ABSTRACT

This paper outlines and appraises NASTRAN's heat transfer capability. The range of applicability of NASTRAN heat transfer is defined. Modeling techniques, input generation, computational accuracy and efficiency, and pre/post processing requirements are explored. This is accomplished through discussion of sample demonstration problems.

Section 1

INTRODUCTION

1.1 General Description of Heat Transfer Problems

Heat conduction is the term applied to the mechanism of internal energy exchange by molecular diffusion processes. The flow of energy passes from high energy molecules to low energy ones, i.e., from a high temperature region to a low temperature region. The distinguishing feature of conduction is that it takes place within the boundaries of a body or between bodies in contact. While temperature, the measure of internal energy, is a scalar quantity, the rate of heat (energy) transfer is directional and can be expressed as a vector related to temperature as

$$\vec{q} = k \frac{\vec{\partial T}}{\partial X} \qquad (1)$$

in which $\vec{q}$ = rate of energy transferred
k = thermal conductivity
X = spatial variable
T = temperature

The primary objective of all heat conduction analysis is to determine spatial distribution and variation in time of temperature in a region of given geometry. To do this, solution of the heat conduction equation requires an appropriate description of boundary (and initial, if necessary) conditions. In its most general form, the heat conduction equation can be written as

$$\dot{Q} = -\nabla(k \cdot \nabla T) + \rho c \frac{\partial T}{\partial t} \qquad (2)$$

where $\dot{Q}$ = heat input per unit volume
ρ = density
c = heat capacity of the material
∇^2 = Laplacian Operator
t = time

This equation essentially expresses a mathematical balance between the rate of thermal energy input to an infinitesimal spatial element, the thermal energy conducted out of the element and the energy stored in it.

1.2 The Analogy Between Elasticity and Heat Transfer

The finite element method is a powerful approximate technique of solving boundary value, initial value and eigen-value problems in engineering and mathematical physics. The method was originally implemented to perform stress analysis of large structural systems. The connection of the method with variational principles quickly led to its use in various fields of solid mechanics. The known mathematical analogies between behaviors of various physical systems ensured extension of the method's use to other areas including heat transfer. Such an analogy for example, exists between the mathematical models of linear elasticity and linear steady-state heat conduction, as shown in Table 1. The analogy of Table 1 is complete, with the exception that elasticity deals with up to 6 degrees of freedom (translations + rotations) while heat transfer deals with only one (one "equivalent" displacement, T).

Since elasticity is the more general of the two analogous phenomena, in practice (in a computer code) the analogy is exploitable in a way that allows one to use a linear elasticity model for analyzing a linear heat conduction problem. For linear heat transfer, MSC/NASTRAN has done exactly that. The linear elasticity mode (SOL 24 for static problems) has been supplemented with special capabilities that handle heat transfer type loading and boundary conditions such as radiation and film convection. These capabilities are activated by "Approach HEAT" which also removes two to five degrees of freedom from the statics mode.

While less obvious and more complex analogies do exist between heat conduction and elasticity for non-linear and transient problems, MSC/NASTRAN treats these under separate modes, or rigid formats. Characteristics, applying differential and matrix equations and rigid format numbers for each mode of heat transfer under MSC/NASTRAN, are shown in Table 2.

Table 1

ANALOGY BETWEEN MATHEMATICAL MODELS OF LINEAR ELASTICITY AND STEADY-STATE HEAT CONDUCTION

	Elasticity of Solids	Heat Conduction
Constitutive Relation	$\sigma = \frac{F}{A} = E \frac{\partial u}{\partial x}$	$q = \frac{Q}{A} = k \frac{\partial T}{\partial X}$
Analogous Quantities	σ: stress tensor	q: heat flux vector
	F: force vector	Q: heat flux vector
	E: elasticity modulus	k: thermal conductivity
	u: displacement vector	T: temperature
	x: spatial variables	X: spatial variables
	$\frac{\partial u}{\partial x}$: strain tensor	$\frac{\partial T}{\partial X}$: gradient vector

Table 2

NASTRAN HEAT TRANSFER MODES

Heat Transfer Mode	Steady-State Linear	Non-Linear Steady-State	Transient
Mathematical (differential) Equations	$k\nabla^2 T = \dot{q}$	$\nabla(k \cdot \nabla T) = \dot{q}(T)$	$\rho c \frac{\partial T}{\partial t} + \nabla(k \cdot \nabla T) = \dot{q}(T,t)$
FEM-Discretized (Matrix) Equations	$[k]\vec{\{T\}} = \vec{\{Q\}}$	$[k]\vec{\{T\}} = \vec{\{Q\}} + \vec{\{Q_T\}}$	$[k]\vec{\{T\}} + [c]\vec{\{\dot{T}\}} = \vec{\{Q\}} + \vec{\{Q_T\}}$
Characteristics	No temperature change in time. Thermal conductivity independent of temperature. Linear bound, cond. and loads.	Non-linear loads such as surface to surface irradiation allowed. Temperature dependent conductivity.	General heat conduction problem.
Solution Method	Matrix solution.	Non-linear algebraic eqs. Iterative solution.	Time-step (Euler) integration
MSC/NASTRAN Rigid Format	SOL 24 "Approach HEAT"	SOL 53	SOL 59

$\{Q\}$ = Temperature independent thermal load vector.
$\{Q_T\}$ = Temperature dependent thermal load vector.
$[k]$ = Thermal conductivity matrix.
$[c]$ = Heat capacity matrix.

Section 2

OVERVIEW OF MSC/NASTRAN HEAT TRANSFER MODE

It should be noted that the MSC/NASTRAN heat transfer capability is strictly for conduction and that other modes of heat transfer (convection, radiation) are only peripherally involved. NASTRAN allows for convection or radiation-type boundary conditions in a given conduction problem. However, it is inappropriate for, and not capable of, thermal analysis of a fluid in motion due to thermal and gravity effects (free convection) or external forces (forced convection). Nor is NASTRAN compatible with heat conduction problems with phase change (freezing or melting) and ablation, characterized by a moving boundary. Within its realm of applicability however, NASTRAN's conduction heat transfer mode constitutes a powerful and efficient analytical tool.

2.1 The Choice of the Appropriate NASTRAN Heat Transfer Mode: Rigid Formats

For steady-state linear heat transfer, modification of the statics mode (rigid format 24) is accomplished by use of the NASTRAN card in the beginning of the executive control deck, as follows:

```
NASTRAN HEAT = 1
.
.
.
.
SOL 24
.
.
CEND
```

Rigid formats 53 and 59 are used for steady-state non-linear, and transient problems, respectively, without the supplementary NASTRAN card.

2.2 NASTRAN Heat Transfer Features

The following is an itemized list of heat transfer features currently supported by MSC/NASTRAN version 60. Description of most capabilities is followed by name(s) of associated NASTRAN bulk data card(s).

- Structural Modeling
  - a) One, two or three-dimensional conduction elements

    1-Dimensional: ROD, BAR, BEAM
    2-Dimensional: TRIA3, QUAD4
    3-Dimensional: TETRA, PENTA, HEXA
  - b) Volume of revolution elements for axisymmetric problems: TRIAAG, TRAPRG
  - c) Surface elements for surface heat transfer modeling: HBDY

    1-Dimensional: POINT type
    2-Dimensional: LINE type
    3-Dimensional: AREA3, AREA4 types
    Axisymmetrical: REV types
  - d) One-dimensional fluid tube element: FTUBE
- Thermal Loads
  - a) Volume heat addition: QVOL
  - b) Boundary thermal loads associated with surface heat transfer.

    Insulated surface: Boundary without SPC or CHBDY (automatic default)
    Fixed temperature surface (single point constraints): SPCD, SPC1
    Surface subject to convective heat flux: $Q = hA\Delta T$
    Surface subject to constant heat flux: QHBDY, QBDY1, QBDY2
    Surface subject to directional radiation flux (radiation from a distant source): QVECT
    Surface-to-surface irradiation: RADLST
  - c) Time dependent loads of the above types: TLOAD

- Constraints
  - a) Single point constraints (fixed temperature): SPCD, SPC1
  - b) Multiple point constraints (linear relationship between temperatures of several points): MPC
  - c) Time dependent constraints of the above types.
- Properties
  - a) Isotropic or composite materials: MAT4
  - b) Temperature dependent thermal conductivity: MATT4
  - c) Temperature dependent emissivity and/or absorptivity (radiation): PHBDY
  - d) Anisotropic behavior (directional variation of properties): MAT5, MATT5
- Input/Output
  - a) Same input format as other NASTRAN nodes.
  - b) Existing structural models used for statics can be used for heat transfer.
  - c) Temperatures at all grid points and directional heat fluxes for all elements are output, on request.
  - d) Temperature output can be requested in NASTRAN input format (for use in thermal stress analysis or problems with temperature dependent elastic properties. Also for use as an initial guess or initial value for non-linear transient heat transfer problems respectively).
- Plotting
  - a) Structural plots of models.
  - b) Temperature contour plots (isotherms) on 2-dimensional elements.

2.3 A Listing of Heat Transfer Related NASTRAN Data Cards

a) Executive Control Deck:

NASTRAN HEAT = 1 (Always precedes executive control deck for linear heat transfer.)

b) Case Control Deck:

TEMPERATURE
THERMAL
FLUX
DLOAD
LOAD
SPC
SET
MPC
TITLE
SUBTITLE
LABEL
SUBCASE
TSTEP
IC

c) Bulk Data Deck:

GRID
GRIDSET
SEQGP
CORDiC
CORDiR
CORDiS
SPOINT
CROD
PROD
CBAR
PBAR
CTRIA3
PSHELL
CQUAD4
PQUAD4
CTETRA
CPENTA
CHEXA
CTRIARG
CTRAPRG
CHBDY
PHBDY
CFTUBE
PFTUBE
MAT4
MAT5
MATT4
MATT5
TEMP
TEMPD
TABLEMi
TABLEDi
SPC1
SPCD
SPCADD
MPC
TSTEP
PARAM
LOAD
NFTUBE
QHBDY
QBDY1
QBDY2
QVECT
QVOL
RADLST
RADMTX
TEMPPi
TEMPRB
TLOADi

2.4 An Example of NASTRAN Heat Transfer Input Data

To give the reader an idea of the complete NASTRAN input data deck required for the heat transfer mode, a simple (purely educational) example problem shown in Figure 1 is presented here. The following integral NASTRAN input data deck is associated with this problem dealing with linear and steady-state heat transfer.

```
NASTRAN HEAT = 1
ID EXAMPLE PROBLEM
SOL 24                                        Executive Control Deck
TIME 1
DIAG 8,13,19
CEND
TITLE = SLAB
THERMAL = ALL
FLUX = ALL                                    Case Control Deck
SPC = 10
LOAD = 11
BEGIN BULK
GRID    1    0    0.    0.    0.    0         Bulk Data Deck
GRID    2    0    1.    0.    0.    0               .
GRID    3    0    2.    0.    0.    0               .
GRID    4    0    3.    0.    0.    0
GRID    5    0    0.    1.    0.    0
GRID    6    0    1.    1.    0.    0
GRID    7    0    2.    1.    0.    0
GRID    8    0    3.    1.    0.    0
GRID    9    0    0.    2.    0.    0
```

COLUMNS

```
1       9       17      25      33      41      49      57      65      73
GRID    10      0       1.      2.      0
GRID    11      0       2.      2.      0
GRID    12      0       3.      2.      0
SPOINT  13
CQUAD4  1       1       1       2       6       5
CQUAD4  2       1       2       3       7       6
CQUAD4  3       1       3       4       8       7
CQUAD4  4       1       5       6       10      9
CQUAD4  5       1       6       7       11      10
CTRIA3  6       2       7       8       11
CTRIA3  7       2       8       12      11
CHBDY   8       3       LINE    4       8                               +BD1
+D1     13      13
CHBDY   9       4       LINE    8       12                              +BD2
+D2     13      13
CHBDY   10      4       LINE    12      11                              +BD3
+D3                                     0.      1.      0.
CHBDY   11      4       LINE    11      10                              +BD4
+D4                                     0.      1.      0.
CHBDY   12      4       LINE    10      9                               +BD5
+D5                                     0.      1.      0.
CHBDY   13      4       LINE    1       2
PQUAD4  1       21      1.
PSHELL  2       21      1.
PHBDY   3       22      1.
PHBDY   4               1.              0.5
```

```
MAT4    21      100.    0.

MAT4    22      20.     0.

QBDY1   11      100.    13

QVOL    11      1000.   2

QVECT   11      500.    -.866   -0.5    0.0     10      11      12


SPC1    10              13

SPC1    10              3

SPCD    11      13              0.

SPCD    11      3               100.

ENDDATA
```

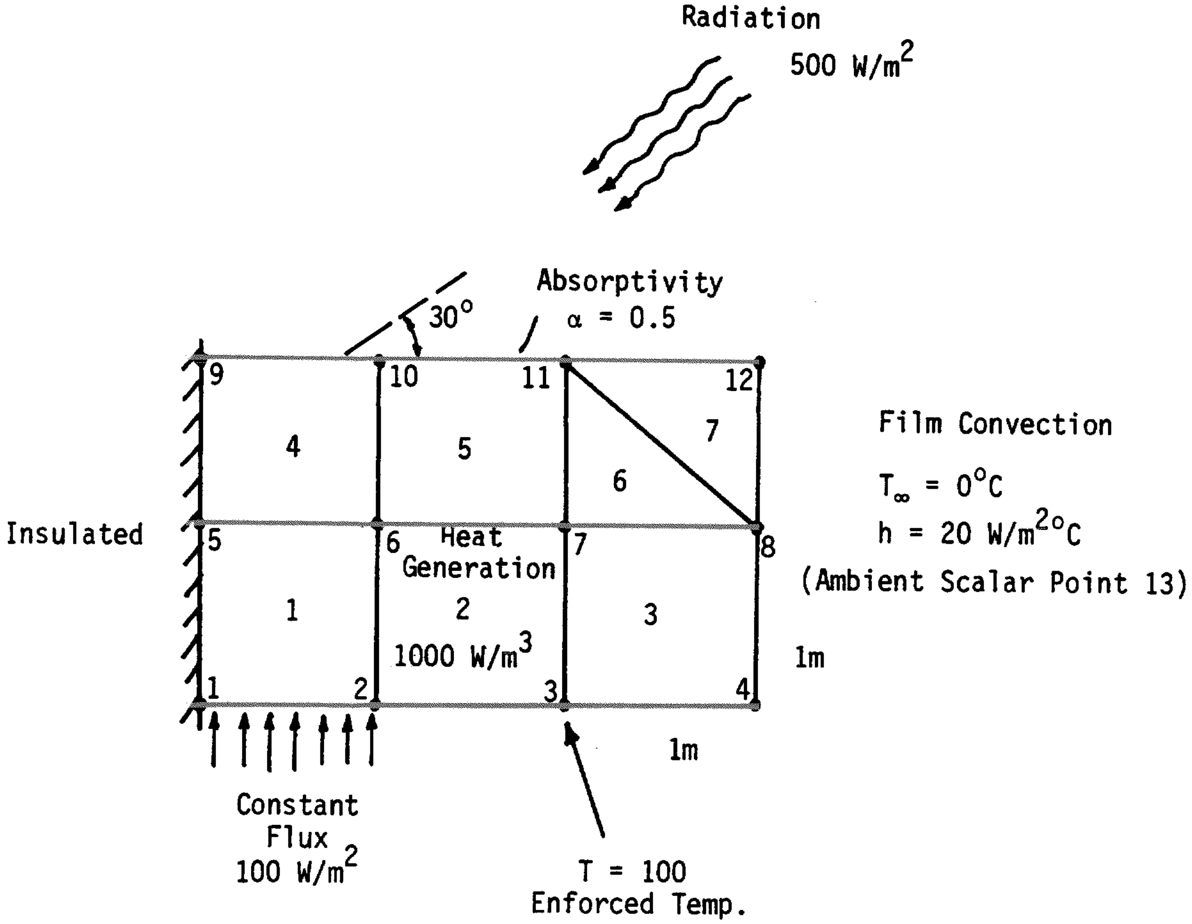

Figure 1 GRAPHICAL PROBLEM STATEMENT FOR EXAMPLE PROBLEM

2.5 Special Techniques and Time Requirements

In heat transfer, as in other NASTRAN modes, the user is encouraged to use his discretion and imagination - in addition to the tools NASTRAN offers - to devise effective means of modeling real-life problems in the best possible way. For most problems, FORTRAN programs, special sorting functions, plotting aids, pre-processors, etc., increase efficiency of the input preparation process.

In the typical application problem there will be one or more areas of the model, whose temperatures are the main objective of the analysis. A finer mesh should be used for those locations. In general, the resolution of the finite element grid should be locally matched with desired accuracy, expected temperature gradients and geometric detail. It is usually useful to model high resolution areas that are the focus of the analysis separately. Techniques increasing efficiency of the solution process in a statics solution (grid number resequencing cyclic symmetry, etc.) should apply equally to heat transfer without exceptions.

Since the degree of freedom at every grid point is only 1 for heat transfer problems, the conduction matrix for a heat transfer problem is roughly one sixth the size of the stiffness matrix in a (2-D) statics problem of the same size. Thus, decomposition time for the stiffness matrix is much shorter. On the other hand, for the same reason, the proportion of total execution time allocated to element generation is much larger, and for some problems comparable to decomposition time.

2.6 A List of Heat Transfer Related Sections in NASTRAN Manuals

The following sections in NASTRAN user's, application and theoretical manual contain detailed information on all heat transfer aspects of NASTRAN and are suggested as further reference:

a) NASTRAN USER'S MANUAL

Volume I

Chapter 1 1.8 Heat Transfer Problems

1.8.1 Introduction to NASTRAN Heat Transfer

1.8.2 Heat Transfer Elements
1.8.3 Constraints and Partitioning
1.8.4 Thermal Loads
1.8.5 Linear Static Analysis
1.8.6 Non-linear Static Analysis
1.8.7 Transient Analysis
1.8.8 Compatibility with Structural Analysis

Chapter 2 2.1 General Description of Data Deck

2.3 Case Control Deck

2.4 Bulk Data Deck

(Section 2.4 is followed by a description of all NASTRAN bulk data cards in alphabetical order. Description of heat transfer related bulk data cards is also included.)

Volume II

Chapter 3 3.2 Case Control Deck

3.2.1 Case Control Structure (Parts related to heat transfer)
3.2.2 Output Options (Parts related to heat transfer)

3.3 Solution Sequence Operations

3.3.16 Linear Heat Transfer Analysis
3.3.17 Non-linear Heat Transfer Analysis
3.3.18 Transient Heat Transfer Analysis

Chapter 4 4.1 Plotting (Parts related to structural and temperature contour plots)

4.1.1 General Capability
4.2.2 Plot Request Card Descriptions

Chapter 6 (Contains all NASTRAN diagnostic messages including those for NASTRAN heat transfer.)

b) NASTRAN THEORETICAL MANUAL

Chapter 8 Heat Transfer Analysis

- 8.1 General Features
- 8.2 Volume Heat Conduction Elements
  - 8.2.1 Constant Gradient Heat Conduction Element
- 8.3 Surface Heat Transfer
  - 8.3.1 Prescribed Heat Flux
  - 8.3.2 Convective Heat Flux
  - 8.3.3 Radiation from a Distance Source
  - 8.3.4 Radiation Exchange Between Surfaces
- 8.4 Methods of Solution
  - 8.4.1 Non-linear Steady-state Analysis
  - 8.4.2 Transient Analysis

c) NASTRAN APPLICATION MANUAL

Chapter 7 Time Estimation and Problem Execution
(Details of time and memory requirements)

Section 3

DEMONSTRATION PROBLEMS

In addition to the previous example problem, several demonstration problems are presented here in summary form. These include one, two, and three-dimensional steady-state problems, a non-linear steady-state problem and a transient problem. The bodies analyzed in these problems, their composition, geometry, properties, thermal loads and boundary conditions to which they are subject, are all hypothetical.

It should be mentioned that, because of their relative simplicity, these problems are not necessarily indicative of NASTRAN's superior modeling and analysis capabilities. However, these aspects have been chosen to differ from problem to problem, so as to require a large spectrum of NASTRAN capabilities.

3.1 One-Dimensional Linear, Steady-State Conduction (Demonstration Problem 1)

The problem chosen for this purpose was one-dimensional heat conduction through a composite wall subject to different ambient conditions (temperatures and heat transfer coefficients) on each of its surfaces. The problem is graphically stated by Figure 2.

This is a simple problem easily solved by a hand calculation to determine the 6 coefficients of the three linear temperature distributions within each material making up the wall, by using 2 boundary and 4 matching conditions.

In the NASTRAN model, 4 grid points and 3 one-dimensional (ROD) elements were used. Table 3 lists the required cards in the NASTRAN bulk data deck for this problem. The NASTRAN solution is accurate to 8 significant digits.

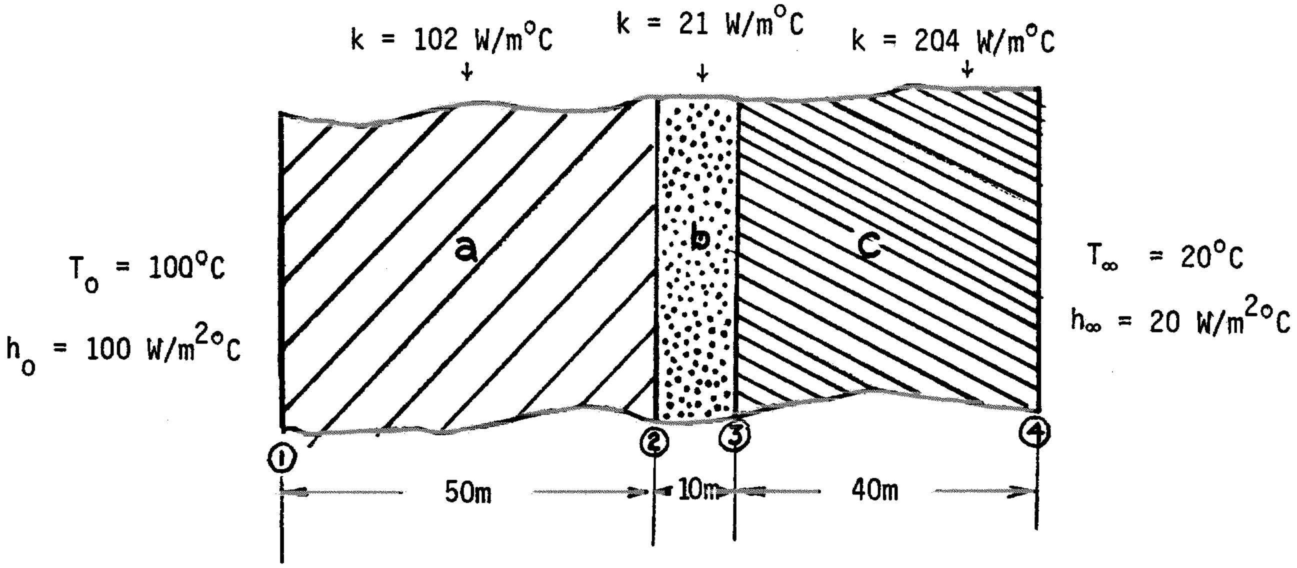

Figure 2 GRAPHICAL STATEMENT OF ONE-DIMENSIONAL LINEAR STEADY-STATE DEMONSTRATION PROBLEM

Table 3

BULK DATA DECK REQUIREMENTS FOR PROBLEM 1

CARD	# OF CARDS	EXPLANATION
GRID	4	One at boundary of each element.
CROD	3	One element for each material.
PROD	3	Element property cards.
CHBDY	2	One for each of the wall surfaces.
PHBDY	2	One for each of the wall surfaces.
MAT4	5	Three for material properties, one for each heat transfer coefficient.
SPOINT	2	One for each ambient point.
SPC1	1	Constraining each of the ambient points.
SPCD	2	One for enforcing temperature on each ambient point.
QVOL	1	Dummy load, with zero magnitude to allow SPCD cards to be referred as LOAD.
TOTAL	25	

3.2 One-Dimensional Non-Linear Steady-State Conduction (Demonstration Problem 2)

To test NASTRAN's non-linear heat transfer mode, the previous problem was again considered, but this time with temperature dependent conductivities and heat transfer coefficients as indicated in the following table:

	10°C	20°C	30°C	40°C	60°C	80°C	100°C	120°C
k_a	-	61.2	-	81.6	102	122.4	142.8	163.2
k_b	-	4.2	-	16.8	25.8	-	-	-
h_∞	183.6	224.4	265.2					

k_c and h_o were taken as uniform and the same as in linear problem.

To model this problem the NASTRAN data deck for the linear problem was modified as follows:

a) The NASTRAN HEAT = 1 card was removed.

b) The SOL 24 card in executive data deck was changed to SOL 53.

c) 100 rod elements and 101 grid points were used instead of 3 and 4 respectively.

d) A TEMPERATURE (ESTIMATE) card was added to case control deck to refer to initial guess.

e) The cards described in Table 4 were added to the bulk data deck.

NASTRAN predicted temperature profiles for demonstration problems 1 and 2 are shown in Figure 3.

Table 4

ADDITIONAL BULK DATA REQUIRED FOR PROBLEM 2

CARD	# OF CARDS	EXPLANATION
MATT4	3	To make properties in three of the MAT4 cards temperature dependent.
TABLEM2	3	To describe temperature dependence of k_a, k_b, k_∞.
PARAM	2	One to specify convergence criterion, one to give maximum number of allowed iterations.
TEMP	101	To provide an initial guess of the temperature distribution for the iterative solution procedure.

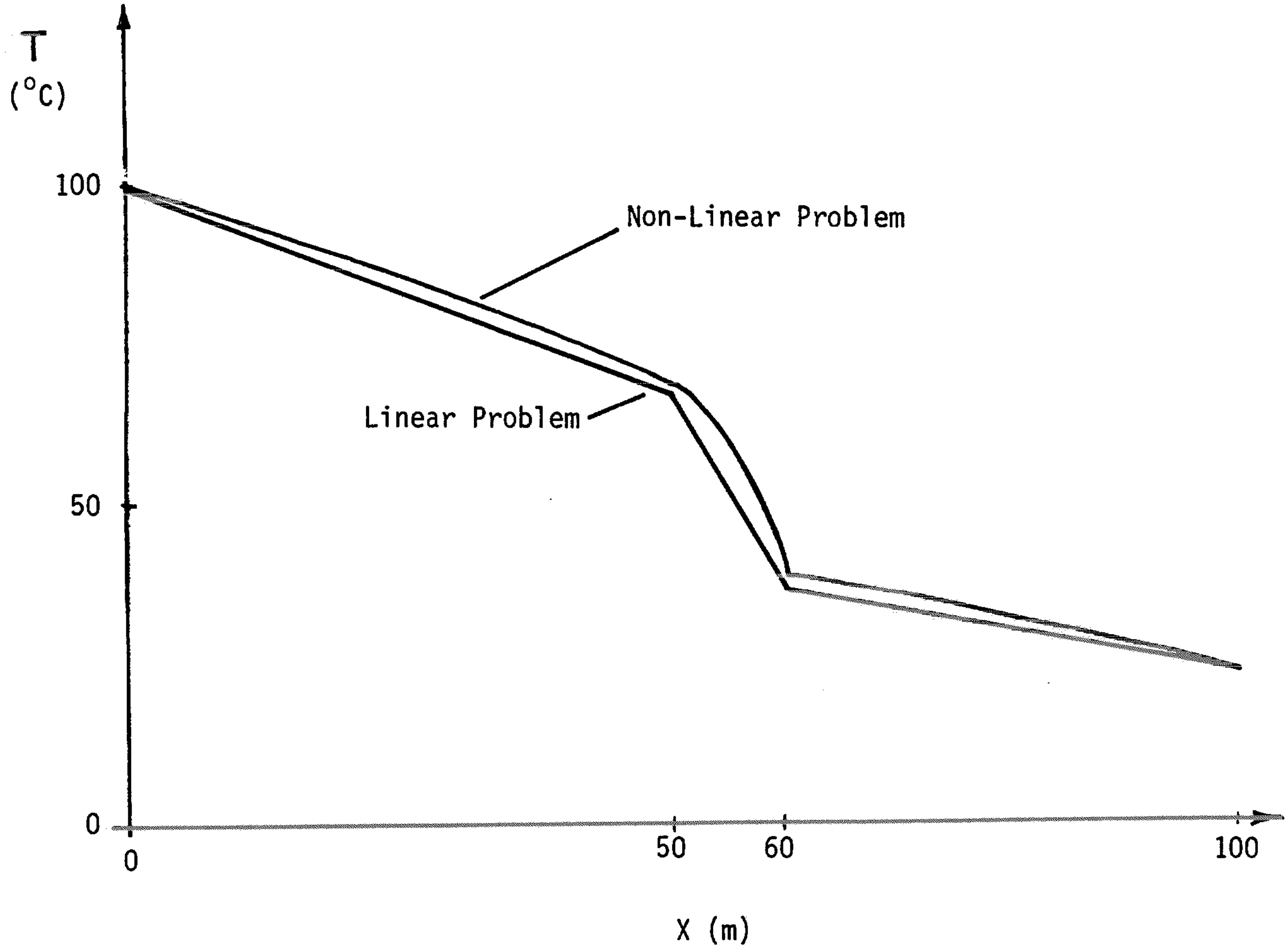

Figure 3 NASTRAN-PREDICTED TEMPERATURE PROFILES IN COMPOSITE WALL FOR DEMONSTRATION PROBLEMS 1 (LINEAR STEADY-STATE CONDUCTION) and 2 (NON-LINEAR STEADY-STATE CONDUCTION)

3.3 One-Dimensional Transient Conduction (Demonstration Problem 3)

The input data for problems 1 and 2 was further modified to model a comparable but transient problem. In this problem the ambient temperatures on each side of the wall are 0°C, heat transfer coefficients are the same, and the initial wall temperature is uniform and 20°C. The transient problem objective is thus the determination of temperature profiles within the wall during the period of cooling from 20°C to 0°C. The heat capacity per unit volume was defined as 78 $\mathrm{Whr/m^{3\circ}C}$ for all three wall materials and 7.8 $\mathrm{Whr/m^{3\circ}C}$ for both films.

The bulk data cards required for the transient problem are listed in Table 5. NASTRAN predicted temperature profiles for this problem are shown in Figure 4.

3.4 Two-Dimensional Heat Conduction (Demonstration Problems 4, 5 and 6)

A large variety of heat transfer problems are in practice reducible to a form requiring only a two-dimensional solution. These usually involve any situation where heat transfer perpendicular to a plane in a body is negligible. Then, only heat transfer analysis of that plane is conducted. Three such demonstration problems will be presented herein.

The first of these - demonstration problem 4 - is graphically stated in Figure 5 (a). The figure may be thought of as the cross-section of a slab imbedded in soil, with one surface facing the ambient atmosphere and two internal lineal heat sources. The problem was modeled using NASTRAN QUAD4 elements as shown in Figure 5 (b). Figure 5 (c) shows the NASTRAN predicted isotherms.

Figure 6 (a-c) similarly shows problem statement, FEM model and NASTRAN temperature solution for demonstration problem 5. This two-dimensional problem concerns the temperature distribution on the triangular cross-section of a slab, which is heated on one side, insulated on another and is convection cooled at a thrid side. There is also a square region of constant temperature within the slab.

Table 5

BULK DATA MODIFICATION NEEDED FOR TRANSIENT PROBLEM 3

CARD	# OF CARDS	EXPLANATION
CHBDY	2	Same purpose as in steady-state problem.
CROD	100	
GRID	101	
MAT4	5	
PHBDY	2	
PROD	3	
QVOL	1	
TABLED1	1	(To define time dependence of load.)
TLOAD1	1	(To make loads time dependent.)
TSTEP	1	To define time step for integration.
TEMP	101	To define initial condition.

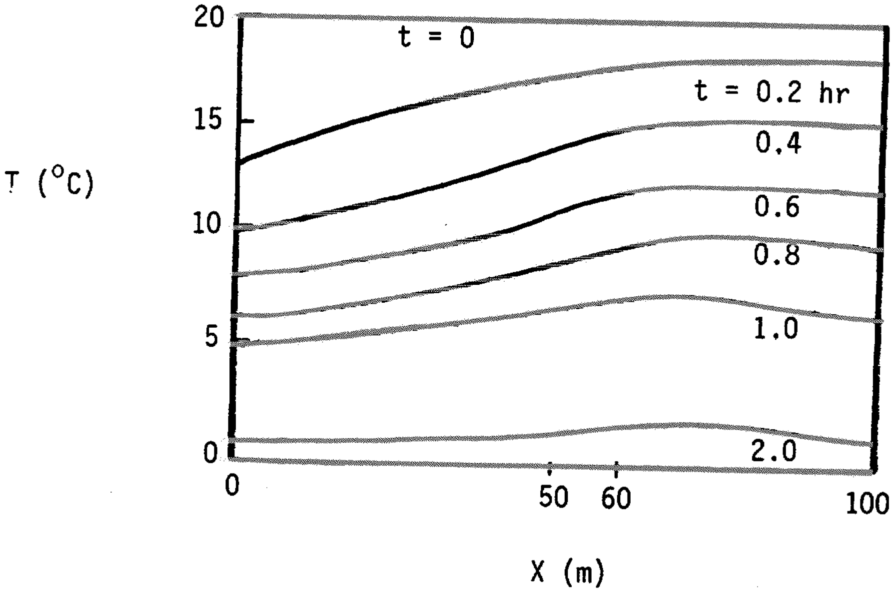

Figure 4 TRANSIENT TEMPERATURE PROFILES IN COOLING WALL (DEMONSTRATION PROBLEM 3) AS PREDICTED BY NASTRAN

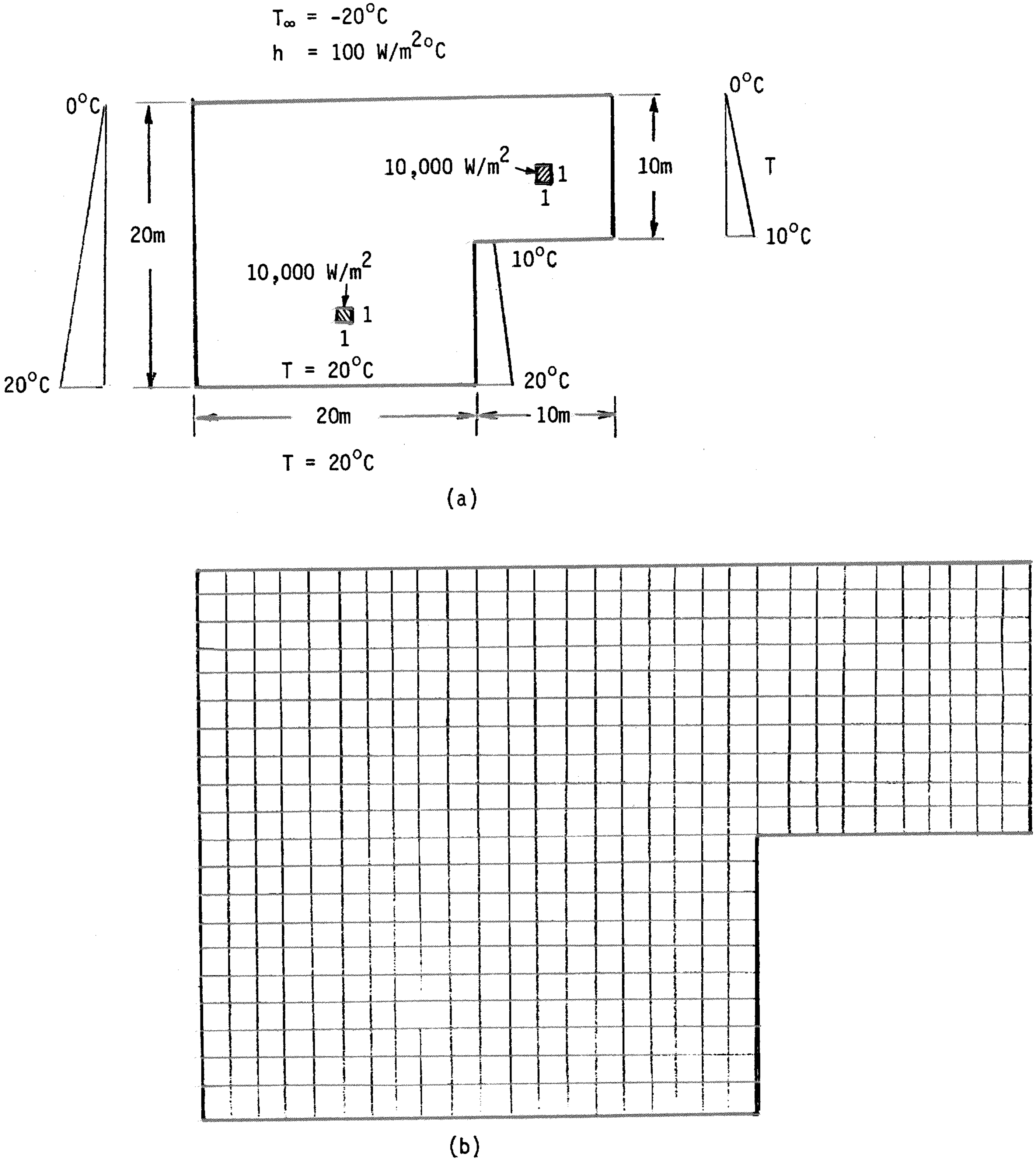

Figure 5 (a) GRAPHICAL STATEMENT OF DEMONSTRATION PROBLEM 4
(b) FEM MODEL SHOWING GRID AND ELEMENTS

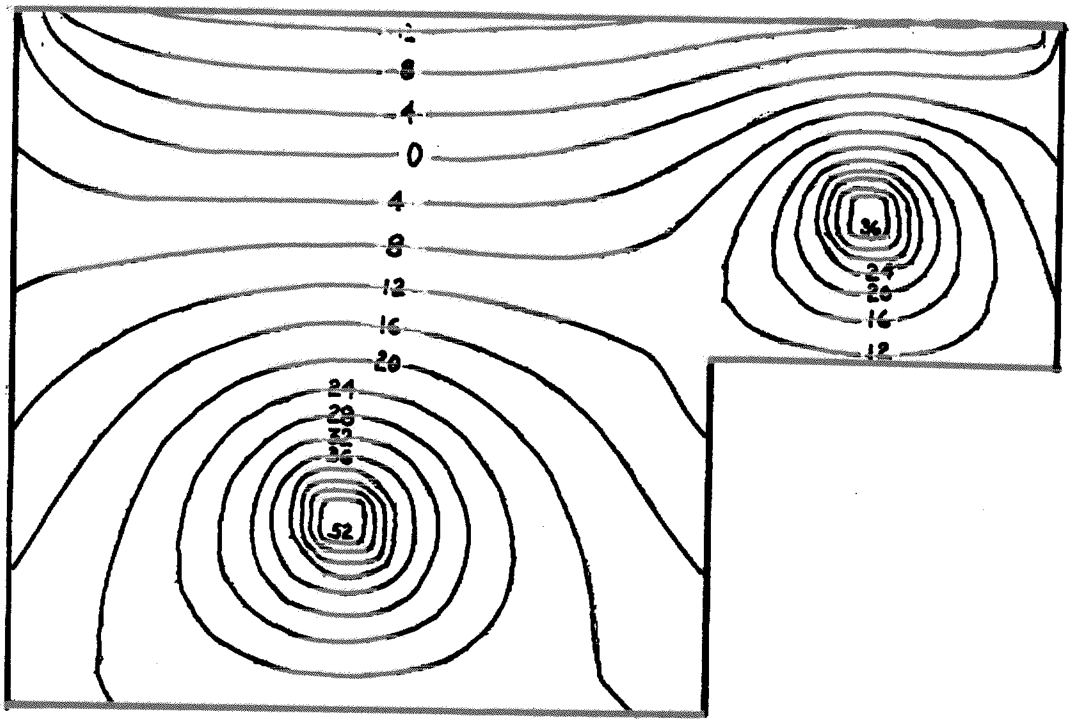

Figure 5 (c) NASTRAN PREDICTED TEMPERATURE CONTOURS FOR SOLUTION OF DEMONSTRATION PROBLEM 4

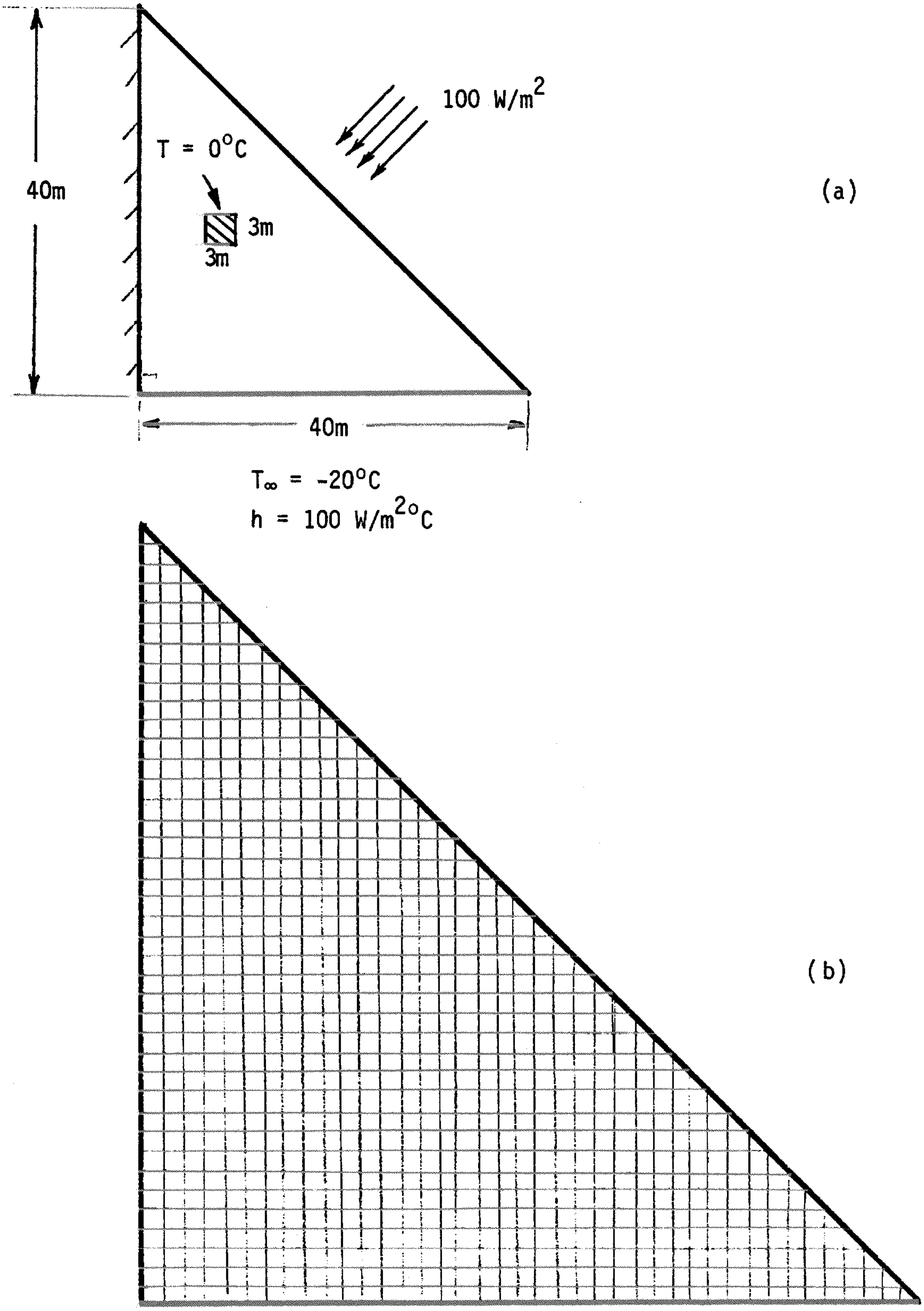

Figure 6 (a) GRAPHICAL PROBLEM STATEMENT FOR DEMONSTRATION PROBLEM 5

(b) FINITE ELEMENT MESH

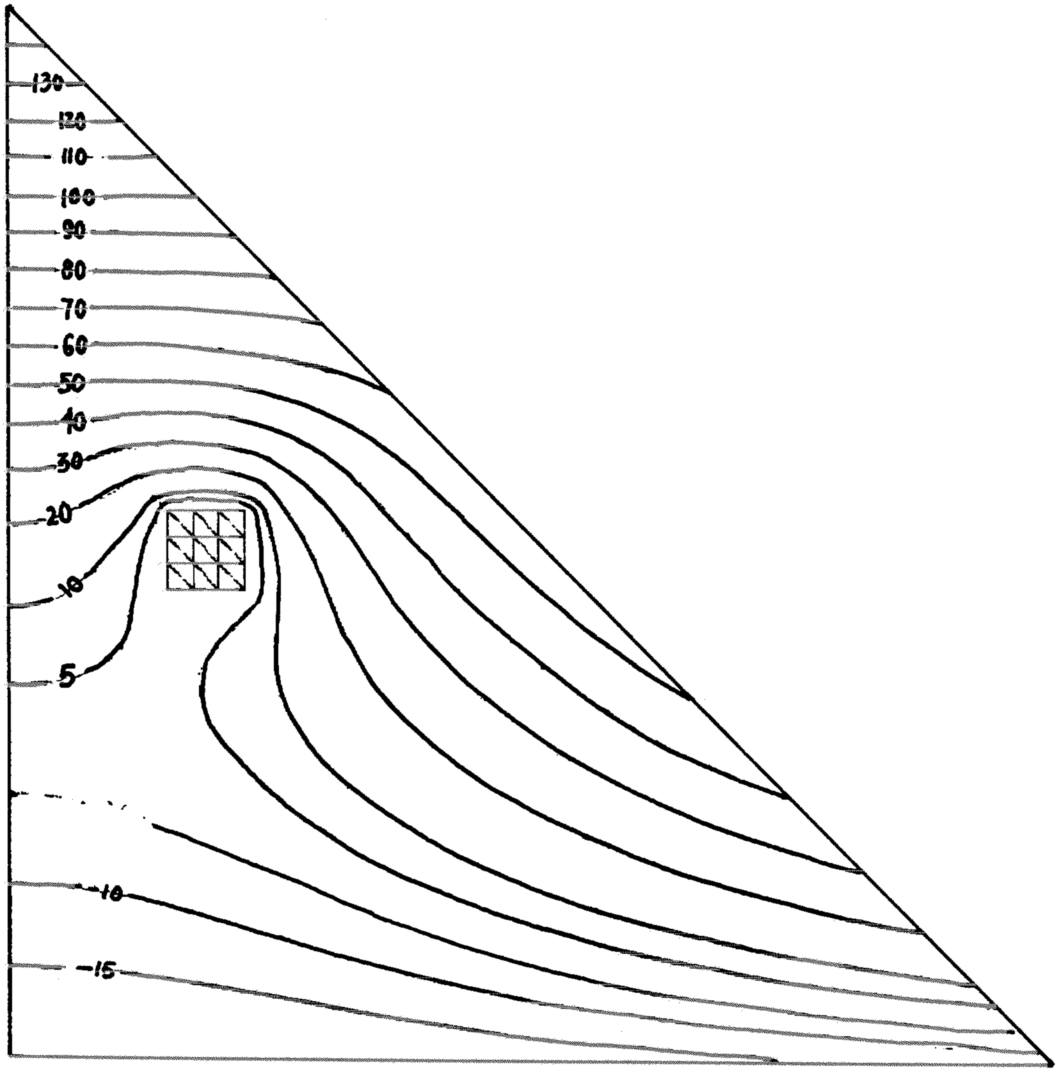

Figure 6 (c) NASTRAN-PREDICTED TEMPERATURE SOLUTION FOR DEMONSTRATION PROBLEM 5

The third 2-D demonstration problem, Figures 7 (a-c), concerns the cross-section of an internally cooled pipe subject to perpendicular radiation heat flux. Because of the symmetry with respect to the horizontal plane bisecting the cross-section, only one-half of it has been modeled.

Table 6 lists NASTRAN bulk data cards used for each of the three 2-dimensional demonstration problems.

3.5 Three-Dimensional Heat Conduction (Demonstration Problem 7)

Figure 8 (a) shows a rectangular slab subject to different convection cooling heat transfer coefficients on each of its faces, and with internal volume heat addition. This is the subject of demonstration problem 7 used to test NASTRAN's three-dimensional heat transfer capability. A quarter-model constructed of stacked NASTRAN 8-cornered HEXA elements was used for this problem (Figure 8 (b)). Figure 8 (c) shows the NASTRAN-predicted temperature solution on visible surfaces of the body, with hand-drawn contours.

The list of NASTRAN bulk data cards used to generate the FEM model for demonstration problem 7 is given in Table 7.

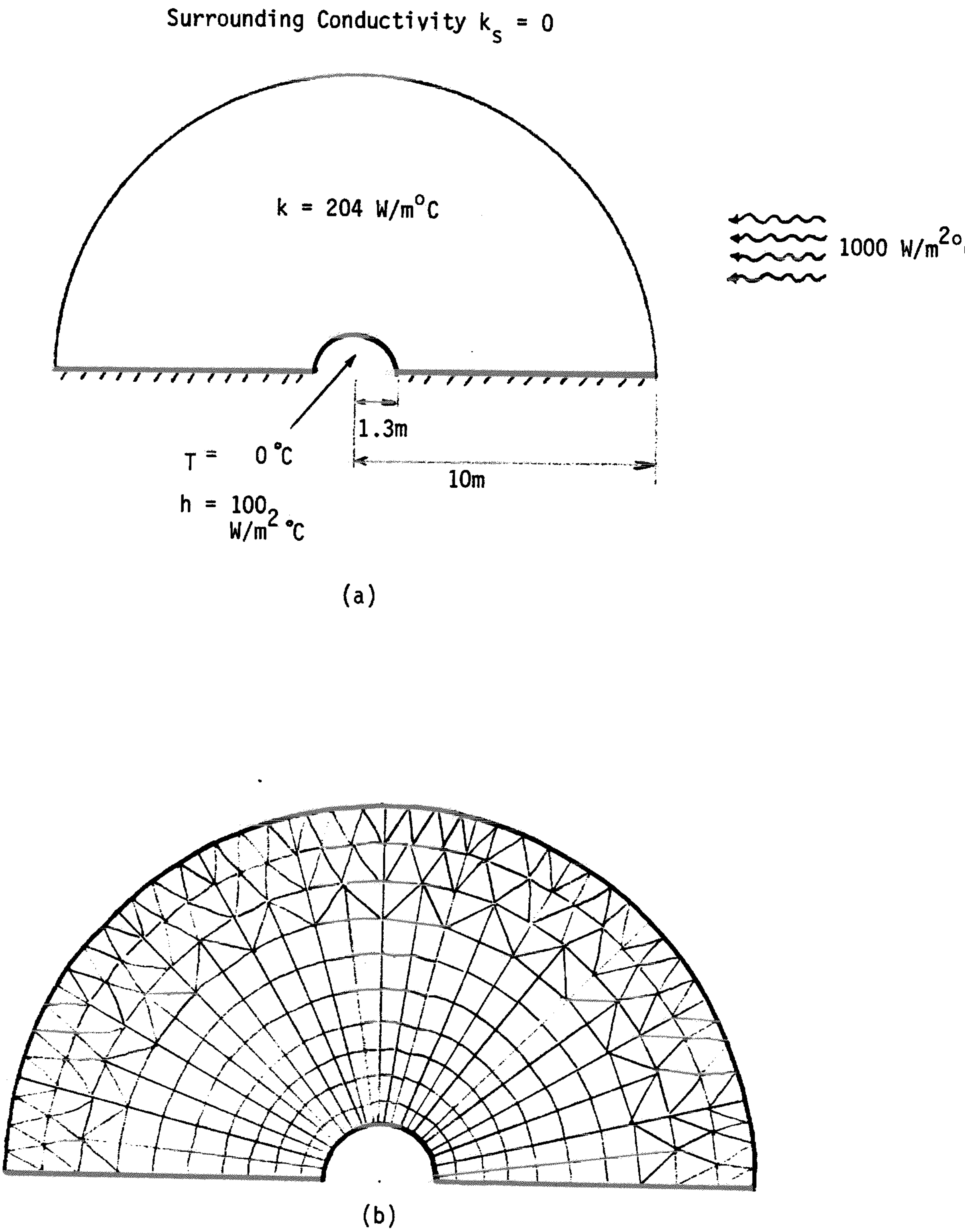

Figure 7 (a) GRAPHICAL PROBLEM STATEMENT
(b) FINITE ELEMENT MESH, FOR DEMONSTRATION PROBLEM 6

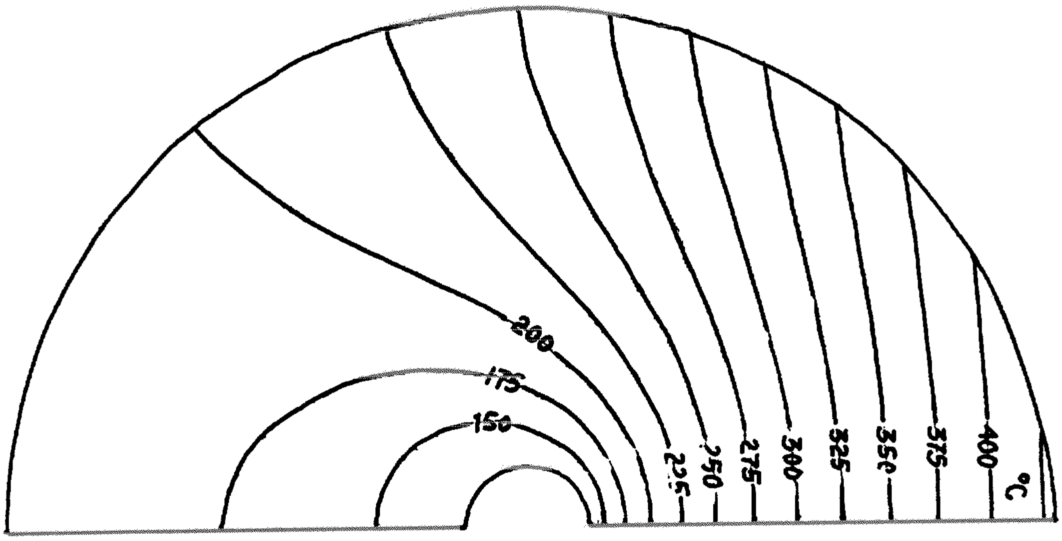

Figure 7 (c) NASTRAN-PREDICTED TEMPERATURE SOLUTION FOR PROBLEM 6

Table 6

NASTRAN DATA CARDS FOR TWO-DIMENSIONAL DEMONSTRATION PROBLEMS

CARD	# OF CARDS			EXPLANATION
	DP-4	DP-5	DP-6	
CHBDY	30	80	24	All of the LINE type. To define boundaries other than insulated or fixed temperature.
CORD2C			1	To define cylindrical coordinate system DP-3
CQUAD4	500	780	168	QUAD4 element convection cards.
CTRIA3		40	192	TRIA3 element convection cards.
GRID	551	861	311	Grid point coordinates.
MAT4	1	2	2	Material properties (conductivity, heat transfer coefficient).
PHBDY	1	1	1	Boundary element property card.
PQUADY	1	1	1	QUAD4 element property card.
PSHELL		1	1	TRIA3 element property card.
QBDY1		7		Surface heat flux (DP-5)
QVOL	2	1		Volume heat addition (DP-4)
QVECT			1	Directional (radiation) heat flux (DP-6)
SPC1	1	1	1	To constraint grid or ambient point temperatures.
SPCD	64	1	1	To enforce grid or ambient point temperatures.
SPOINT	1	1	1	To define an ambient scalar ambient point.
TOTAL	1150	1177	705	

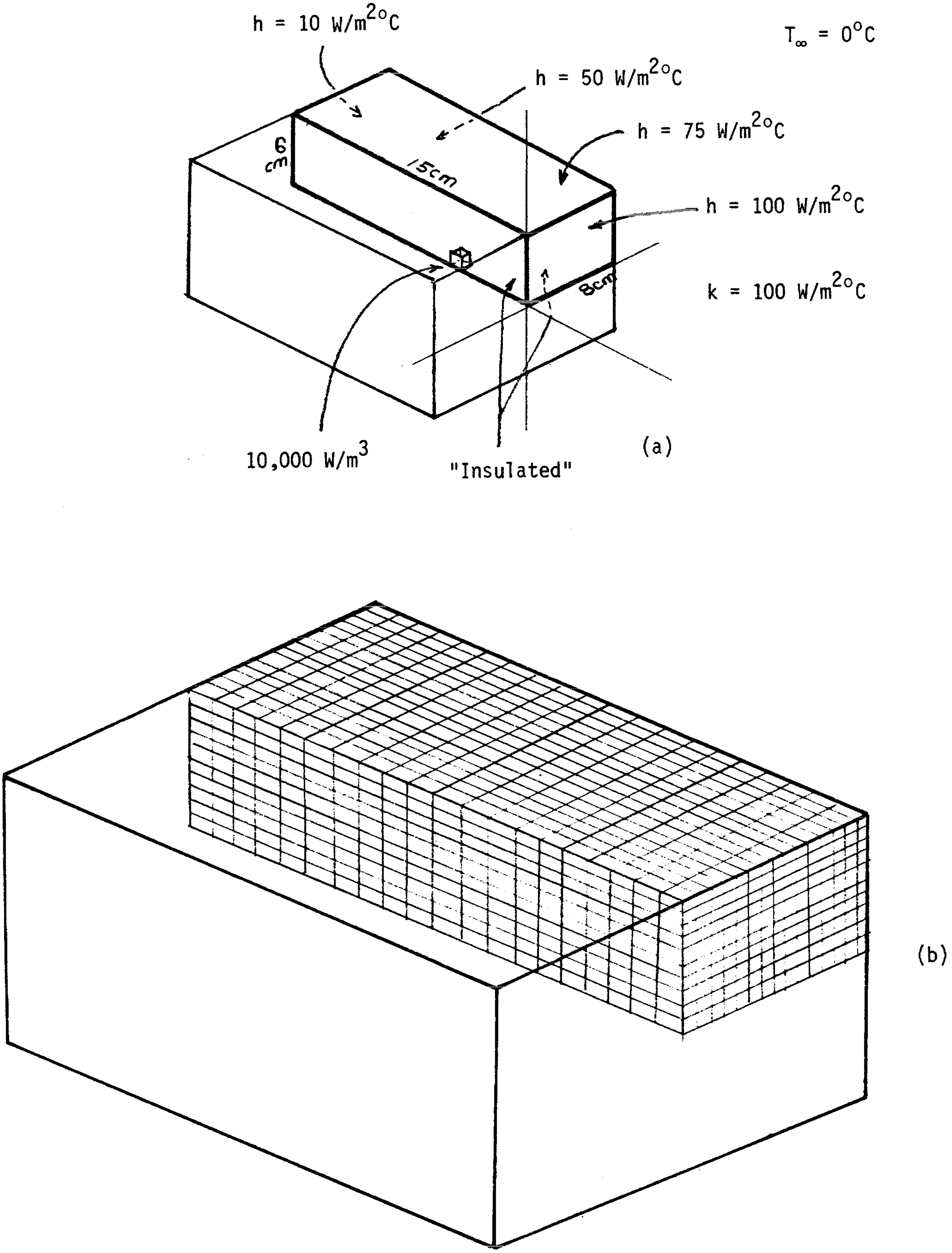

Figure 8 (a) GRAPHICAL PROBLEM STATEMENT AND
(b) FEM MESH FOR DEMONSTRATION PROBLEM 7

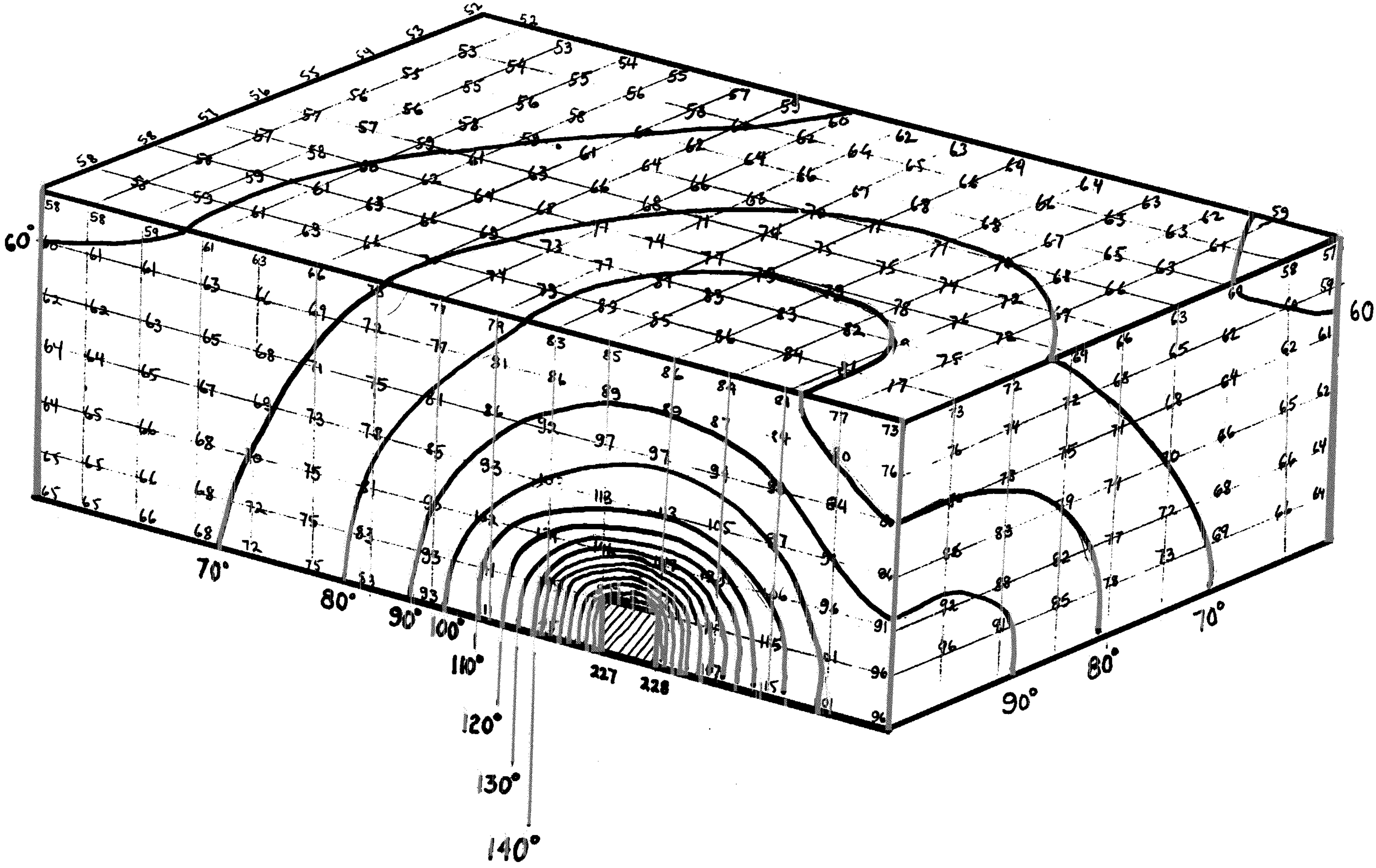

Figure 8 (c)
NASTRAN TEMPERATURE SOLUTION ON THREE SURFACES OF SLAB, FOR

Table 7

BULK DATA REQUIRED FOR PROBLEM 7

CARD	# OF CARDS	EXPLANATION
GRID	1008	Grid cards.
CHEXA	720	Connection cards for HEXA elements.
PSOLID	1	Element property cards for HEXA elements.
MAT4	5	One for conductivity, 4 for heat transfer coefficients.
QVOL	1	Volume heat addition.
SPC1	1	To constrain ambient scalar points.
SPCD	1	To enforce ambient temperatures.
SPOINT	1	To define ambient (scalar) point.
CHBDY	306	To describe boundaries subject to convective cooling (AREA4 type).
PHBDY	4	HBDY element property card.

Section 4

DISCUSSION AND RECOMMENDATIONS

4.1 General

MSC/NASTRAN offers three types of heat conduction analysis capability with a large array of available finite element types and virtually without geometric limitation. Each of the three heat transfer rigid formats is equipped with versatile features providing for a wide variety of situations encountered in heat transfer analysis. While not compatible with certain heat transfer problems (for example, conduction with phase change), the MSC/NASTRAN heat transfer capability constitutes a powerful and efficient analytical tool within its realm of applicability.

Currently the MSC/NASTRAN heat transfer capability remains a peripheral extension of NASTRAN's main applications in solid mechanics and is therefore a subset of a much larger program package than that needed for heat transfer. This is the ideal arrangement for heavy users of NASTRAN solid mechanics capabilities, who on occasion (usually prior to thermal stress analysis) would like to perform heat transfer analyses. It is, however, hard to refute arguments of those who propose that using NASTRAN for heat transfer alone is an overkill, considering the investment in rental fees and education of users.

4.2 Efficiency and Reliability

Table 8 documents model generation and execution times for demonstration problems discussed in Section 3. Finite difference solutions of problems 2 to 7 by an experienced analyst involved comparable execution times and programming times of the order of or somewhat shorter than model generation times. However, for problems encountered in practice, the benefits of using NASTRAN could be much more pronounced. If possible at all, a finite difference solution procedure for complex problems would be an extremely cumbersome and lengthy affair.

Table 8

SUMMARY OF TIME REQUIREMENTS

Problem Description		Problem Type*	# of Grid Points	# of Elements	# of HBDY Elements	Execution (CPU) Time Min.	Sec.	Model (NASTRAN Input) Generation Time, Man-Days**
Demonstration Problems	1	L1	4	3	2	0	10	less than ½
	2	N1	101	100	2	0	21	½
	3	T1	101	100	2	0	40	½
	4	L2	551	500	30	0	53	1
	5	L2	861	820	80	1	17	1½
	6	L2	311	360	24	0	39	2
	7	L3	1008	720	306	3	05	2

* L = steady-state linear, N = steady-state non-linear, T = transient, 1-2-3 = 1, 2 or 3-dimensions.

** For moderately experienced user. Add 50% for subsequent debugging and trouble-shooting.

4.3 Static Analysis vs. Heat Transfer

Simply due to the reduced number of degrees of freedom for the same number of grid points involved, heat transfer problems are simpler and more economical to model and analyze than static problems. Consequently for the same cost, a heat transfer problem can be modeled with a finer grid resolution, thus producing results with greater accuracy, than a static problem. Normal heat transfer problems, however, are usually difficult to describe. The formal statement of the problem generally requires some research to establish the right boundary conditions.

There is also some discrepancy in the way execution time is distributed among different operations during heat transfer and statics problems, as shown in Table 9.

4.4 Other Analogous Capabilities

Users should be reminded that the MSC/NASTRAN statics mode and its heat transfer extension imply several other analogous capabilities such as electrostatics, ideal/irrotational flow, mass transfer and other diffusion phenomena. With proper knowledge of the particular analogy, MSC/NASTRAN heat transfer features can be tailored to be used for each of these areas.

4.5 Suggestions for Future Expansions

The following are suggestions for possible future MSC/NASTRAN heat transfer expansions:

a) Coupled heat transfer/stress analysis capability (for thermal stress analysis or stress analysis with temperature dependent elastic properties).

b) Transient conduction heat transfer capability with freezing/melting-ablation provision.

c) Temperature contour plots on surfaces and sections of solid elements. (While "deformed" plots and arrows are adequate for most stress analysis problems, contours are more useful in thermal analysis.)

Ultimately one would like to see a convection heat transfer capability. However this implies support of computational fluid mechanics, a broad and developing area that has yet to be supported by mature program packages such as NASTRAN.

Table 9

DISTRIBUTION OF EXECUTION TIME FOR TYPICAL HEAT TRANSFER AND STRESS ANALYSIS PROBLEMS

	Sample 3-D Heat Transfer Problem*		Sample 3-D Stress Analysis Problem**	
	Time (sec)	%	Time (sec)	%
Initial Processing	666.3	13.7	101.5	1.4
Element Generation	1636.1	33.8	1365.7	18.5
Decomposition	2336.3	48.3	5196.6	70.5
Forward/Backward Substitution	115.2	2.4	96.3	1.3
Stress (Flux) Recovery, etc.	81.8	1.8	601.5	8.3
TOTAL	4835.7	100.0	7361.6	100.0

* with about 9850 HEXA and PENTA elements, 2200 HBDY elements. RMS baud with ~ 235.

** with about 2350 HEXA and PENTA elements. RMS baud with ~ 121.