NASTRAN THERMAL ANALYZER IN A UNIFIED FINITE-ELEMENT TREATMENT OF THERMO-STRUCTURAL ANALYSES

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ABSTRACT

For solution accuracy, modeling efficiency and cost effectiveness, the NASTRAN Thermal Analyzer (NTA) is suited to treat large-scale unified thermo-structural analyses with the NASTRAN (NAsa STRuctural ANalysis) computer program. The mathematical similitude between these two distinct disciplines of thermal and structure is examined. It serves as the theoretical basis upon which the implementation of the thermal capability in NASTRAN was accomplished. The program structure, the functional flow, the solution algorithms, the organization of an input data deck and the solution capabilities of NTA are summarized. Emphasis is placed on the interface of the unified approach in thermo-structural analyses where stresses, deflections, vibrations and bucklings induced by the effect of temperature change are of concern. Attentions are also directed to the pre-processor and post processors. As a specially designed pre-processor, the VIEW program is capable of generating exchange factors which can be output, at user's option, in formats compatible with that required by NTA. Two post processors that serve specific objectives are included. They are the thermal variance analysis and the graphical displaying capability of temperatures in color or B&W.

INTRODUCTION

The NASTRAN Thermal Analyzer is a general-purpose thermal analysis computer program that has been developed and integrated in the NASTRAN System (Refs. 1, 2). This thermal analysis capability was implemented using applicable functional modules of NASTRAN which had been developed for structural analysis originally. However, a number of new modules were developed and added to satisfy unique requirements for thermal analysis. They comprised new elements and new solution algorithms. The feasibility of utilizing the structural elements and functional modules in thermal application lies with the mathematical similitude that exists in the two distinct disciplines. The intrinsic modular structure of NASTRAN permits a direct abstraction of its matrix functional modules to be arranged in proper solution sequences for thermal analysis. As a consequence, the NTA is unique in that its thermal model is fully compatible with the structural NASTRAN model at the grid point and element level. This feature is invaluable in unified treatment of thermo-structural analyses especially for problems of large size and complex configuration, where stresses, deflections, vibrations and bucklings induced by the temperature effect are of concern.

This paper starts with an examination of the mathematical similitude between the two disciplines of thermal and structure after both governing equations are cast in the matrix form following the finite element methodologies. Equivalence of terms between the two physical systems will be identified as they are essential to use structural functional modules or terminologies in thermal analysis. The program structure which conforms to that of the NASTRAN will be presented. The most frequently employed bulk data cards will be listed. They are thermal conduction elements, boundary surface elements, material properties, thermal loadings, etc. The three solution algorithms spanning the whole spectrum of interested thermal problems will be included.

In aerospace applications, thermal radiation plays an important role in heat transporting process. Geometric view factors are required in thermal analysis when radiative exchanges prevail. The pre-processor VIEW (Refs. 3, 4) was designed to compute the exchange factors. This stand-alone software program is in full compatibility with the NTA. At the input end, the VIEW uses the same boundary surface elements CHBDY* of the NTA model to define radiatively active surfaces. At the other end of output, an option to output the exchange factors in formatted cards directly useable in an input data deck of the NTA is available to users. The functional structure and the program organization of VIEW together with the unique data card $VIEW will be presented. A partial listing of a typical data deck to generate view factors, results and an NTA input data deck embracing the exchange factors in the formatted card forms of RADLST and RADMTX will be illustrated.

Regarding post processors, a few relevant programs that are operational at Goddard Space Flight Center will be included. They serve specific objectives. The thermal variance analysis (Ref. 5) and the visual display of temperatures or temperature gradients (Ref. 6) will be described.

THEORETICAL BASIS FOR PROGRAM IMPLEMENTATION

Theoretical finite element treatment of thermal conduction analysis and its extensions to include radiative exchanges can be cited in Refs. 7-9. The NTA was implemented in accordance with the general heat equation in the matrix form as follows

$$[C]\left\{\dot{T}\right\} + [K]\left\{T\right\} = \left\{Q^{\ell}\right\} + \left\{Q^{n}\right\} \qquad (1)$$

where

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

$\left\{\dot{T}\right\}$ = a vector of rate-change-of-temperatures at grid points

*Names of actual NTA cards are capitalized and underlined.

$[C]$ = a symmetric matrix of heat capacitance

$[K]$ = a symmetric matrix of thermal conductance

$\{Q^g\}$ = a vector of applied thermal loads (constant or time-dependent)

$\{Q^n\}$ = a vector of nonlinear thermal loads.

The preceding expression implies three classes of problems that require separate solution algorithms. As stands, Eq. (1) represents an unsteady-state heat equation. However, it represents a steady-state case when the term $\{\dot{T}\}$ vanishes, and the linear and nonlinear steady-state cases are treated differently.

The NTA is a component in the NASTRAN system and mathematical similitude can be drawn between the structural and thermal systems (Fig. 1). A number of elements, modules, and the input and output parameters of NASTRAN were used in "borrowed" forms for the NTA as a consequence. They include the input file processor, the geometry processor, constraining, partitioning of matrices, etc. together with all structural finite elements except the excessive DOF's (degrees-of-freedom) at each vertex of an element being constrained properly.

PROGRAM STRUCTURE AND FUNCTIONS

The NTA also shares the same program structure as the structural counterpart. Its input and output formats were so designed that they are fully compatible with those of NASTRAN. A complete NTA input data deck consists of three parts:

(1) Executive Control Deck
(2) Case Control Deck
(3) Bulk Data Deck

Their functions are listed in Fig. 2. The functional flow of the bulk data cards relative to the definition, constraints and thermal loadings of a thermal model is shown in Fig. 3. The Bulk Data Deck constitutes the main body of a complete input data deck. The frequently used bulk data cards appear in Fig. 4.

In a model, the heat conducting structure is formed by heat conduction elements that are interconnected at grid points. Various heat conduction elements are provided. They consist of 1-D rods, 2-D triangular and quadrilateral plates and axisymmetric rings of triangular as well as trapezoidal cross-sections, and 3-D solids such as wedges, tetrahedra and hexahedra, as presented in Fig. 5. Also included are scalar heat conduction elements (CELASi) which may serve as linear thermal conductors connecting pairs of grid points with specified thermal conductances. The CHBDY is a special boundary surface element which serves as a medium in exchanging heat from external environment to the overlaid conduction element through the attached grid points.

Thermal loads of constant and time-varying quantities may be applied directly to grid points, or via the boundary surface elements. The types of thermal load included in this program are the concentrated load applied to a grid point, the internally generated heat within an element, and the uniform heat flux as well as the directional thermal radiant source applied to the surface of an element.

Various constraints can be applied to grid points. The single-point constraint is used in the steady-state case to specify prescribed temperature at a grid point. The multipoint constraint is used to specify a linear relationship of temperatures at selected grid points. Omitted points are constrained to reduce the number of unknown temperatures in the transient thermal analysis.

The NTA has been provided with three specialized solution algorithms that are able to yield accurate, efficient and stable solutions. They are:

(1) Linear steady-state case: This solution is of a matrix inversion process,

(2) Nonlinear steady-state case: This solution employs an iterative process,

(3) Transient thermal analysis including both linear and nonlinear boundary conditions: This integration algorithm uses the modified Newmark-β method (Ref. 10), which allows a user to select a value for the parameter β in the range of $0 \leqslant \beta \leqslant 1$. This expression together with special cases is given in Fig. 6.

To solve a specific type of physical problem, the NASTRAN has a formatted and permanently stored sequence of macro-instructions to execute mathematical modules, and it is called a Rigid Format. Therefore, three Rigid Formats have been formed for NTA. Other NASTRAN features such as the DMAP (direct matrix abstraction program) and ALTER (a similar user-oriented program modification but to a lesser degree) are also available to the NTA users.

With NASTRAN, the NTA is especially suited to treat large-scale unified thermo-structural problems. The only limitations on the problem size are those imposed by practical considerations of the execution time and by the ultimate capacity of auxiliary storage devices. There is no dimension statement in the program.

In unified thermo-structural analyses, the grid point temperature data, as required by NASTRAN to analyze thermally induced structural responses, are provided directly by the NTA through the TEMP data cards. This can be achieved by using a pair of compatible models. Specifically, the input data decks for these two distinct disciplines share the same basic model of the finite element discretization. Two separate input card decks, however, are still required. Either the NASTRAN structural model or the NTA thermal model can be the first to become available in the back-to-back analyses. Alterations of cards in the input deck for the second model need be made only from the one first in existence to accommodate constraints, loadings, material properties, parameters, etc. in accordance with the problem description. While remaining useable for those cards defining grid points and connection cards (element descriptions), they generally constitute the main body of a bulky input data deck, which would be the most labor-intensive and time-consuming effort to model and prepare independently. When thermo-structural analyses are performed in tandem, the structural model, satisfying mechanical requirements and design criteria, is usually the first to be created. The modification or transformation of model is, therefore, from a NASTRAN structural model to an NTA thermal model.

A PREPROCESSOR – VIEW

The VIEW program (Ref. 3) was specifically designed to yield the view factors, F_{ij}, and then the exchange factors, A_iF_{ij}, that are required in thermal analysis with surfaces that are active in radiative exchanges. The VIEW was originally designed to run on an IBM System/360 operating under OS (Operating System), with a minimum region size of 110 K bytes. This computer program takes into account the presence of any intermediate surfaces. It computes these view factors either by the contour integration or by the double area summation method. The former is known to be more accurate but less efficient. Either method may be selected or a criterion may be specified which causes the program to select the best method based upon the geometry of the problem.

As a preprocessor to NTA, the following compatibility requirements are featured:

(1) Accept GRID and CHBDY from the NTA model as the input to VIEW for surface definition,

(2) Produce the output RADLST and RADMIX in the formats acceptable to the NTA model.

Additional features of this program include:

(3) A restart capability, which protects a user against having to rerun an entire problem should a computer failure occur.

(4) The ability to dynamically allocate available core space, thus allowing the user to request the amount of space in the computer required for ones problem by using the region parameter on the job card. There is no maximum number of elements to which the user is limited, except that the computer's capacity may not be exceeded.

(5) The ability to accept one or a combination of two input formats. The VIEW program can accept both data formats of the RAVFAC-type and the NASTRAN-type inputs.

(6) The ability to run several problems in sequence in one job submission. Each problem run is referred to as a "case."

Five basic element shapes may be described by using the NTA data card CHBDY. Each of these shapes has a given name as shown in the table:

Element Shape	Name
Circular plate	POINT element
Rectangular plate	LINE element
Conical or cylindrical shell	REV element
Triangular plate	AREA3 element
Quadrilateral plate	AREA4 element

Describing the dimension and location of these five elements is accomplished by using grid points.

The functional flow of the VIEW program is given in Fig. 7, and the organization of an input data deck is shown in Fig. 8. The unique input data card $VIEW is used to define element characteristics such as the specifications of sub-element mesh sizes in x and y directions for surface integrations, the shading flags, etc.

The listing of a typical input data deck of VIEW and a typical output are reproduced in Fig. 9. The exchange factors in the force directly admissible to an NTA data deck is illustrated in Fig. 10.

POST PROCESSORS

(1) Thermal Variance Analysis

This solution capability developed and integrated in NTA is capable of assessing the sensitivity of temperature variance resulting from uncertainties inherent in input parameters, which may include geometry, material properties, applied thermal loads, etc. The computational process is to modify the input data, to calculate partial derivatives of the output temperatures and to compute the variances of the output quantities.

Two new data cards /VARY and /PARM were introduced for modifying the input bulk data. A module VARIAN was added to compute variance of any output quantity ϕ, and it is based on the relationship of the form

$$\text{Variance}(\phi) = \left[\Sigma \left(\frac{\partial\phi}{\partial S_k} \cdot \Delta S_k\right)^2\right]^{1/2}$$

(2) Visual Display of Temperatures

The capability of visual display of temperatures or temperature gradients in color or B&W has been installed at GSFC. The Grinnell GMR-275 Image Display System together with a software package MOVIE • BYU have served as a post processor to NTA to show temperature results graphically. The basic capability of the Grinnell GMR-275 includes the following:

(A) Color or black and white display of up to 512 X 512 pixel images with 8-bits of data at each pixel.

(B) Software-controlled hardware-implemented zoom and pan.

(C) Three 8 X 10 look-up tables to control false color displays.

(D) Vector drawing.

(E) Split-screen.

The software MOVIE • BYU (Brigham Young University) contains several components which are Fortran programs for the display and manipulation of data representing mathematical, topological or architectural models where geometry may be described in terms of polygonal elements or contour line definitions. The source of the polygonal element data can be a finite-element analysis. The program has hidden line, contour, animation, shading, and full color capabilities in addition to many others. For a detailed description of the system, consult Ref. 6.

Applied thermal loads or temperature results at grid points can be displayed in color using the described hardware and software system. The input for MOVIE • BYU can be prepared by preprocessing the NTA Bulk Data Deck and thermal load or temperature card decks to produce Geometry and Function files. The displays which were produced in color (five slides shown at the presentation only) associated blue with cold temperatures and red with warm temperatures.

CONCLUDING REMARKS

Features and capabilities of the NTA are summarized in the following:

- A general-purpose heat transfer analysis computer program using finite-element method
- Linear and nonlinear transient and steady-state cases
- Conduction in discretized elements with temperature-variable (DOF) output at grid points
- Boundary conditions:
  - (1) Specified temperatures at grid points
  - (2) Thermal loadings with
    - (A) Internal (volumetric) heat generation
    - (B) External heat flux
      - (A) Constant
      - (B) Directional
      - (C) Time-dependent
  - (3) Convective boundary with
    - (A) Constant convective film coefficient
    - (B) Temperature-dependent convective film coefficient
  - (4) Radiative boundary with
    - (A) Diffuse-grey surfaces
    - (B) Specular surfaces (Ref. 9)
- Arbitrary initial temperatures prescribed at grid points

- Material properties:
  (1) Isotropic and anisotropic thermal conductivity properties
  (2) Temperature-dependent thermal conductivity or convective film coefficient in nonlinear steady-state case
  (3) Temperature-dependent emissivity and absorptivity in transient-state case (Ref. 11)
  (4) Temperature-dependent convective film coefficient and heat capacitance in transient-state case (Ref. 12)
- Provision of user selected β-value for stability in transient solution algorithm
- Graphical displaying capabilities
  (1) Conduction elements
  (2) Boundary surface elements
  (3) On-line printer plot of temperature vs. time and $\partial T/\partial t$ vs. time at grid points
  (4) Isothermal contour plot
- Miscellaneous
  (1) DMAP, ALTER
  (2) Restart, punch-card or tape output, etc.
  (3) Direct matrix input to [c] or [k]
  (4) Ability to be used as a conventional lumped-mass thermal network
- Preprocessor
  The VIEW program
- Post processors
  (1) Thermal variance analysis
  (2) Visual displays of temperature and temperature-gradient in color or b&w

The advantage of using NTA in thermo-structural analyses over other combinations is clearly shown in Fig. 11. The convenience and useability of NTA is further enhanced with the addition of the post processors. These features provide a flexibility far beyond that available in other known software systems in the public domain. This fact, combined with the NTA's proven reliability, has made it a valuable tool in the analytical arsenal suitable for unified thermo-structural analyses.

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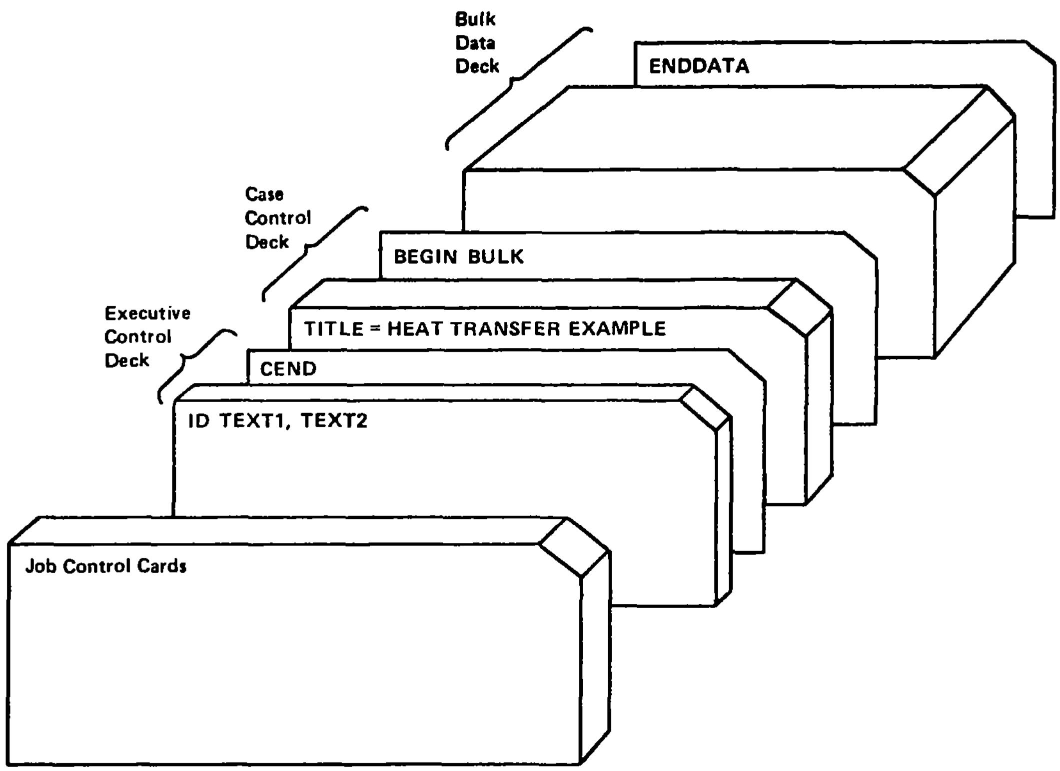
$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + \underbrace{[K]\{X\} = \{F(t)\}}_{\text{STEADY-STATE HEAT EQUIATION}}$$

$$\underbrace{[C]\{\dot{X}\} + [K]\{X\} = \{F(t)\}}_{\text{TRANSIENT-STATE HEAT EQUATION}}$$

SYMBOL	STRUCTURAL SYSTEM		THERMAL SYSTEM
$\{X\}$	DISPLACEMENT		TEMPERATURE
$\{\dot{X}\}$	VELOCITY		RATE CHANGE OF TEMPERATURE
$\{F\}$	APPLIED LOAD	(EQUIVALENCE)	HEAT SOURCE OR THERMAL LOAD
$[K]$	STIFFNESS	⟶	THERMAL CONDUCTANCE
$[C]$	DAMPING		HEAT CAPACITANCE
$[M]$	MASS		NONE

Figure 1. Mathematical Similitude between Structural and Thermal Systems



1. Executive Control Deck
   (a) To identify the job
   (b) To select solution type
   (c) To limit maximum CPU time in min.
   (d) To select types of execution
   (e) To embrace DMAP sequence if used

2. Case Control Deck
   (a) To select loading and boundary condition sets
   (b) To request output

3. Bulk Data Deck
   (a) To define the finite-element model
   (b) To specify loading and boundary conditions

Figure 2. NASTRAN Thermal Analyzer Program Structure

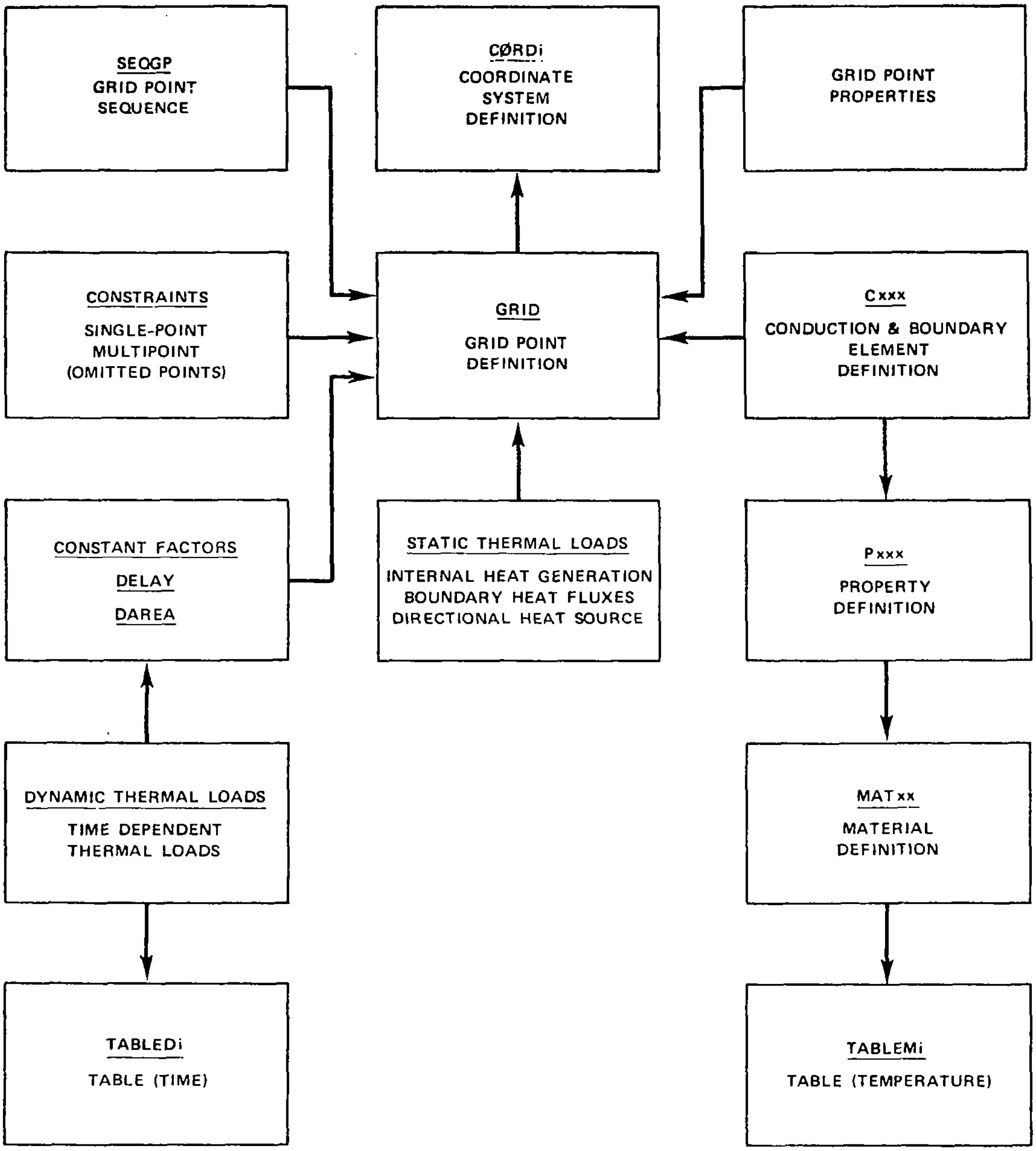


Figure 3. Functional Diagram of the NTA Bulk Data Cards in a Thermal Model

GEOMETRIC DEFINITION:

CORDii
GRID, GRDSET, SEQGP
EPØINT
SPØINT

ELEMENTS

HEAT CONDUCTION:

CBAR, CRØD
CELASi
CDAMPi
CQUADi, CTRIAi
CHEXAi, CTETRA, CWEDGE

BOUNDARY SURFACE:

CHBDY (POINT, LINE, REV, AREA3, AREA4, ELECYL)

ELEMENT PROPERTIES

PBAR, PRØD
PQUADi
PTRIAi
PHBDY

THERMOPHYSICAL PROPERTIES

MAT4, MAT5
MATT4, MATT5
TABLEMi

CONSTRAINT AND PARTITIONS:

SPC, SPC1
MPC
ASET, ØMIT, ØMIT1

THERMAL LOADINGS:

DAREA
DELAY
DLØAD
NOLINi
QBDY1, QBDY2
QHBDY
QVECT
QVØL
TABLEDi
TLØADi

RADIATIVE EXCHANGE DESCRIPTION:

RADLST
RADMTX

MISC:

DMIG
NFTUBE
PARAM
TEMP, TEMPD
TF
TSTEP
/
$

Figure 4. Bulk Data Cards Frequently used in Thermal Analysis

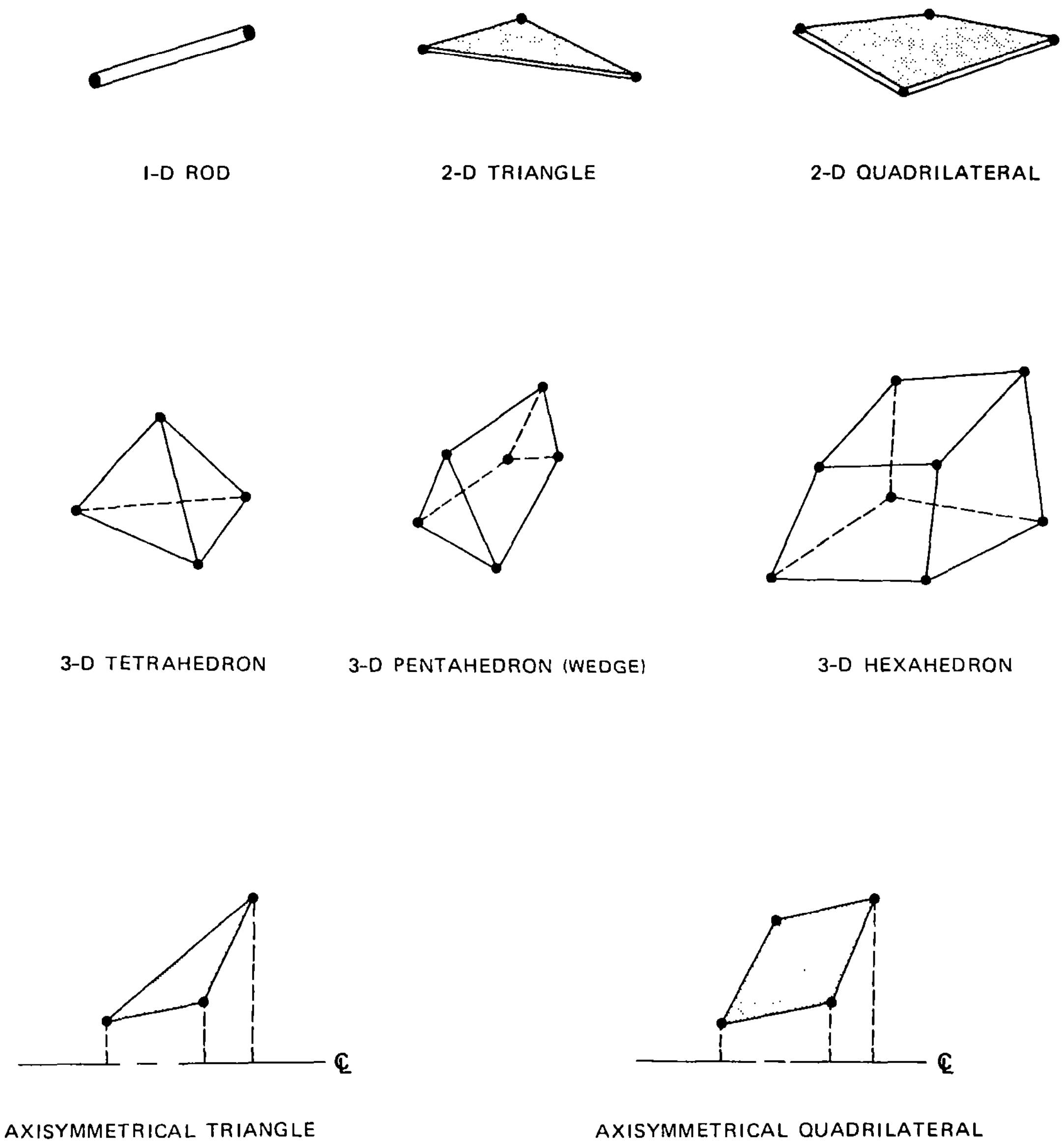


Figure 5. Representative Heat Conduction Elements

$$[K]\left\{\beta T_{n+1} + (1-\beta)T_n\right\} + \frac{1}{\Delta t}[C]\left\{T_{n+1} - T_n\right\}$$

$$= \left\{\beta Q^I_{n+1} + (1-\beta)\left\{Q^I_n\right\}\right\} + (1+\beta)\left\{Q^n_n\right\} - \beta\left\{Q^n_{n-1}\right\}$$

$$\left[\frac{1}{\Delta t}[C] + \beta[K]\right]\left\{T_{n+1}\right\}$$

$$= \left[\frac{1}{\Delta t}[C] - (1-\beta)[K]\right]\left\{T_n\right\} + \left\{\beta Q^I_{n+1} + (1-\beta)Q^I_n\right\} + (1+\beta)\left\{Q^n_n\right\} - \beta\left\{Q^n_{n-1}\right\}$$

β = 0 EULER INTEGRATION
β = ½ CENTRAL DIFFERENCES
β = 1 BACKWARD DIFFERENCES

Figure 6. The Modified Newmark-Beta Method

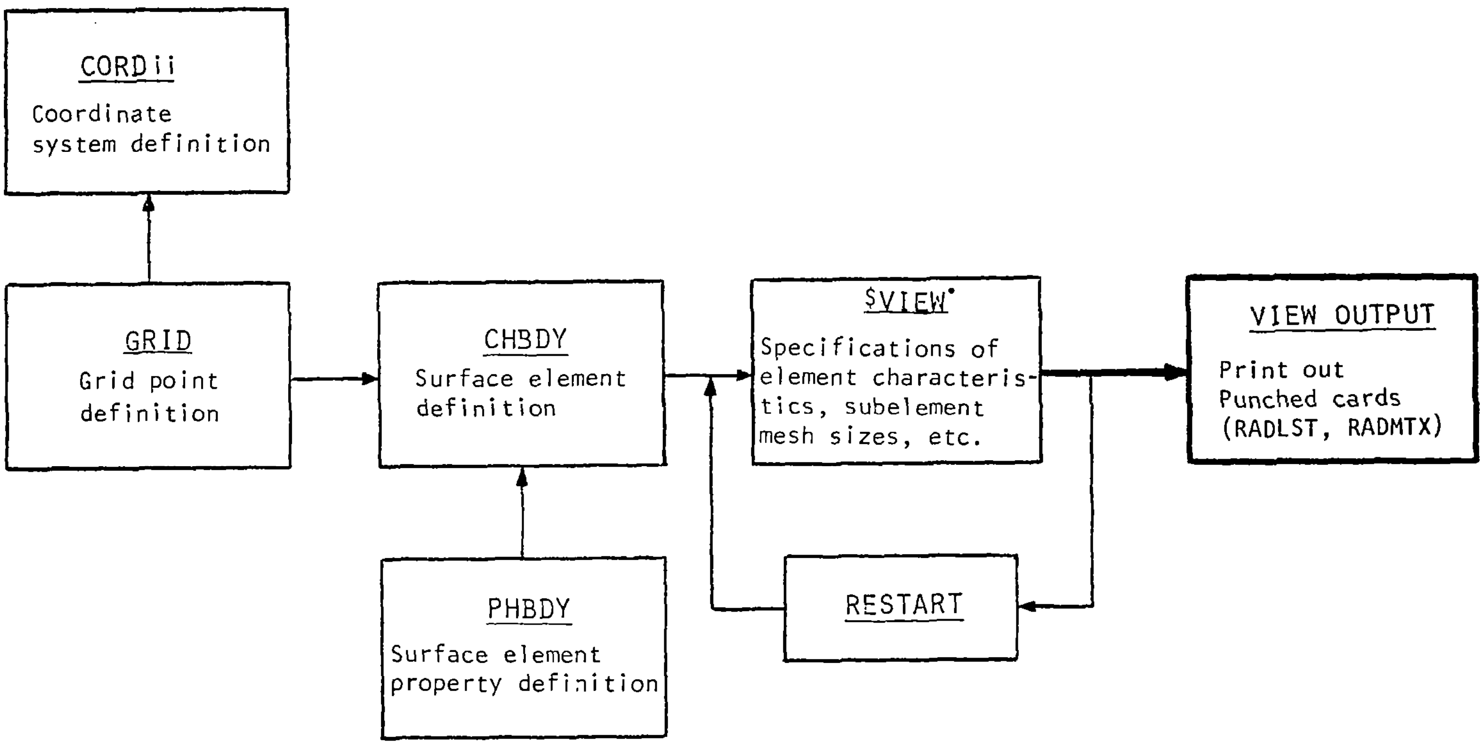
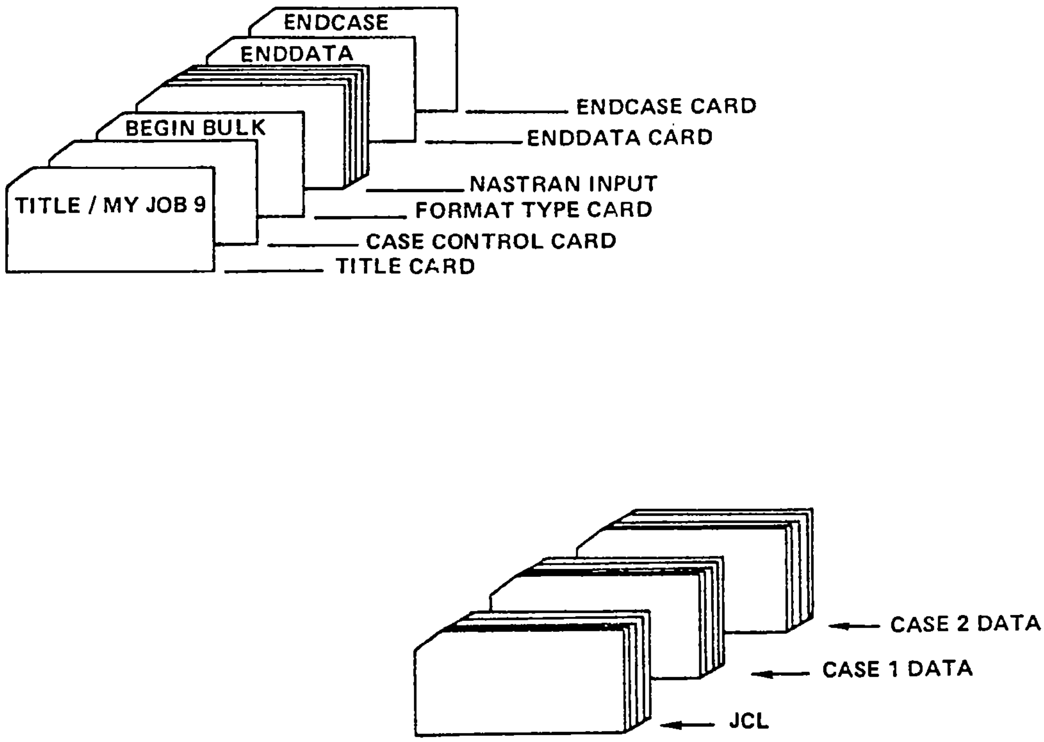


Figure 7. Functional Diagram of VIEW to Generate View Factors



1	2	3	4	5	6	7	8	9	10
$VIEW	IVIEW	KSHD	KBSHD	NB	NG	DISLIN			
$VIEW	14	0	1	5	7	-.25			

Figure 8. Organization of a VIEW Input Data Deck and the Unique Input Data Card of $VIEW

```
//B9EFPT01 JOB ([redacted]1831C,T,B00081,001H00),YYY,MSGLEVEL=(2,0)
// EXEC VIEW,REGION=175K
TITLE     *** SAMPLE PROBLEM NO. 1 ***
CASE=          1
BEGIN BULK
CHBDY          10          AREA4          10       11       12       13       50
CHBDY          20          REV            20       30                         55
CHBDY          30          AREA4          100      103      102      101      60
CHBDY          40     10   POINT          50                                65    +C1
+C1                                               0.0      0.0      1.
CHBDY          50     10   POINT          40                              65      +C2
+C2                                               0.0      0.0     -1.0
$VIEW          50       0        1        25       15
$VIEW          55       1        0        10       20
$VIEW          60       0        1        15       15
$VIEW          65       1        1         5        5
PHBDY          10          .786
GRID           10          2.5      -5.0      0.0
GRID           11          2.5       5.0      0.0
GRID           12         -2.5       5.0      0.0
GRID           13         -2.5      -5.0      0.0
GRID           100         2.5      -2.5     10.0
GRID           101         2.5       2.5     10.0
GRID           102        -2.5       2.5     10.0
GRID           103        -2.5      -2.5     10.0
GRID           20           .5
GRID           30           .5               10.0
GRID           40
GRID           50                            10.0
ENDDATA
ENDCASE
```

```
                                       VIEW FACTORS
                                       ************
                                                                                         VF SUM FROM
ELEMENT     AREA          ELEM TO ELEM = VIEW FACTOR          ELEM TO ELEM = VIEW FACTOR      ELEMENT
*******     ****          ***********    ***********          ***********    ***********    ***********

   10    0.50000E 02****************************************************************************************
                             10 -   20 =0.673263E-01             20 -   10 =0.107153E 00
                             10 -   30 =0.503031E-01             30 -   10 =0.100606E 00
                                                                                            0.11763E 00

   20    0.31416E 02****************************************************************************************
                             20 -   30 =0.728946E-01             30 -   20 =0.916021E-01
                                                                                            0.18005E 00

   30    0.25000E 02****************************************************************************************
                                                                                            0.19221E 00

   40    0.78600E 00****************************************************************************************
                                                                                            0.0

   50    0.78600E 00****************************************************************************************
                                                                                            0.0
```

Figure 9. A Typical Program Input to Generate View Factors and the Output

```
GRID     29                 105.0     30.0      25.98
GRID     41                 0.0       60.0      0.0
GRID     43                 30.       60.0      0.0
GRID     45                 60.       60.0      0.0
GRID     47                 90.       60.0      0.0
GRID     49                 105.0     60.0      25.98
MAT4     302      .16       3.9
PARAM    SIGMA    5.67E-12
PARAM    TABS     273.16
PHBOY    401                          .85       .85
PQUAD2   301      302       .5
OVLCT    751      .14       .866      0.0       -0.5      41        42        43        &OV5
RADLST   41       42        43        44        45        46        47        48
RADMTX   1        .0        .0        .0        .399E 01.0          .0        .0        &5C00000
&5COC000.320E 01
RADMTX   2        .0        .0        .129E 02.0          .0        .0        .813E 01
RADMTX   3        .0        .776E 02.0          .0        .0        .181E 02
RADMTX   4        .0        .320E 01.813E 01.181E 02.0
RADMTX   5        .0        .0        .0        .399E 01
RADMTX   6        .0        .0        .129E 02
RADMTX.  7        .0        .776E 02
RADMTX   8        .0
TEMP     901      1         500.0     3         500.0     21        500.0
TEMP     901      41        500.0     9         280.0     29        280.0
TEMP     901      49        280.0
TEMP     951      1         500.0     3         500.0     21        500.0
TEMP     951      41        500.0     9         280.0     29        280.0
TEMP     951      49        280.0
TEMPD    901      10.0
TEMPD    951      500.0
TLOAD2   601      751       0                   0.0       1.E5      0.0       0.0       &TL2
&TL2     0.0      0.0
TSTEP    888      60        10.0      1
ENDDATA
```

Figure 10. A Typical Input Data Deck Containing RADLST and RADMTX

Approach	Conventional Method	Unified Finite-Element Method
View Factor Generation	(Surfaces)	
Thermal Analysis	(Nodal-Network)	(Finite Elements)
Structural Analysis (NASTRAN)	(Finite Elements)	
Total	3 Different Models	1 Basic Model

Figure 11. Number of Models Required for Thermo-Structural Analysis Including Radiative Exchanges