1. Analogy of a thermal conductor and a structural spring.

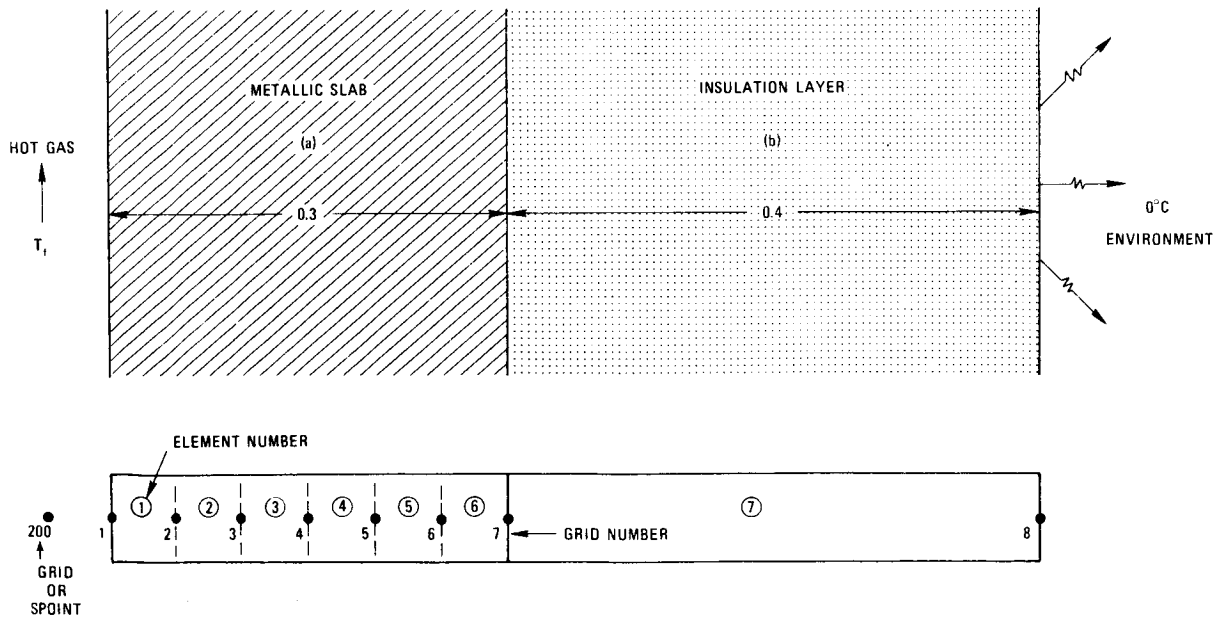


Figure 2. The composite slab and its finite-element representation.

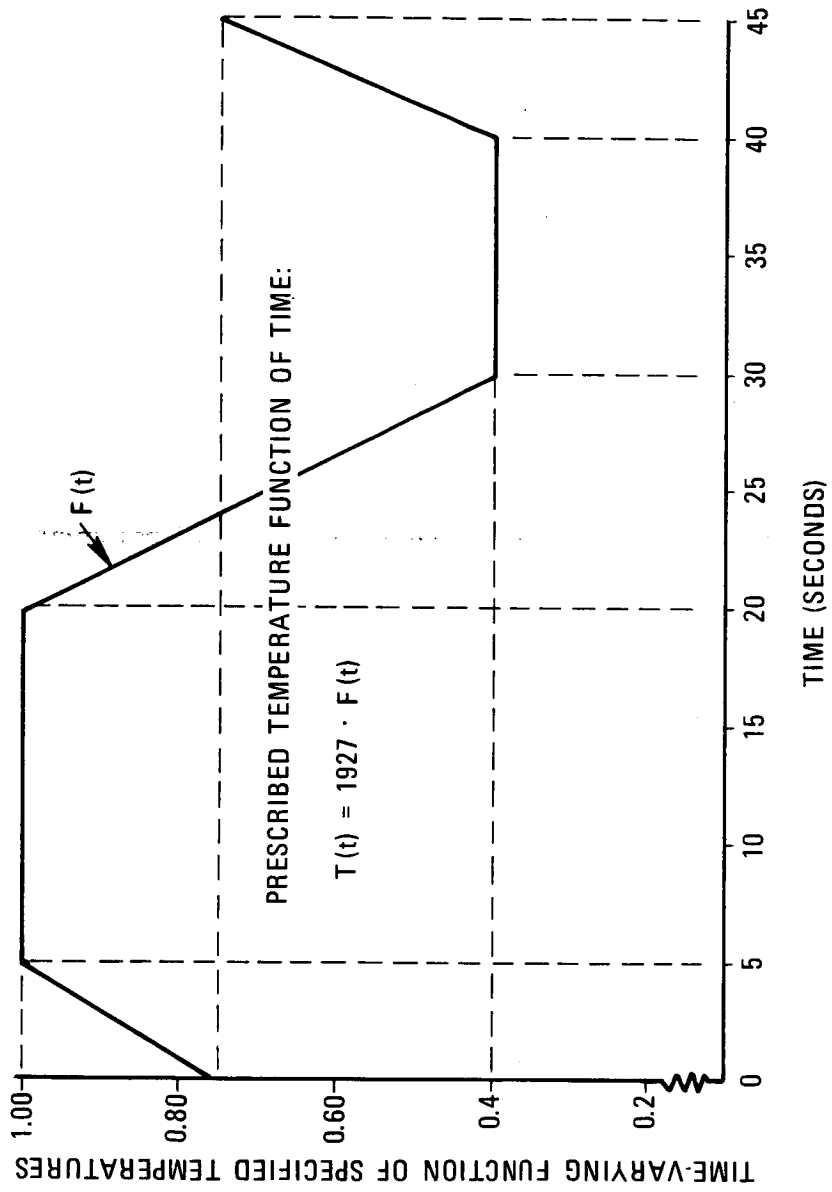


Figure 3. Time-dependent prescribed temperatures of the hot flowing gas.

```

$ EXECUTIVE CONTROL DECK
ID 102 LEE, NASA-GSFC, SYSTEMS DIVISION, THERMAL SYSTEMS BRANCH
APP HEAT
SOL 9
TIME 5
DIAG 8,13,14
$ INSERT ALTER PACKET HERE IF USED
CEND

```

```

$ CASE CONTROL DECK
ECHO=ROTH
TITLE=DIFFERENT MODELING TECHNIQUES FOR PRESCRIBED TEMPERATURE
SUBTITLE=IN TRANSIENT THERMAL ANALYSIS
LABEL = ***** A TITLE FOR THE CASE IDENTIFICATION *****
DLOAD=401
IC=701
ISF=P=601
TEMP(MATERIAL)=1
OUTPUT
ELFORCF=ALL
DLOAD=ALL
THERMAL=ALL
BEGIN BULK

```

```

. 1 .. 2 .. 3 .. 4 .. 5 .. 6 .. 7 .. 8 .. 9 .. 10 .
$ BULK DATA DECK
$ GRID POINTS
GRID 1 0.00 0.0 0.0
GRID 2 0.05 0.0 0.0
GRID 3 0.10 0.0 0.0
GRID 4 0.15 0.0 0.0
GRID 5 0.20 0.0 0.0
GRID 6 0.25 0.0 0.0
GRID 7 0.30 0.0 0.0
GRID 8 0.70 0.0 0.0
$ POINT 200
$ CONDUCTION ELEMENTS
CROD 1 101 1 2 2 101 2 3
CROD 3 101 3 4 4 101 4 5
CROD 5 101 5 6 6 101 6 7
PROD 101 102 1.0
MAT4 102 0.00225 0.144
CROD 7 1101 7 8
PROD 1101 1102 1.0
MAT4 1102 0.0002 1.163
$ CONVECTIVE BOUNDARY IN CONTACT WITH HOT GAS
CHBDY 1001 1002 POINT 1 81
E1 200
PHBDY 1002 1003 1.0
MAT4 1003 0.071
$ RADIATION TO AN ENVIRONMENT OF ZERO DEGREE
CHBDY 9001 9002 POINT 8 8CY001
8CY001 1.0 0.9 1.0 0. 0.
PHBDY 9002
RADLST 9001
RADMTX 1 1.0
PARAM SIGMA 5.67E-12
PARAM TABS 273.16
$ INITIAL CONDITIONS
TEMP 701 200 1927.0
TEMPD 701 20.0
$ TIME INCREMENTS AND INTEGRATION STEPS
TSTEP 601 15 1.0 2 83
83 15 2.00 2
$ ESTIMATED TEMPERATURES
TEMPD 1 1927.0
$ *****
$ *****
ENDDATA

```

Figure 4. A listing of input data deck of the \bar{N} TA model.

```

LABEL= FIXED TEMPERATURE AT SPOINT 200 VIA CELAS2,DAREA & TLOAD2
$ *****
$ CONSTANT PRESCRIBED TEMPERATURE APPLIED AT SPOINT 200
CELAS2 301 1.E6 0 1927.E6 0 0.0 0.0 +FLD2
DAREA 501 200 0
TLOAD2 401 501 0
+TLD2 0.0 0.0
$ *****

```

CASE (1)

```

LABEL= FIXED TEMPERATURE AT SPOINT 200 VIA CELAS2,SLOAD & TLOAD2
$ *****
$ CONSTANT PRESCRIBED TEMPERATURE APPLIED AT SPOINT 200
CELAS2 301 1.E6 0 1927.E6 0 0.0 0.0 +FLD2
SLOAD 501 200 0
TLOAD2 401 501 0
+TLD2 0.0 0.0
$ *****

```

CASE (2)

```

$ *****
$ CONSTANT PRESCRIBED TEMPERATURE APPLIED AT GRID 200
CUAMP2 301 1.E3 0 1927.0 1
TEMP 1 200
$ TO BYPASS PROGRAM RESTRICTION OF TRANSIENT LOAD INPUT
CELAS2 301 1.E6 0 0.0 0.0 0.0 +FLD2
DAREA 501 200 0
TLOAD2 401 501 0
+TLD2 0.0 0.0
$ *****

```

CASE (3)

```

LABEL= FIXED TEMPERATURE AT SPOINT 200 VIA EPOINT,DMIG,DAREA & TLOAD2
$ *****
$ CONSTANT PRESCRIBED TEMPERATURE APPLIED AT SPOINT 200
EPOINT 2001 1 1927.0 0 1.E5 0.0 +TL
DMIG 200 0 200 1.0
DMIG 2001 0 200 -1.0
DAREA 501 2001 0
TLOAD2 401 501 0
+TL 0.0
$ *****

```

CASE (4)

Figure 5. Bulk Data cards used in various modeling techniques for specifying constant prescribed temperatures.

```

LABEL= TIME-DEPENDENT PRESCRIBED TEMPERATURE VIA CELAS2,QVECT,TABLED1 & TLOAD2
$ *****
$ TIME-DEPENDENT PRESCRIBED TEMPERATURE APPLIED AT GRID 200
CELAS2 301 1.E6 200 1
CHBDY 20001 20002 POINT 200
+CHBDY1 -1.0 0.0 0.0 +CHBDY1
PHBDY 20002 1.0 1.0
QVECT 501 1927.E6 5011 20001
TABLED1 5011
+TABL1 0.0 0.75 5.0 1.0 20.0 1.0 30.0 0.4 +TABL1
+TABL2 40.0 0.4 45.0 0.75 ENDT +TABL2
TLOAD2 401 501 0.0 1.E5 0.0 0.0 +TLD2
+TLD2 0.0 0.0
$ *****

```

CASE (5)

```

LABEL= TIME-DEPENDENT PRESCRIBED TEMPERATURE VIA CELAS2,QVECT,TLOAD1 & TABLED1
$ *****
$ TIME-DEPENDENT PRESCRIBED TEMPERATURE APPLIED AT GRID 200
CELAS2 301 1.E6 200 1
CHBDY 20001 20002 POINT 200
+CHBDY2 -1.0 0.0 0.0 +CHBDY2
PHBDY 20002 1.0 1.0
QVECT 501 1927.E6 1.0 0.0 0.0 20001
TLOAD1 401 501 4011
TABLED1 4011
+TABL1 0.0 0.75 5.0 1.0 20.0 1.0 30.0 0.4 +TABL1
+TABL2 40.0 0.4 45.0 0.75 ENDT +TABL2
$ *****

```

CASE (6)

```

LABEL= TIME-DEPENDENT PRESCRIBED TEMPERATURE VIA CELAS2,QHBDY,TLOAD1 & TABLED1
$ *****
$ TIME-DEPENDENT PRESCRIBED TEMPERATURE APPLIED AT GRID 200
CELAS2 301 1.E6 200 1
CHBDY 20001 20002 POINT 200
+CHBDY2 -1.0 0.0 0.0 +CHBDY2
PHBDY 20002 1.0 1.0
QHBDY 501 POINT 1927.E6 1.0 200
TLOAD1 401 501 4011
TABLED1 4011
+TABL1 0.0 0.75 5.0 1.0 20.0 1.0 30.0 0.4 +TABL1
+TABL2 40.0 0.4 45.0 0.75 ENDT +TABL2
$ *****

```

CASE (7)

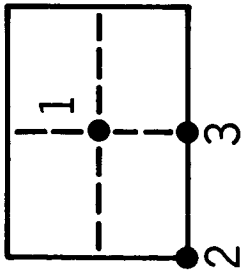
```

LABEL=TIME-DEPENDENT PRESCRIBED TEMPERATURE VIA EPOINT,DMIG,DAREA,TLOAD1,TABLED1
$ *****
$ TIME-DEPENDENT PRESCRIBED TEMPERATURE APPLIED AT SPOINT 200
EPOINT 2001
DMIG FIXED 0 1 1 1
DMIG FIXED 200 1 2001 1.0
DMIG FIXED 2001 0 200 -1.0
DAREA 501 2001 0 1927.0
TLOAD1 401 501 4011
TABLED1 4011
+TABL1 0.0 0.75 5.0 1.0 20.0 1.0 30.0 0.4 +TABL1
+TABL2 40.0 0.4 45.0 0.75 ENDT +TABL2
$ *****

```

CASE (8)

Figure 6. Bulk Data cards used in various modeling techniques for specifying time-varying prescribed temperature functions.

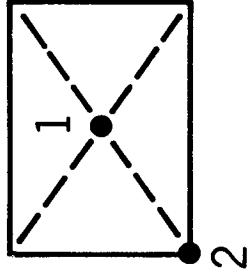


$$Q_1 = 1/4 Aq$$

$$Q_2 = 1/16 Aq$$

$$Q_3 = 1/8 Aq$$

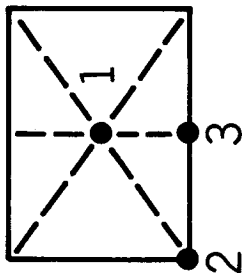
(a)



$$Q_1 = 1/3 Aq$$

$$Q_2 = 1/6 Aq$$

(b)

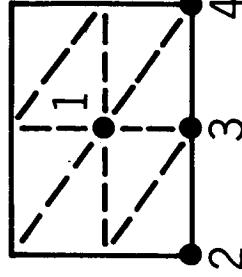


$$Q_1 = 1/3 Aq$$

$$Q_2 = 1/8 Aq$$

$$Q_3 = 1/12 Aq$$

(c)



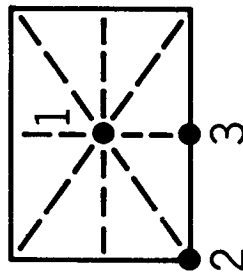
$$Q_1 = 1/4 Aq$$

$$Q_2 = 1/24 Aq$$

$$Q_3 = 1/8 Aq$$

$$Q_4 = 1/12 Aq$$

(d)

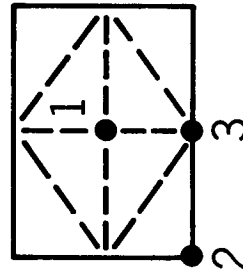


$$Q_1 = 1/3 Aq$$

$$Q_2 = 1/12 Aq$$

$$Q_3 = 1/12 Aq$$

(e)



$$Q_1 = 1/6 Aq$$

$$Q_2 = 1/24 Aq$$

$$Q_3 = 1/6 Aq$$

(f)

Q_i = Total thermal energy entering into the i th grid point
 q = A uniform thermal flux applied to the plate of an area A

Figure 7. Typical patterns of the node valency of a constant Area A .