Thermal Analysis User's Guide

Contents

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Chapter

1 Introduction to the NX Nastran Thermal Analysis User's Guide

- *General Capabilities*
- *Example Problem Input Files*

The *NX Nastran Thermal Analysis User’s Guide* describes the heat transfer-specific material within NX Nastran required for performing thermal analyses.

The information contained here can be augmented with material available in the *NX Nastran Quick Reference Guide*, and the *NX Nastran User’s Guide* as well as the *NX Nastran Handbook for Nonlinear Analysis*. These manuals can provide greater depth of coverage regarding finite element basics, modeling, input file structure, and nonlinear solution techniques.

1.1 General Capabilities

- Solution methods:
  - Steady state, linear and/or nonlinear (SOL 153).
  - Transient, linear and/or nonlinear (SOL 159).
- Heat conduction:
  - Temperature-dependent conductivity.
  - Temperature-dependent specific heat.
  - Anisotropic thermal conductivity.
  - Latent heat of phase change.
  - Temperature-dependent internal heat generation.
  - Weighted temperature gradient dependent internal heat generation.
  - Time-dependent internal heat generation.
- Free convection boundaries:
  - Temperature-dependent heat transfer coefficient.
  - Weighted temperature gradient dependent heat transfer coefficient.
  - Time-dependent heat transfer coefficient.
  - Nonlinear functional forms.
  - Weighted film temperatures.
- Forced convection:
  - Tube fluid flow field relationships - H(Re,Pr).
  - Temperature dependent fluid viscosity, conductivity, and specific heat.
  - Time-dependent mass flow rate.
  - Temperature-dependent mass flow rate.
  - Weighted temperature gradient dependent mass flow rate.

- Radiation to space:
  - o Temperature-dependent emissivity and absorptivity.
  - o Wavelength dependent emissivity and absorptivity.
  - o Time-dependent exchange.
- Radiation enclosures:
  - o Temperature-dependent emissivity.
  - o Wavelength-dependent emissivity.
  - o Diffuse view factor calculations with self and third-body shadowing.
  - o Adaptive view factor calculations.
  - o Net view factors.
  - o User-supplied exchange factors.
  - o Radiation matrix control.
  - o Radiation enclosure control.
  - o Multiple radiation enclosures.
- Applied heat loads:
  - o Directional heat flux.
  - o Surface normal heat flux.
  - o Grid point nodal power.
  - o Temperature-dependent heat flux.
  - o Weighted temperature gradient dependent heat flux.
  - o Time-dependent heat flux.
- Temperature boundary conditions:
  - o Specified constant temperatures for steady state and transient.
  - o Specified time-varying temperatures for transient.
- Initial conditions:
  - o Starting temperatures for nonlinear steady state analysis.
  - o Starting temperatures for all transient analyses.
- Thermal control systems:
  - o Local, remote, and time-varying control points for free convection heat transfer coefficients.

- Local, remote, and time-varying control points for forced convection mass flow rates.
- Local, remote, and time-varying control points for heat flux loads.
- Local, remote, and time-varying control points for internal heat generation rates.
- Transient nonlinear loading functions.
- Perfect conductor algebraic constraint temperature relationships.

- Output graphical display - basic:
  - Heat flows for conduction and boundary surface elements.
  - Temperature versus time for grid points.
  - Enthalpy versus time for grid points.
  - Isothermal contour plots.

- Miscellaneous:
  - NX Nastran DMAP and DMAP Alter capability.
  - NX Nastran restart capability.
  - Direct matrix input to conduction and heat capacitance matrices.
  - Lumped mass and discrete conductor representations.

1.2 Example Problem Input Files

Example problem input files are supplied with delivery. Refer to the *NX Nastran Installation and Operations Guide* for the location of these files.

Chapter

2 Thermal Capabilities

- *Elements*
- *Thermal Loads*
- *Convection and Radiation Boundary Conditions*
- *Temperature Boundary Conditions and Constraints*
- *Initial Conditions*

2.1 Elements

NX Nastran is an analysis code based on the finite element method. Fundamental to the method is an element library, available for building discretized numerical models that approximate the structure or system of interest. Several categories of elements exist to facilitate model generation: conduction elements, surface elements, and specialty elements.

Conduction Elements

Conduction elements are defined by the configuration generated when geometric grid points are connected in specific orientations and, for heat transfer, obey Fourier's Law. These elements can be characterized geometrically as being either one, two, or three dimensional, or axisymmetric. Besides being associated with geometry, these elements have the material properties for thermal conductivity, density, and specific heat associated with them. A typical element definition Bulk Data entry is given below for a 2-D element:

1	2	3	4	5	6	7	8	9	10
CQUAD4	EID	PID	G1	G2	G3	G4	THETA or MCID	ZOFFS	
			T1	T2	T3	T4			

Conduction Elements Available for Heat Transfer

The following table presents the conduction elements available for heat transfer. These elements include one-dimensional elements, shell elements, axisymmetric elements, and solid elements.

1-D	2-D	AXIS	3-D
CBAR	CQUAD4	CTRAX3	CHEXA
CBEAM	CQUAD8	CTRAX4	CPENTA
CBEND	CTRIA3	CTRAX6	CTETRA

CONROD	CTRIA6	CTRAX8	
CROD		CTRIAX6	
CTUBE			

Surface Elements

Wherever a boundary condition is applied to the surface of a conduction element, it must be interfaced with a surface element. Surface elements provide the geometric connection between the structural conduction elements and the applied convection, radiation, or heat flux loads. In particular, surfaces that participate in radiation enclosures derive their cavity identity and their radiation material property pointers from the surface element Bulk Data description. Similarly, free- and forced-convection Bulk Data entries are identified through their mating surface element identification numbers.

Surface Elements Available for Defining Heat Transfer Boundaries

The following table presents the surface elements available for convection and radiation boundary conditions and certain applied heat flux loads.

Element	CHBDYE	CHBDYG	CHBDYP
Surface Types	All	REV	POINT
		AREA3	LINE
		AREA4	ELCYL
		AREA6	FTUBE
		AREA8	TUBE

Surface element geometries are associated with surface types. Of the three forms of surface elements, the CHBDYG and the CHBDYP have their TYPE explicitly defined on their Bulk Data entries. The CHBDYE deals with the geometry type implicitly by reference to the underlying conduction element. The surface element Bulk Data entries are given below:

1	2	3	4	5	6	7	8	9	10
CHBDYG	EID		TYPE	IVIEWF	IVIEWB	RADMIDF	RADMIDB		
	G1	G2	G3	G4	G5	G6	G7	G8	

CHBDYE	EID	EID2	SIDE	IVIEWF	IVIEWB	RADMIDF	RADMIDB		

CHBDYP	EID	PID	TYPE	IVIEWF	IVIEWB	G1	G2	GO	
	RADMIDF	RADMIDB	GMID	CE	E1	E2	E3		

Special Elements

Several types of special elements are available for added modeling flexibility. Complicated elements can be introduced into the system through generalized matrix input in the form of DMI, DMIG, and TF.

Lumped thermal capacitance can be defined with the use of CDAMPi (i = 1, 2, 3, 4, 5) entries.

Simple conduction elements are represented by CELASi (i = 1, 2, 3, 4) elements. The software calculates heat conduction for CELASi elements as

$q = K \times \Delta T$

where K is the value entered directly on the CELAS2 and CELAS4 entries, or the PELAS entry for CELAS1 and CELAS3 elements. For example, if you would like to use a CELASi element to represent the heat conduction through a bar with a specific cross sectional area, length, and thermal conductivity, the input "K" would be calculated as

K = Thermal conductivity x Area /Length

See the CELASi element remarks in the *Quick Reference Guide* for additional inputs requirements.

Key Points Regarding Elements

- All element Bulk Data connection inputs signify that an element connection is performed among grid points.
- Every element must have a unique element identification number (EID) with respect to all other elements in the problem. This requirement applies to conduction elements, surface elements, and specialty elements.
- Element definitions reference Bulk Data property entries that supply supplemental information about geometry and governing relationships, and subsequently refer to material property entries.

2.2 Thermal Loads

NX Nastran makes a clear distinction between loads and boundary conditions. This distinction refers more to solution sequence methods than with the physical phenomena involved. In general, the specification of surface flux and internal heat generation are defined as loads. Loads are readily identified from their Bulk Data entries because they possess a load set identification (SID). This identifier has ramifications regarding the application of the load via Case Control. Case Control is discussed briefly in "Interface and File Communication", but is introduced here for clarity.

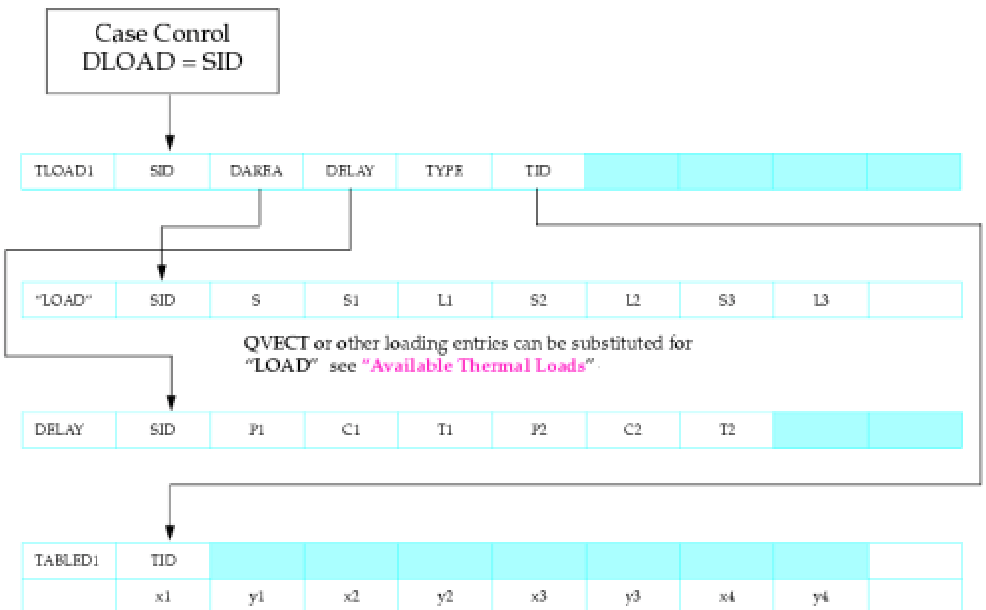
The Case Control Section:

- Selects loads and constraints (temperature boundary condition).
- Requests printing, plotting, and/or punching of input and output data (plot commands are discussed in the *NX Nastran User's Guide* and "Interface and File Communication" of this guide). Punch files are generally intermediate files of data saved for use in a subsequent computation. Two common examples for heat transfer are the punch files of view factors that result from an execution of the VIEW MODULE, and a punch file of temperatures from a thermal solution to be used in a subsequent thermal-stress analysis.
- Defines the subcase structure for the analysis.

For the current discussion, consider the selection of loads. In order to activate any of the loads stipulated in the Bulk Data Section, a load request must be made from the Case Control Section.

Key Points in Requesting Loads from Case Control

- LOAD = SID; where SID is an integer used in steady state analysis (SOL 153) to request application of the load Bulk Data labeled with the given SID. Only one LOAD command per subcase may be specified in the Case Control Section.
- DLOAD = SID; used in transient analysis (SOL 159) to request the application of the dynamic load Bulk Data with the given SID. Only one DLOAD command per subcase may be specified in the Case Control Section.
- For steady state analysis, any number of loads defined in the Bulk Data may be referenced from a single Case Control request by specifying all loads of interest to have the same SID.
- For transient analysis, the static load entries are not selected by the Case Control SID; rather, they reference a TLOADi entry (DAREA field). The SID required for Case Control selection is given on the TLOADi entry (SID field). The schematic for this process is illustrated below.



- Unlike the steady state case where many loads may utilize the same SID, every TLOADi entry must have a unique SID. To apply multiple loads in a transient analysis, the multiple TLOADi first must be combined using a DLOAD Bulk Data entry. The SID on the DLOAD Bulk Data entry then becomes the reference SID on the DLOAD Case Control command.
- Nonlinear transient forcing functions (NOLINi) are requested in Case Control with the NONLINEAR = SID command. They are only available for transient analysis and cannot be referenced on the DLOAD Bulk Data entry.

Available Thermal Loads

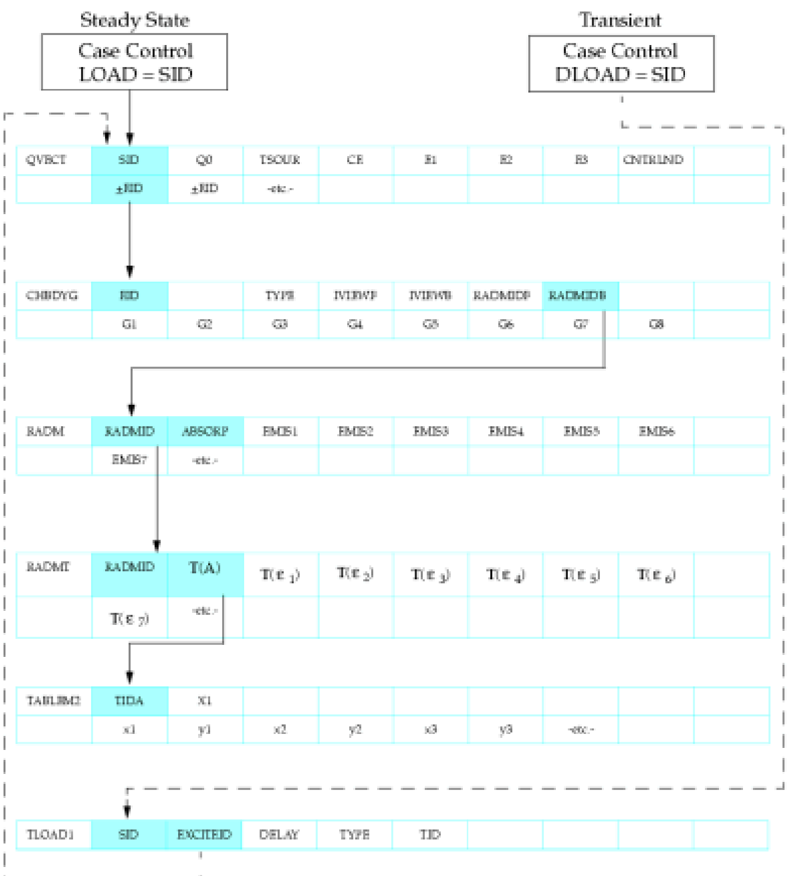
QVECT	Directional heat flux from a distant source.
QVOL	Volumetric internal heat generation.
QHBDY	Heat flux applied to an area defined by grid points.
QBDY1	Heat flux applied to surface elements.

QBDY2	Heat flux applied to grid points associated with a surface element.
QBDY3	Heat flux applied to surface elements with control node capability.
SLOAD	Power into a grid or scalar point.
NOLIN1	Nonlinear transient load as a tabular function.
NOLIN2	Nonlinear transient load as a product of two variables.
NOLIN3	Nonlinear transient load as a positive variable raised to a power.
NOLIN4	Nonlinear transient load as a negative variable raised to a power.

A complete description of the capability of each load type may be found in the appropriate Bulk Data entry description in the *NX Nastran Quick Reference Guide*.

Thermal Load Flowchart

The schematic below illustrates the Bulk Data relationship for a directional surface heat flux when temperature-dependent surface properties are important. Some typical surface loads are QVECT, QHBDY, QBDY1, QBDY2, and QBDY3.



2.3 Convection and Radiation Boundary Conditions

The specification of boundary conditions was introduced in “Elements”. NX Nastran treats the application of radiation and convection as boundary conditions. Unlike flux loads, convection and radiation are therefore not Case Control selectable. The implications of this are twofold. In transient analysis, the transient load methodology (see “Thermal Loads”) is unavailable, and in steady state analysis, the solution sequence mechanism for load incrementing does not apply. To mitigate these shortcomings, transient control is introduced into the boundary conditions through the use of the control node. In addition, although the ability to do load incrementing is lost for these boundary conditions, their inclusion in a comprehensive tangent matrix significantly enhances both the overall stability and convergence rate.

Available Boundary Conditions

• CONV	Free convection
• CONVM	Forced convection (fluid “element”)
• RADBC	Radiation exchange with space
• RADSET	Radiation exchange within an enclosure

Free Convection Application

Free convection heat transfer is available through the CONV Bulk Data entry. In NX Nastran, free convection is governed by relationships of the following forms:

- $$q = H \cdot (T - TAMB)^{expf}(T - TAMB)$$
- $$q = H \cdot u_{CNTRLND}(T - TAMB)^{expf}(T - TAMB)$$
- $$q = H(T^{expf} - TAMB^{expf})$$
- $$q = H \cdot u_{CNTRLND}(T^{\exp f} - TAMB^{\exp f})$$

where

H	=	free convection heat transfer coefficient
T	=	surface temperature
TAMB	=	ambient temperature
$u_{CNTRLND}$	=	value of the control node (dimensionless)

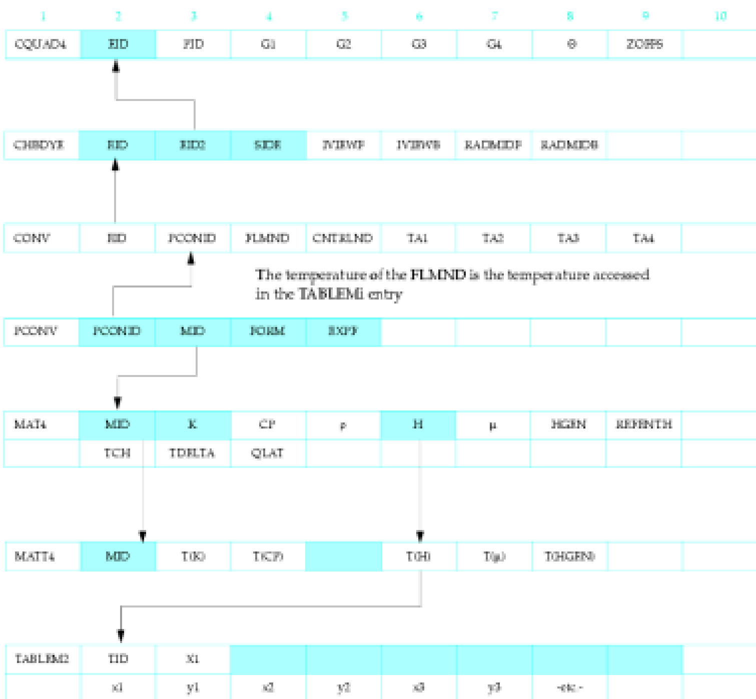
Key Points – Free Convection Application

- Free convection allows thermal communication between a surface and an ambient environment through a heat transfer coefficient (H) and a surface element (CHBDYi).
- Free convection heat transfer coefficients are supplied on MAT4 Bulk Data entries. The coefficient can be made temperature dependent by using the MATT4 entry.
- The access temperature for the temperature-dependent coefficient can be varied by specifying the film node field (FLMND on CONV).

- Time dependence can be introduced into the heat transfer coefficient through the control node entry (CNTRLND on CONV).

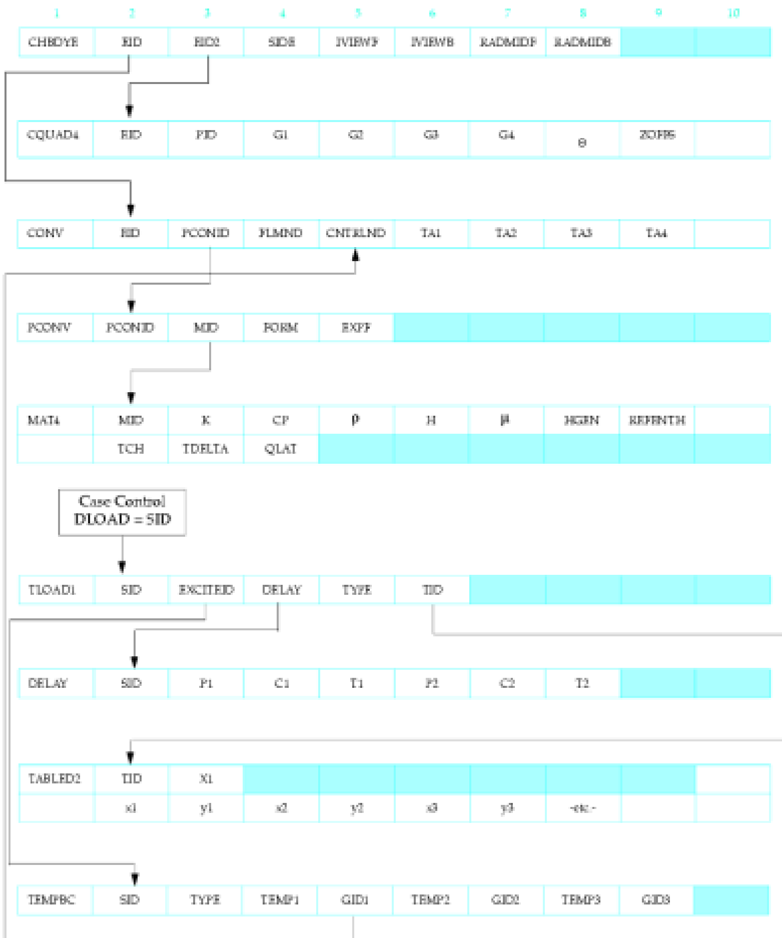
The following schematic illustrates the Bulk Data relationships for temperature- dependent-free convection and time-dependent-free convection.

Free Convection – Temperature-Dependent Heat Transfer Coefficient



CHBDYE	Provides the surface element for convection application through reference to the underlying conduction element (CQUAD4).
CONV	Stipulates the application of free convection and identifies the film node, control node, and ambient node or nodes.
PCONV	Provides supplemental information on the form of the convection relationship to be applied.
MAT4	Provides the free convection heat transfer coefficient.
MATT4	Provides for the free convection heat transfer coefficient temperature dependence.
TABLEM2	Specifies the actual table data for the heat transfer coefficient versus temperature.

Free Convection – Time-Dependent Heat Transfer Coefficient



Forced Convection Application

Streamwise-upwind Petrov-Galerkin Element (SUPG)

Forced convection is available through the CONVM Bulk Data entry. Forced convection in NX Nastran is limited to one-dimensional fluid flows. An SUPG element formulation allows for energy transport due to streamwise advection and diffusion and displays good spatial and temporal accuracy. Heat transfer between the fluid stream and the surroundings is accounted for through a forced convection heat transfer coefficient based on locally computed Reynolds and Prandtl numbers. The pertinent heat transfer behavior is listed as follows:

1. Streamwise energy transport due to advection plus streamwise diffusion
   a. FLAG = 0 , no convective flow
   b. FLAG = 1 , diffusion and convection transport
2. Heat transfer coefficient to fluid tube wall
   a. $\text{If FORM} = 0, \text{ then } h = (coef \cdot Re^{EXPR} \cdot Pr^{EXPP})$

b. $$\text{If FORM} = 1\text{, then } \frac{hK}{d} \; (= coef \cdot Re^{EXPR} \cdot Pr^{EXPP})$$

where

$$Re = \frac{DV\rho}{\mu}$$

$$Pr = \frac{C_p\mu}{k}$$

Key Points – Forced Convection

Controlling Mass Flow Rate

- The actual mass flow rate is specified by using a control node for mass flow, the CNTMDOT field on the CONVM Bulk Data entry. For forced convection, the control node can supply active or passive/local or remote system mass flow rate control. It is the user's responsibility to ensure continuity of mass flow rate from element to element.

- The material properties of interest for determining energy transport and forced convection heat transfer coefficients are given on the MAT4 Bulk Data entries. Temperature-dependent material properties are given through the MATT4 statement, and a film node is available for the look-up temperature. The heat transfer coefficient (H) given on the MAT4 statement is for free convection ONLY.

- As with all boundary conditions, CONVM can only communicate to the structure through a surface element. The CHBDYP specification is identified on the CONVM entry as the EID field.

Courant Number for Forced Convection

- Time dependence can be introduced into the flow field mass flow rate through the control node (CNTMDOT on CONVM). Accurate resolution of the evolving flow field (transient analysis) requires some user control over the Courant number (CN).

$$CN \equiv V \cdot \frac{\Delta t}{L}$$

where

V	=	Velocity of fluid
Δt	=	Time step size
L	=	Element length

For good resolution of transient flow fields, it is recommended that CN ≤0.10. Since the element length and mass flow rate are specified, this implies that the user must control the time step size. This may eliminate the use of the automatic time step selection scheme.

Radiation to Space

A radiation boundary condition can be specified with a RADBC Bulk Data entry. This form of radiant exchange is solely between the surface element and a blackbody space node. The following relationships apply:

1. If CNTRLND = 0, $$q = (\sigma \cdot FAMB) \cdot (\varepsilon_e T_e^4 - \alpha_e T_{amb}^4)$$

2. If CNTRLND > 0, $$q = (\sigma \cdot FAMB \cdot u_{CNTRLND}(\varepsilon_e T_e^4 - \alpha_e T_{amb}^4))$$

Key Points - Radiation Boundary Conditions

- Two PARAMETERS are required for any radiation calculation to be performed:

  TABS – Defines the absolute temperature scale.

  SIGMA – The Stefan-Boltzmann constant.

  PARAMETERS are discussed in “Parameters” in the *NX Nastran Quick Reference Guide*. For these Bulk Data Section PARAMETERS, the statement would look like:

  PARAM,SIGMA,5.67E-08

  PARAM,TABS,273.16

- The emissivity and absorptivity material surface properties are specified on the RADM Bulk Data entry. They may be constant, temperature-dependent (RADM/RADMT), and/or wavelength band-dependent (RADM/RADBND).

- Wavelength dependence is specified in a piecewise linear curve fashion with discrete break points defined on a RADBND Bulk Data entry. There can only be one set of break points in any given analysis, and any RADM definition must have break points that are coincident with those on the solitary RADBND. The theoretical treatment within NX Nastran of spectral radiation effects are discussed in some detail in “Radiation Exchange – Real Surface Approximation”.

- As with all boundary conditions, RADBC may only be used when it is applied to a surface element (CHBDYi).

- Time dependence can be introduced into the RADBC in two ways. The Control Node Multiplier (CNTRLND) can be made to follow a specified time function, and the temperature of the ambient node (NODAMB) can be a function of time. Each has a unique effect on the overall heat transfer.

- RADBC is the only Bulk Data entry besides QVECT that uses the material’s absorptivity property in its calculations. For all enclosure radiation calculations, absorptivity is assumed to be equal to emissivity.

Enclosure Radiation Exchange

Thermal radiation exchange among a group of surface elements is treated as a radiation enclosure. Defining radiation enclosures and accounting for the subsequent radiation heat transfer can be the most complicated and computationally expensive thermal calculation. As with the radiation boundary condition, the material surface properties can be constant, temperature dependent, and/or wavelength dependent. One of the more troublesome aspects of enclosure exchange is the geometric concept of view factors that relate the relative levels of radiant exchange between any and all individual surfaces in the enclosure set. A number of options are available for the calculation of view factors for black or gray diffuse surface character. "View Factor Calculation Methods" describes the basis for enclosure exchange and the view factor calculation methods.

1. Enclosure options:

   NX Nastran is used to calculate the diffuse view factors using one of its two view factor modules. Once generated, the RADLST/RADMTX punch files can be retained for use in subsequent thermal runs that utilize the same geometry. Since view factor calculations tend to be lengthy, calculating them once and then reusing them is the preferable procedure. The INCLUDE Bulk Data entry is used to identify the view factor files to be used in the subsequent thermal analyses.

   View factors or exchange factors can be determined independently outside of NX Nastran and used in NX Nastran Thermal Analysis if the formats are consistent with the RADLST/RADMTX files that NX Nastran generates. The RADLST Bulk Data entry defines the type of matrix being used.

2. Calculation process – Radiant enclosure exchange where the view factors exist

   a. All conduction element surfaces involved in a radiation enclosure must be identified with surface elements (CHBDYi). The CHBDYi description of the surface element identifies the surface material entry (RADM). Multiple (and mutually exclusive) cavities may be defined within NX Nastran for modeling convenience, and to minimize the computation time.

   b. When the RADLST/RADMTX entries are available for the analysis, view factors need not be calculated. This is true as long as the existing RADLST/RADMTX entries are either already in the Bulk Data Section or are included in the input file through the Bulk Data INCLUDE entry. A punch file of view factors may have been generated in a prior run.

   c. Including radiant enclosure exchange in an analysis is requested using the RADSET entry. RADSET identifies those cavities to be considered for enclosure radiation exchange.

   d. For an analysis where the view factors exist then, the following Bulk Data entries constitute the minimum required subset:

      CHBDYi

      RADLST

      RADMTX

      RADSET

      RADM/ RADMT / RADBND

      In addition to these entries, include the parameters SIGMA and TABS.

      The above process is illustrated in the following schematic.

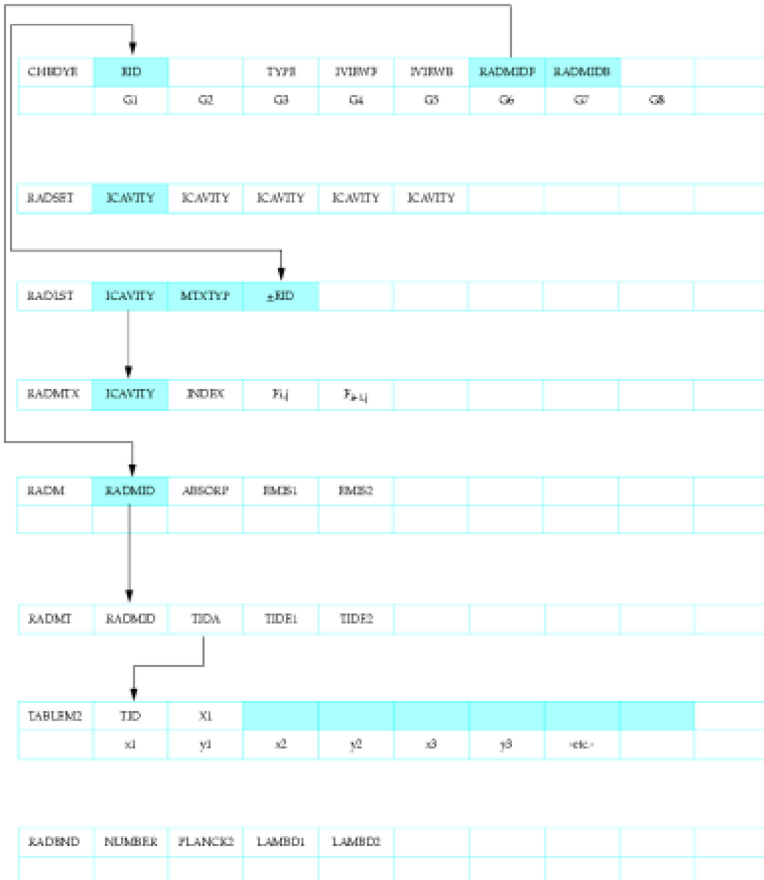


Figure 2-1. Enclosure Radiation with Existing View Factors

RADSET	Selects the radiation cavities to be included in the overall thermal analysis.
RADLST	Specifies which elements are to participate in a cavity experiencing radiation exchange.
RADMTX	Provides the $F_{ij}=A_j f_{ji}$ exchange factors for all the surface elements of a radiation enclosure specified in the corresponding RADLST.
CHBDYG	Identifies the radiation surface geometry and material.
RADM	Provides the surface properties for absorptivitiy and emissivity.
RADMT	Provides the identification for any surface material properties that are temperature dependent.
TABLEMi	Defines a tabular function for use in generating temperature-dependent material properties.
RADBND	Provides Planck's second constant and the wavelength break points used for spectral radiation exchange analysis. There can only be one RADBND statement in a given analysis, regardless of the number of cavitities. While this forces every exchange surface to have identical waveband break points, there may be different RADM/RADMT for potentially every surface.

3. Calculation process – Radiant enclosure exchange where the view factors must be calculated

a. All conduction element surfaces involved in a radiation enclosure must be identified with surface elements (CHBDYi). The CHBDYi description of the surface element identifies the surface material entry (RADM) as well as the cavity identification (VIEW). Multiple cavities may be defined within NX Nastran for flexible modeling, user convenience, and eliminating shadowing calculations in determining view factors when groups of elements see only themselves to the exclusion of other groups of elements.

b. Since no RADLST/RADMTX exists for this problem, they will be calculated. The calculation of view factors is instigated by including the VIEW Bulk Data entry which is referenced from the CHBDYi entries. VIEW lumps together those surface elements of a common cavity identification and provides some guidance regarding how the elements interact relative to any required shadowing calculations.

c. Only one RADCAV Bulk Data entry exists for each cavity. This entry has an array of information available on it that is used to control the global aspects of the view factor calculation for the cavity in question.

d. If the finite difference view factor module (default which may be described as an area subdivision method) is to be used for the view factor calculation, the entries discussed thus far are adequate for this part of the calculation. The minimum subset of Bulk Data entries for this method of view factor calculation is:

   For view factor calculation, use

   CHBDYi

   VIEW

   RADCAV

   To complete the thermal analysis, use

   RADSET

   RADM / RADMT / RADBND

   In addition, include the parameters TABS and SIGMA.

e. If the Gaussian integration view factor calculation (the adaptive method) is desired, the VIEW3D Bulk Data entry must be included. It too is associated with a cavity ID, and includes fields which provide calculation control limits. The minimum subset of Bulk Data entries for this method of view factor calculation is:

   For view factor calculation, use

   CHBDYi

   VIEW

   VIEW3D

   RADCAV

   To complete the thermal analysis, use

   RADSET

   RADM / RADMT / RADBND

   In addition, include the parameters TABS and SIGMA.

   "View Factor Calculation Methods" describes the calculation of view factors in added detail.

The schematic below illustrates the Bulk Data interrelationship involved in the determination of view factors and depicts the additional entries required to complete the thermal analysis.

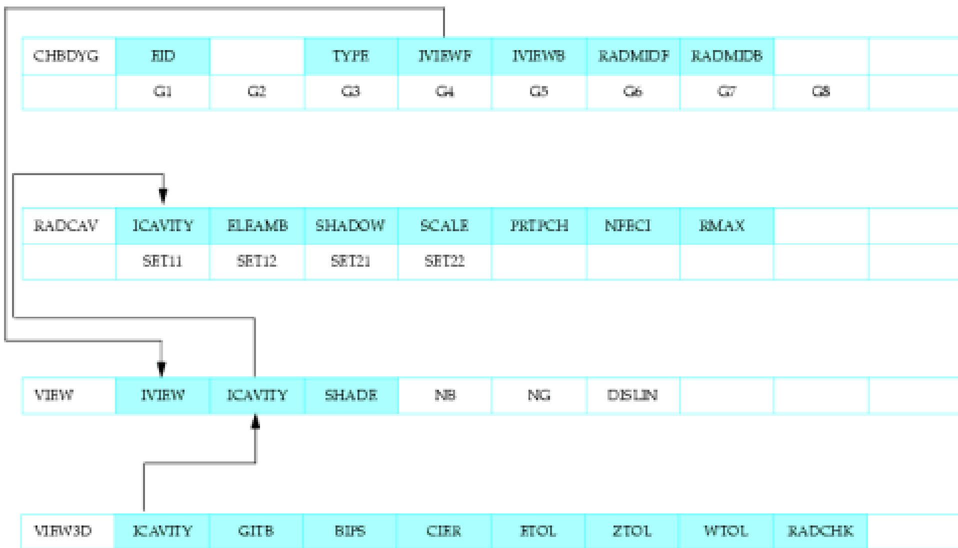


Figure 2-2. Enclosure Radiation – View Factor Calculation Required Input

CHBDYG	Identifies the radiation surface geometry and material.
VIEW	Groups the surface elements into their respective radiation cavities and provides control information for using the finite difference method when determining view factors (VIEW module). The VIEW Bulk Data entry also specifies that view factors be calculated.
RADCAV	Identifies the characteristics of each radiation cavity and provides control information for using the finite difference method when determining view factors (VIEW module).
VIEW3D	Provides the control quantities involved in using the Gaussian integration adaptive view factor module (VIEW3D module).

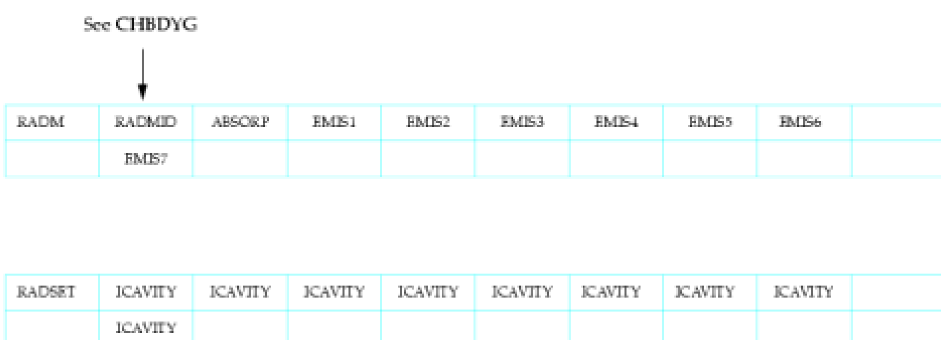


Figure 2-3. Additional Enclosure Radiation Input Required to Determine the Radiation Exchange Thermal Response

RADM	Provides the surface properties for absorptivity and emissivity.

RADSET	Selects the radiation cavities to be included in the overall thermal analysis.

2.4 Temperature Boundary Conditions and Constraints

A temperature boundary condition can be useful in defining independent GRID point or SPOINT temperature in an analysis. This applies to grid points associated with conduction elements, surface elements, ambient points, control nodes, or film nodes as well as to scalar points. The methods available for specifying these temperatures are discussed below. Temperature boundary conditions are treated like loads because they are selected from the Case Control Section.

Available Temperature Boundary Conditions and Constraints

SPC	The single-point constraint is selected in the Case Control Section with SPC = SID. For heat transfer, an SPC may be used to define a temperature for steady state analysis or transient analysis if the boundary condition over all time is to remain at a constant value. This is the recommended approach to fixed temperature specification for both steady state and transient analysis. In the constant value case, these degrees of freedom are eliminated from the analysis set and therefore cannot influence the iterative convergence criteria. In steady state analysis, SPCs are subcase selectable. In transient analysis, SPCs must be selected above the subcase level. When used with SPCD, SPC1 can also be used to specify nonzero temperature boundary conditions.
TEMPBC	This form of boundary temperature specification is more flexible than the SPC definition since it can be used to define a temperature that varies with time throughout a transient analysis. The basic procedure for transient specification when the value varies with time is to use the dynamic load process as discussed in the load section (see "Thermal Loads"). The SID on the TEMPBC is referenced by a TLOADi Bulk Data entry (DAREA field). The TLOADi entry must be selected using the Case Control command (DLOAD = SID). Field 3 for TYPE is specified either as STAT or TRAN as desired. For steady state (STAT type) analysis, the Case Control command is SPC = SID where the SID is field 2 of the TEMPBC entry. For transient (type = TRAN) analysis, this boundary specification cannot eliminate the degrees of freedom from the analysis set. Rather, it internally implements a penalty method for maintaining the desired temperature value. The fixed matrix conductance term has a set value of 1.0E+10. In some instances, this magnitude may overwhelm the convergence criteria. In these cases, there is another approach to specified temperatures that can circumvent the problem (see the following discussion of CELASi).
CELASi	These 1-D elements provide a convenient resistive network element that can be used for thermal system modeling as well as for driving temperature boundary conditions. They may automatically have one end set to a zero or grounded value. A heat load (QHBDY) applied at the free end can be constant or time varying. The load and matrix conductance values can be adjusted to minimize the influence over the iterative convergence criteria.

MPC	Otherwise known as a multipoint constraint. This constraint can be used to specify a grid point temperature to be a weighted combination of any number of other grid point temperatures. An MPC is requested in the Case Control Section with the MPC = SID command. For transient analysis, an MPC must be requested above the subcase level.

Key Points – Temperature Boundary Conditions

Key points for temperature boundary conditions are:

- No Bulk Data file may utilize more than one method for temperature specification. For example, an SPC entry and a TEMPBC entry of the type = STAT cannot exist in the same file.

- Whenever a TEMPBC entry of type = TRAN temperature boundary condition is specified in an analysis, the CONV field of the solution control entry (TSTEPNL) must be a U specification.

- Temperature initialization (see “Initial Conditions”) should always be set for all TEMPBC entries of type = TRAN temperature boundary conditions. Additionally, all temperature initial conditions must agree with the specified boundary conditions. For the MPC relationship then the initial temperature specifications must satisfy the given identity.

- In SOL 153, singularities in the stiffness matrix can be constrained automatically by Bulk Data entry PARAM,AUTOSPC,YES. However, AUTOSPC does not provide the correct action for the nonlinear stiffness matrix in SOL 159.

2.5 Initial Conditions

Setting initial temperatures is required in several situations. In steady state analysis, temperatures are usually required as a starting point for the nonlinear iteration process. In transient analysis, initial temperature specifications define the state from which the solution evolves.

Steady State Analysis

Since most heat transfer problems are nonlinear due to material properties, variable boundary conditions, or radiation exchange, iteration is employed in the solution of the system equations. An initial temperature guess is required to initialize any temperature-dependent properties or boundary conditions. A good initial estimate can be helpful in achieving a converged solution.

Case Control Required:	TEMP(INIT) = SID
Bulk Data Entries:	TEMP – Defines starting temperature on specific grid points.
	TEMPD – Automatically defines starting temperature on any remaining grid points not specified with a TEMP entry.

Transient Analysis

Transient analysis, whether linear or nonlinear, employs a starting temperature as the initial condition from which the solution evolves. These starting temperatures are not, in general, arbitrary temperatures. Any noninitialized temperatures are presumed to have a value of zero.

Case Control Required:	IC = SID.
Bulk Data Entries:	TEMP – Defines initial temperature on specific grid points.
	TEMPD – Automatically defines initial temperature on any grid points not set with a TEMP Bulk Data entry.

Chapter

3 Interface and File Communication

- *Introduction to Interface and File Communication*
- *Execution of NX Nastran*
- *Input Data*
- *Files Generated by NX Nastran*
- *Plotting*

3.1 Introduction to Interface and File Communication

This chapter describes the inputs and outputs for NX Nastran thermal anlaysis. The input is described in terms of an input data file that may be generated by hand or by a suitable preprocessor. Among the five separate sections involved in the general input is a complete description of the model, including:

- The type of analysis being performed.
- The problem geometry as modeled.
- The conduction elements that approximate the structure.
- The surface elements that allow the structure to communicate with the boundary conditions.
- The boundary conditions associated with convection and radiation.
- The loads associated with applied fluxes for all load conditions of interest.
- The specification of the known temperatures in the analysis.
- Requests for the desired output quantities along with their format and form.

3.2 Execution of NX Nastran

The NX Nastran input file is a text file that is given a filename and a .dat extension (e.g., EXAMPLE1.dat). To execute NX Nastran, type a system command followed by the name of the input file. The .dat extension is automatically assumed by NX Nastran if there is no file extension associated with the specified filename. A typical execution is

```
NASTRAN EXAMPLE1
```

3.3 Input Data

NX Nastran input requires records that are 80 characters (or columns) in length. The input file is comprised of five sections that must be assembled in the following sequence:

Table 3-1. Structure of the NX Nastran Input File

NASTRAN Statement	Optional
File Management Statements	Optional
Executive Control Statements	Required Section
CEND	Required Delimiter
Case Control Commands	Required Section
BEGIN BULK	Required Delimiter
Bulk Data Entries	Required Section
ENDDATA	Required Delimiter

The records of the first four sections are input in free-field format, and only columns 1 through 72 are used for data. Any information in columns 73 through 80 may appear in the printed echo, but is not used by the program. If the last character in a record is a comma, then the record is continued to the next record.

The Bulk Data entries have special free-field rules, but may be specified as fixed field. Both options are described in the *NX Nastran User's Guide*. The Bulk Data entries may also make limited use of columns 73 through 80 for the purpose of continuation.

NASTRAN Definition(s) (Optional Statement)

The NASTRAN definition statement is optional and is used in special circumstances (see the "nastran Command and NASTRAN Statement" in the *NX Nastran Quick Reference Guide*).

File Management Statements (Optional Section)

The File Management Section is optional and follows the NASTRAN definition(s). It ends with the specification of an Executive Control statement. This section provides for database initialization and management along with job identification and restart conditions. The File Management statements are described in the "File Management Statements" in the *NX Nastran Quick Reference Guide* .

Executive Control Statements (Required)

The Executive Control Section begins with the first Executive Control statement and ends with the CEND delimiter. It identifies the job and the type of solution to be performed. It also declares the general conditions under which the job is to be executed, such as maximum time allowed and the type of system diagnostics desired. If the job is to be executed with a solution sequence, the actual solution sequence is declared along with any alterations to the solution sequence that may be desired. If Direct Matrix Abstraction is used, the complete DMAP sequence must appear in the Executive Control Section. The Executive Control statements and examples of their use are described in the *NX Nastran Quick Reference Guide* .

Case Control Commands (Required)

The Case Control Section follows CEND and ends with the BEGIN BULK delimiter. It defines the subcase structure for the problem, defines sets of Bulk Data, and makes output requests for printing, punching, and plotting. A general discussion of the functions of the Case Control Section and a detailed description of the commands used in this section are given in the "Case Control Commands" in the *NX Nastran Quick Reference Guide* .

Steady State Heat Transfer – SOL 153

- A separate subcase must be defined for each unique combination of thermal loads (LOAD Case Control command), temperature constraints (SPC and MPC command), and nonlinear iteration strategy (NLPARM command).

- The LOAD Case Control command references the static thermal load entries: QVOL, QVECT, QHBDY, and QBDYi. Each subcase defines a set of loads that can then be subdivided into a number of increments for the nonlinear solution process (NLPARM Bulk Data entry).

  The load step is labeled by the cumulative load factor. The load factor varies from 0 to 1 in each subcase. Specifically, the load step ends with 1, 2, 3, etc. for the first, the second, and the third subcase, respectively. The data blocks containing solutions can be generated at each increment or at the end of each subcase, depending on the intermediate output option specified on the INTOUT field of the NLPARM Bulk Data entry. Data blocks are stored in the database for the output process and restarts.

- The SPC Case Control command references the temperature boundary conditions in the SPC Bulk Data entry. The applied temperature boundary condition is also subdivided in the subcase in an incremental fashion.

- The MPC Case Control command references the algebraic temperature constraints in the MPC Bulk Data entry. In heat transfer we can think of MPCs as perfect conductor networks.

- The TEMP(INIT) Case Control command references the initial temperatures that are required for all nonlinear analyses. An initialized temperature distribution must be defined using TEMP and/or TEMPD Bulk Data entries.

- Output requests for each subcase are processed independently. Requested output quantities for all the subcases are appended after the computational process for actual output operation. Available outputs are as follows:

THERMAL	Temperatures for GRID points and SPOINTs.
FLUX	Inner element temperature gradients. Heat flows for CHBDYi elements.
OLOAD	Applied linear loads.
SPCF	Steady state heat of constraint for maintaining specified temperature boundary conditions.

- NX Nastran data may be output in either SORT1 or SORT2 formats. SORT1 output provides a tabular listing of all grid points or elements for each loading condition. SORT2 output is tabular listings of loading conditions for each grid point or element. SORT1 output is the steady state default format. SORT2 is generated by requesting XYPLOTS.

- Restarts are controlled by the PARAMeters SUBID and LOOPID. The Case Control command THERMAL(PUNCH) can be used to generate temperature punch files suitable for restart initial conditions or thermal stress analysis loads.

Transient Heat Transfer – SOL 159

- Only one set of temperature constraints (via the MPC and SPC Case Control command) may be requested and must be specified above the subcase level. Any DMIG and/or TF used must also be selected above the subcase level.

- A subcase must be defined for each unique combination of transient thermal load conditions (DLOAD command) and nonlinear iteration strategy (TSTEPNL command).

  Each subcase defines a time interval starting from the last time step of the previous subcase, and the time interval requested is subdivided into the appropriate time steps. The data blocks containing solutions are generated at the end of each subcase to store in the database for output process and restarts.

- The DLOAD and/or NONLINEAR command must be used to specify time-dependent loading conditions. The static thermal load entries QVOL, QVECT, QHBDY, and QBDYi may be used in defining a dynamic load as specified by the TLOADi entry. The set identification number (SID) on the static load entries is specified in the DAREA field of the TLOADi entry. The TEMPBC (of TRAN type) Bulk Data entry may be requested in the same fashion.

  The input loading functions may be changed for each subcase or continued by repeating the same DLOAD request. However, it is recommended to use the same TLOADi Bulk Data entry for all subcases in order to maintain continuity, since the TLOADi entry defines the loading history as a function of cumulative time.

- Temperature initial conditions are requested above the subcase level with the IC Case Control command. Initial temperatures are specified on TEMP and/or TEMPD Bulk Data entries.

- Output requests for each subcase are processed independently. Requested output quantities for all the subcases are appended after the computational process for the actual output operation. The available output is as follows:

ENTHALPY	Grid point enthalpies.
THERMAL	Grid point temperatures.
FLUX	Element gradient and fluxes.
OLOAD	Applied linear loads.
SPCF	Heat of constraint.
HDOT	Enthalpy gradient with respect to time.

- NX Nastran data may be output in either SORT1 or SORT2 output format. SORT1 output is a tabular listing of all grid points or elements for each time step in transient analysis. In transient analysis, SORT1 output is requested by placing a PARAM,CURVPLOT,+1 in the Bulk Data.

  SORT2 is the default format for transient analysis.

- Restarts are controlled by the parameters STIME, LOOPID, and SLOOPID. See the *NX Nastran Handbook for Nonlinear Analysis*, Section 9.2.2 for a discussion of restarts for nonlinear transient analysis. The Case Control command THERMAL(PUNCH) can be used to generate temperature punch files suitable for restart initial conditions or for thermal stress analysis loads.

Bulk Data Entries (Required)

The Bulk Data Section follows BEGIN BULK and ends with the ENDDATA delimiter. It contains all of the details of the model and the conditions for the solution. BEGIN BULK and ENDDATA must be present even though no new Bulk Data is being introduced into the problem or if all of the Bulk Data is coming from an alternate source, such as user-generated input. The format of the BEGIN BULK entry is in free-field format. The ENDDATA delimiter must begin in column 1 or column 2. In general, only one model can be defined in the Bulk Data Section. However, some of the Bulk Data, such as the entries associated with loading conditions, direct input matrices, and transfer functions, may exist in multiple sets. Only sets selected in the Case Control Section are used in any particular solution. The Bulk Data entries associated primarily with thermal analysis are included in "Bulk Data Entries".

Miscellaneous Input

The input file might also include required resident operating system job control language (JCL) statements. The type and number of JCL statements varies with the particular computer installation.

The input file may be formed by the insertion of other files with the INCLUDE statement. This INCLUDE statement may be specified in any of the five parts of the input file.

Comments may be inserted in any of the parts of the input file. They are identified by a dollar sign ($) in column 1. Columns 2 through 72 may contain any desired text.

3.4 Files Generated by NX Nastran

Upon successful execution of an NX Nastran job, a variety of files are automatically created. These files have the following filename extensions and descriptions as shown below:

.dat	The input file describing the model, the type of solution, the output requests, etc. Generated with a text editor or preprocessor.
.f06	The main output file containing the printed output such as temperature, temperature gradients, heat flows, etc.
.f04	A history of the assigned files, disk space usage, and modules used during the analysis. Useful for debugging.
.log	A summary of the command lines options used and the execution links.
.DBALL	A database containing the input files, assembled matrices, and solutions. Used for restarting the job for additional analysis.
.MASTER	The file containing the master directory of the files used by the run and the physical location of the files on the system. This file is also needed for a restart job.
.USRSOU	Used only for advanced DMAP applications. This file may be deleted after the run is finished. It is not needed for restarts.
.USROBJ	Used only for advanced DMAP applications. This file may be deleted after the run is finished. It is not needed for restarts.
.plt	Contains the plot information requested with the NASPLT command specified in the input file.
.pch	Contains the punch output as requested in the input file.
.xdb	Graphics database used for postprocessing of the results.

miscellaneous scratch files	Several scratch files are generated during the analysis which NX Nastran automatically deletes upon completion of the run.

SCR (scratch) Command

If no restarts or database manipulations are planned, then the MASTER, DBALL, USRSOU, and USROBJ files can be automatically deleted (scratched) upon completion of the run by adding the statement SCR = YES to the execution command. For example,

```
NASTRAN EXAMPLE1 SCR=YES
```

Failure to delete these files may prohibit subsequent reruns of the same input file.

The .dat, .f06, .f04, .log, and .pch files are ASCII files and can be viewed using any text editor. The remaining files are binary, and as such, cannot be viewed. The binary files are not intended to be used directly; they are used for additional analysis, such as restarts or postprocessing. If no restarts are planned, you may specify “scr = yes” when submitting the input file for execution. The .DBALL, .MASTER, .USROBJ, and .USRSOU files are placed on the scratch directory and are automatically deleted upon completion of the run.

The .USEROBJ and .USRSOU files are intended only for DMAP users and may be deleted after the run is complete. The .plt file is a binary file that contains the plotting information generated by NASPLT, the NX Nastran internal plotting feature. If NASPLT is not used, the .plt file is deleted following the completion of the run. If punch output is specified, the .pch file is retained when the run is complete. The .xdb binary file is the graphic database used by graphics pre- and postprocessors. It is requested using PARAM,POST in the Bulk Data Section. (Refer to the description of PARAM,POST in the *NX Nastran Quick Reference Guide*.)

3.5 Plotting

NX Nastran has the ability to generate structural plots or X-Y plots rom batch program executions. Such plots are requested by placing data commands at the end of the Case Control Section. Plot requests are separated from the Case Control by the OUTPUT(PLOT), OUTPUT(XYPLOT), or OUTPUT(XYOUT) commands. Data above this command is not recognized by the plotter.

For virtually any type of plotter hardware, the plotter programs are executed by

```
NASPLT ‘name.plt’
```

for a “CALCOMP-like” plot, or by

```
TEKPLT ‘name.plt’
```

for a “TEKTRONIX-like” plot. The ‘name.plt’ is the filename of the plot file generated from NX Nastran. These programs are delivered with the utility files.

The following discussion is limited to a description of all of the commands required to obtain undeformed structure, thermal contour, and X-Y plots in thermal analysis.

Structural Plotting

In thermal analysis, structural plotting is applied to display the model geometry (undeformed structure plots) and the temperature distribution across the model (thermal contour plots). The structural plotting is requested in the Case Control Section by the plotting commands from an OUTPUT(PLOT) command to either a BEGIN BULK, OUTPUT(XYPLOT), or OUTPUT(XYOUT) command.

Plot Set Selection

NX Nastran plots consist of element images. Grid points are identified by the intersection of the elements. Note that the surface elements CHBDYE, CONV, CONVM, and RADBC cannot be plotted. The SET command is required to specify sets of elements for plotting. Examples are as follows:

SET 1 = ALL

SET 2 = BAR, QUAD4, EXCEPT 10, 50 THRU 90 BY 20

SET 3 = 1, 5 THRU 10, 100 THRU 105, 210

SET 4 = ALL EXCEPT HBDY

In these examples, SET 1 includes all elements, SET 2 includes all CBAR and CQUAD4 elements except elements 10, 50, 70, and 90, SET 3 includes a subset of elements selected by their ID numbers, and SET 4 includes all elements except CHBDYi surface elements.

Only one set of elements can be selected for a particular plot. To request an undeformed structural plot, the following two commands are required:

FIND SCALE, ORIGIN j, SET i

PLOT SET i, ORIGIN j

where i identifies one of the sets described in the SET command and j defines an origin for the plot. If j is equal to i, the program finds the origin automatically and positions the plot in the center of the viewing window. If some other origin is desired, the ORIGIN command should be used. In particular, the ORIGIN command should be used if more than ten plot sets are requested.

Parameter Definition Commands

The parameter definition commands are described in the *NX Nastran User's Guide*. A set of commonly used commands is as follows:

- PLOTTER = {NAST}

  Selects plotter. The default is NAST.

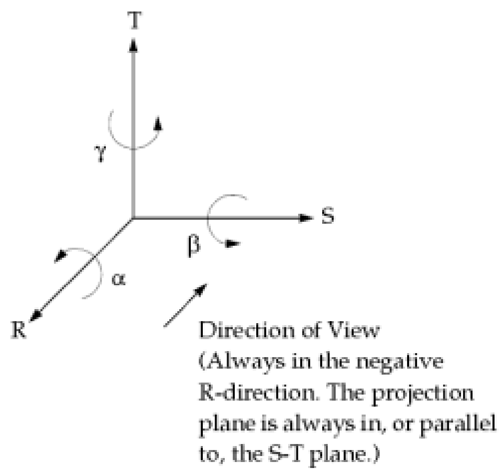
- AXES R, S, T

  VIEW γ, β, α

  where:

R, S, T	=	X or MX, Y or MY, Z or MZ (where “M” implies the negative axis)
γ, β, α	=	three angles of rotation in degrees (Real)

  Defines the orientation of the object in relation to the observer. The observer's coordinate system is defined as R, S, T, and the basic coordinate system of the object is defined as X, Y, Z. The angular relationship between the two systems is defined by the three angles α, β, and γ as follows:



The two coordinate systems are coincident (i.e., X is coincident with R, etc.) for $\gamma = \beta = \alpha = 0$. The sequence in which the rotations are taken was arbitrarily chosen as: γ , the rotation about the T-axis; followed by β, the rotation about the S-axis; followed by α, the rotation about the R-axis. Normally, α is not used since it does not affect the appearance of the S-T projection, only its orientation on the page. The default values of the rotations are γ = 34.27×, β = 23.17×, and α = 0.0×, which produce a plot in which unit vectors on the X-, Y-, and Z-axes have equal lengths.

The default view described above may be altered in two ways. The structural axes that coincide with the R-, S-, T-axes may be interchanged by means of the "AXES R, S, T" command, and the view angles can be rotated by the "VIEW γ, β, α " command. The default forms of these commands are

```
AXES X, Y, Z
VIEW 34.27, 23.17, 0.0
```

To view the structure from the positive Y-axis, use the commands

```
AXES Y, Z, X
VIEW 0.0, 0.0, 0.0
```

that points the Z-axis toward the right and the X-axis upward in the plot, or use

```
AXES Y, MX, Z
VIEW 0.0, 0.0, 0.0
```

that points the X-axis toward the left (in this expression MX means that the minus X-axis coincides with S) and points the Z-axis upward. Note that the expression

```
AXES Y, X, Z
```

provides a mirror image of the structure. In order to avoid a mirror image, the sequence of axes must obey the right-hand rule.

The structure can be viewed from the position Z-axis by the expression

```
AXES Z, X, Y
VIEW 0.0, 0.0, 0.0
```

Other combinations of AXES and VIEW commands produce any desired views of the structure. For example,

```
VIEW 45.0, 0.0, 0.0
```

provides a view midway between the positive X- and Y-axes of the basic coordinate system.

- CSCALE = $\left\{\frac{0.5}{cs}\right\}$

  Controls the spacing of the characters; the default value is 0.5. A value of 1.8 produces good spacing of output characters. The CSCALE command must immediately precede the PLOTTER selection command. If a second CSCALE command is used, a second PLOTTER selection command must also be used.

- PTITLE = {any legitimate character string}

  Title to be printed at the top of the plot on the line below the sequence number. The default value for the text is all blanks.

Undeformed Structural Plots

Requests for undeformed plots take the following general form:

PLOT i1, i2 THRU i3 , i4 , etc., SET j, ORIGIN k, LABEL

$$\left\{\begin{array}{l}\text{GRID POINTS}\\ \text{ELEMENTS}\\ \text{BOTH}\end{array}\right\}$$

The following entries are optional:

- i1, i2 THRU i3, i4, etc. – List of subcases; the default is to plot all subcases.

- LABEL $\left\{\begin{array}{l}\underline{\text{GRID POINTS}}\\ \text{ELEMENTS}\\ \text{BOTH}\end{array}\right\}$ – Label either the grid points and/or the elements with the ID numbers.

Thermal Contour Plots

Requests for thermal contour plots are similar to requests for undeformed structural plots. All axes, view, and set commands are the same. The only changes are the addition of one CONTOUR command and one modification to the PLOT command.

The CONTOUR command specifies that contour data is to be prepared for a subsequent plot command. For thermal analysis, this command has the form

```
CONTOUR MAGNIT
```

where “MAGNIT” is a mnemonic for a “magnitude” data request that satisfies the data processing requirement for thermal temperature contours. The CONTOUR command should be placed immediately before the associated PLOT execution command. A THERMAL Case

Control command must appear for all grid points that are specified in the plot set definition of contour plots.

The only change necessary to the PLOT command is the specification of CONTOUR plots. The PLOT command then appears as:

```
PLOT CONTOUR, SET i, OUTLINE
```

The OUTLINE entry (optional) requests that only the outline of all the elements in the specified set be displayed. If this entry is not specified, all of the elements included in the specified set are displayed.

To plot thermal contours at any time step of a transient analysis, the PLOT command must specify the desired time or time range. The PLOT command then takes the form

```
PLOT CONTOUR, TIME t1 , t2 , SET i, OUTLINE
```

Here the contour plot(s) is created for all parts of the model in SET i and at time steps within the range of t_1 and t_2 . If only t_1 is specified, the plot is generated at $t=t_1$.

Examples of Structure Plot Requests

The following examples are typical plot packets for thermal analysis. BEGIN BULK or OUTPUT(XYPLOT) command is shown as a reminder to the user to place the plot request packet properly in the Case Control Section, i.e., at the end of the Case Control Section or just before any X-Y output requests.

Example 1

The following sequence causes an undeformed structural plot to be selected for the entire model, using the default values for AXES and VIEW.

```
OUTPUT (PLOT)
SET 1 = ALL
FIND SCALE, ORIGIN 1, SET 1
PLOT SET 1
BEGIN BULK
```

Example 2

The following sequence causes temperature contours over the entire model to be plotted using all default orientation view angles.

```
OUTPUT (PLOT)
SET 1 = ALL
FIND SCALE, ORIGIN 1, SET 1
CONTOUR MAGNIT
PLOT CONTOUR, SET 1
OUTPUT(XYPLOT)
```

Example 3

The following sequence causes three plots to be generated.

```
OUTPUT (PLOT)
SET 1 = ALL
SET 2 = BAR, QUAD4
SET 3 = 14 THRU 44, 100 THRU 147, 210
$FIRST PLOT
FIND SCALE, ORIGIN 1, SET 1
PLOT SET 1, ORIGIN 1
$SECOND PLOT
```

```
AXES Z, X, Y
VIEW 0.0, 0.0, 0.0
FIND SCALE, ORIGIN 2, SET 2
PLOT SET 2, ORIGIN 2
$THIRD PLOT
FIND SCALE ORIGIN 3, SET 3
PLOT SET 3, ORIGIN 3, LABEL BOTH
BEGIN BULK
```

The first plot uses the default values for AXES and VIEW. The second plot uses the indicated overrides. The third plot uses the same view options as the previous plot, which is the default for multiple plots. It also uses the option to label both grid points and elements. Note that in all cases the FIND command immediately precedes the PLOT command and follows any AXES or VIEW commands that are explicitly present. Any other sequence for these commands results in improperly scaled plots.

Example 4

The following sequence generates three plots using more spacing of characters.

```
OUTPUT (PLOT)
CSCALE = 1.8
PLOTTER NAST
SET 1 = ALL
SET 2 = QUAD4
$FIRST PLOT
PTITLE = BASIC MODEL
FIND SCALE, ORIGIN 1, SET 1
PLOT SET 1, ORIGIN 1
$SECOND PLOT
PTITLE = LABEL GRIDS
FIND SCALE, ORIGIN 2, SET 2
PLOT SET 2 LABEL GRIDS
$THIRD PLOT
PTITLE = THERMAL CONTOURS
CONTOUR MAGNIT
PLOT CONTOUR, TIME 5.0, ORIGIN 1, SET 1, OUTLINE
BEGIN BULK
```

The first plot is a simple undeformed structural plot of the entire model and has the title “BASIC MODEL”. The second plot is the same type of plot for all CQUAD4 elements in the model. The plot title is “LABEL GRIDS”. This plot has its own scale and magnification factor as requested by its unique FIND SCALE command. The third plot is a contour plot over the entire model for the temperatures at time 5.0. Since this plot does not have its own FIND SCALE command, the view has the same orientation as does the first plot. Its title is “THERMAL CONTOURS.”

X-Y Plotting

In transient thermal analysis, X-Y plotting is used to track the temperature-time history or the heat flux/time history of grid points. It can also be applied in steady state analysis to plot temperature versus a set of grid points. In addition to the plots, X-Y tabular output may be printed or punched, and a summary of data (e.g., maximum and minimum values as well as the locations of these values) may be obtained for any X-Y output.

The X-Y output is requested via a packet in the Case Control Section. This packet includes all of the commands between either OUTPUT(XYPLOT) or OUTPUT(XYOUT) and either BEGIN BULK or OUTPUT(PLOT).

X-Y Plotter Terminology

A single set of plotted X-Y pairs is known as a "curve." Curves are the entities that the user requests to be plotted. The surface (paper, microfilm frame, etc.) on which one or more curves is plotted is known as a "frame." Curves may be plotted on a whole frame, an upper-half frame, or a lower-half frame. Grid lines, tic marks, axes, and axis labeling may be chosen by the user. The program selects defaults for parameters that are not selected by the user. Only two commands are required for an X-Y output request. They are

- X-Y output section delimiter – OUTPUT(XYPLOT) or OUTPUT(XYOUT).
- At least one operation command.

The terms OUTPUT(XYPLOT) and OUTPUT(XYOUT) are interchangeable and either form may be used for any of the X-Y output requests. If the output is limited to printing and/or punching, a plotter selection command is not required. The operation command(s) is used to request various forms of X-Y output.

If only the required commands are used, the graphic control options assume all the default values. Curves using default parameters have the following general characteristics:

- Tic marks are drawn on all edges of the frame. Five spaces are provided on each edge of the frame.
- All tic marks are labeled with their values.
- Linear scales are used.
- Scales are selected such that all points fall within the frame.
- The plotter points are connected with straight lines.
- The plotted points are not identified with symbols.

The above characteristics may be modified by inserting any number of parameter definition commands before the operation command(s). The following is an overview of the parameter definition commands and the operation commands for thermal analysis. A more complete description is contained in "X-Y PLOT Commands" in the *NX Nastran Quick Reference Guide*.

Parameter Definition Commands

The parameter definition commands are described in "X-Y Output Command Summary" in the *NX Nastran Quick Reference Guide*. A set of commonly used commands is listed as follows:

- PLOTTER = {NAST}

  Selects plotter. The default is NAST.

- CLEAR

  Causes all parameter values except titles (XTITLE, YTITLE, YTTITLE, YBTITLE, TCURVE) to revert to their default values.

- CSCALE = cs (Real)

  See the *Parameter Definition Commands* section of *Structural Plotting*.

- CURVELINESYMBOL = cls (Integer)

Request for points to be connected by lines (cls = 0), identified by symbol |cls| (cls < 0), or both (cls > 0); default value is 0. The following symbols are available:

Symbol Number	Symbol
0	no symbol
1	x
2	•
3	+
4	–
5	Ž
6	○
7	□
8	◇
9	△

If more than one curve per frame is required, the symbol number is incremented by 1 for each curve.

- TCURVE = {any legitimate character string}

  Curve title.

- XTITLE = {any legitimate character string}

  Title to be used with the x-axis.

- YTITLE = {any legitimate character string}

  Title to be used with y-axis. This command pertains only to whole frame curves.

- XMIN = x1 (Real)

  XMAX = x2 (Real)

  Specifies the limits of the abscissa of the curve; the default values are chosen to accommodate all points.

- YMIN = y1 (Real)

  YMAX = y2 (Real)

  Specifies the limits of the ordinate of the curve; the default values are chosen to accommodate all points. This command pertains only to whole frame curves.

- XGRID = $\left\{\begin{array}{c} \text{YES} \\ \underline{\text{NO}} \end{array}\right\}$

  Request for drawing in the grid lines parallel to the y-axis at locations requested for tic marks; the default value is NO. This command pertains only to whole frame curves.

- YGRID = $\left\{ \begin{matrix} \text{YES} \\ \underline{\text{NO}} \end{matrix} \right\}$

  Request for drawing in the grid lines parallel to the x-axis at locations requested for tic marks; the default value is NO. This command pertains only to whole frame curves.

Operation Commands

When a command operation is encountered, one or more frames is generated using the current parameter specifications. The form of this command as applied in thermal analysis is

Operation one or more (required)	Curve Type one only (required)	Subcase List (optional)	Curve Request(s) (required)
XYPLOT	FLUX	i_1, i_2, i_3,	
XYPRINT	OLOAD	i_4, THRU i_5	“frames”
XYPUNCH	SPCF	i_6, etc.	
XYPEAK	TEMP		
XYPAPLOT	VELO	Default is all subcases	

Note

Continuation commands may not be used until the subcase list section is reached.

Operation

The entries in the operation field have the following meanings:

XYPLOT	Generates X-Y plots for the selected plotter.
XYPRINT	Generates tabular printer output for the X-Y pairs.
XYPUNCH	Generates punched command output for the X-Y pairs. Each command contains the following information:
x	X-Y pair sequence number.
x	X-value.
x	Y-value.
x	Command sequence number.
XYPEAK	Output is limited to the printed summary page for each curve. This page contains the maximum and minimum values of y for the range of x.
XYPAPLOT	Generates X-Y plots on the printer. The x-axis moves horizontally along the page and the y-axis moves vertically along the page. Symbol ‘*’ identifies the points associated with the first curve of a frame, then for successive curves on a frame the points are designated by symbols O, A, B, C, D, E, F, G, and H.

Curve Type

Only one type of curve field may appear in a single operation command. However, there is no limit to the number of such commands. The entries in the curve type field have the following meaning:

Curve Type	Meaning
FLUX	Element flux output
OLOAD	Load
SPCF	Single-point force of constraint
TEMP	Temperature in the physical set
VELO	Enthalpy in the physical set

Subcase List

The subcase list generates output for the subcase numbers that are listed. The subcase list must be in ascending order. Default is all subcases for which solutions were obtained.

Curve Request(s)

The word “frames” represents a series of curve identifiers of the following general form:

```
/a1(b1,c1) ,a2(b2,c2),etc./d1(e1,f1) ,d2(e2,f2) ,etc./etc.
```

The information between slashes (/) specifies curves that are to be drawn on the same frame. The symbol a1 identifies the grid point or element number associated with the first plot on the first frame. The symbol a2 identifies the grid point or element number associated with the second plot on the first frame. The symbols d1 and d2 identify similar items for plots on the second frame, etc. AII plot requests on one command are sorted by grid point or element ID to improve the efficiency of the plotting process. Symbols are assigned in order by grid points or element identification number.

The symbols b1 and b2 are codes for the items to be plotted on the upper half of the first frame, and c1 and c2 are codes for the items to be plotted on the lower half of the first frame. If any of the symbols b1, c1, b2, or c2 are missing, the corresponding curve is not generated. If the comma (,) and c1 are absent along with the comma (,) and c2, full frame plots are prepared on the first frame for the items represented by b1 and b2. For any single frame, curve identifiers must all be of the whole frame type or all of the half frame type, i.e., the comma (,) following b1 and b2 must be present for all entries or absent for all entries in a single frame. The symbols e1, f1, e2, and f2 serve a similar purpose for the second frame, etc. If continuation commands are needed, the previous command may be terminated with any one of the slashes (/) or commas (,) in the general format.

Item codes are fully described in “Item Codes” in the *NX Nastran Quick Reference Guide*. For curve types OLOAD, SPCF, TEMP, and VELO in thermal analysis, use item code T1. For X-Y plots of heat fluxes (curve type FLUX), the item codes are

Element Type	Code	Item
Conductive Elements	4	x gradient
	5	y gradient
	6	z gradient
	7	x flux
	8	y flux
	9	z flux
CHBDYi Elements	4	Applied load
	5	Free convection
	6	Forced convection

	7	Radiation
	8	Total

Examples of X-Y Output Request Packets

The following examples are applied in transient thermal analysis to display the temperature or heat flux as a function of time. The BEGIN BULK or OUTPUT(PLOT) command is shown as a reminder to the user to place the X-Y output request packet properly in the Case Control Section, i.e., at the end of the Case Control Section or just ahead of any structure plot requests.

Example 1

The following sequence causes a single whole frame to be plotted for the temperature of grid point 5, using the default parameter values:

```
OUTPUT(XYPLOT)
XYPLOT TEMP/5 (T1)
BEGIN BULK
```

Example 2

The following sequence causes a single frame (consisting of an upper half frame and a lower half frame) to be plotted using the default parameter values:

```
OUTPUT(XYPLOT)
XYPLOT FLUX/70 (7,9) ,80(7,9)
OUTPUT (PLOT)
```

Each half frame contains two curves. The x-direction heat fluxes of the CHEXA element number 70 and the CPENTA element number 80 are plotted on the upper half frame. The z-direction heat fluxes are plotted on the lower half frame for these two elements.

Example 3

The following sequence causes three whole frames to be plotted using the default parameter values:

```
OUTPUT(XYPLOT)
XYPLOT VELO /11(T1),12(T1)
XYPLOT OLOAD/21(T1),22(T1)
XYPLOT SPCF /31(T1),32(T1)
OUTPUT (PLOT)
```

Each frame contains two curves. The first plot is the enthalpy at grid points 11 and 12. The second plot is the linear loads applied at grid points 21 and 22. The third plot is the single-point forces of constraint applied at grid points 31 and 32.

Example 4

The following sequence causes two whole frame plots to be generated, one for CHBDYi element numbers 10 and 20 and the other for CHBDYi element numbers 30 and 40:

```
OUTPUT(XYPLOT)
XTITLE = TIME IN SECONDS
YTITLE = FREE CONVECTION AND RADIATION OF THE CHBDYi ELEMENTS
XGRID = YES
YGRID = YES
CURVELINESYMB = 6
XYPLOT FLUX/10(5),10(7) ,20(5) ,20 (7) /30(5) ,30(7) ,40(5) ,40(7)
```

```
BEGIN BULK
```

Each plot contains the free convection and radiation heat flows for two CHBDYi elements. The default parameters are modified to include titles and grid lines in both the x-direction and y-direction. Distinct symbols are used for each curve. The first curve is identified by circles (○), the second curve by squares (□), the third curve by diamonds (◇), and the fourth curve by triangles (△).

Example 5

The following sequence causes three whole frames to be generated:

```
OUTPUT(XYPLOT)
XTITLE = TIME
YTITLE = TEMPERATURE
XGRID = YES
YGRID = YES
XYPLOT TEMP/1(T1),2(T1),3(T1)
YTITLE = Y-FLUX OF THE QUAD4 ELEMENTS
XYPLOT FLUX/10(8)
YTITLE = FORCED CONVECTION OF THE CHBDYi ELEMENTS
XYPLOT FLUX/31(6), 32(6)
BEGIN BULK
```

The first plot is the temperatures for grid points 1, 2, and 3. The second plot is the heat flux in the y-direction for CQUAD4 element number 10. The third plot is the forced convection heat flows for CHBDYi element numbers 31 and 32. The default parameters are modified to include titles and grid lines in both the x-direction and y-direction.

X-Y Plots for SORT1 Output

It is often convenient to display the distribution of temperature versus a sequence of grid points. The identification numbers of the sequence of grid points to be plotted should be listed on a SET1 Bulk Data entry.

The requests for X-Y plots appear in the Case Control Section in the standard form. For example,

```
OUTPUT(XYPLOT)
XTITLE = ZAXIS
YTITLE = TEMPERATURE
XGRID = YES
YGRID = YES
CURVELINESYMB = 6
XYPLOT TEMP/99(T1)
BEGIN BULK
.
.
.
PARAM,CURVPLOT,1
PARAM,DOPT,3
SET1,99,1,THRU,10
```

This example generates an X-Y plot from grid point temperatures. The abscissa of the curve reflects the grid point IDs listed on the SET1 Bulk Data entry with an SID of 99, and the ordinate reflects the temperatures at these grid points. In the Bulk Data, PARAM,CURVPLOT,1 suppresses SORT2-type processing and requests that X-Y plots be made with the abscissas relating to grid point locations. Parameter DOPT controls the x spacing of these curves. The allowable values of this parameter are shown in the following table:

Value of DOPT	Scaling for Abscissa
0 (default)	$\lVert g_j - g_i \rVert$
1	$\lvert x_j - x_i \rvert$
2	$\lvert y_j - y_i \rvert$
3	$\lvert z_j - z_i \rvert$
4	1

The default for DOPT is the length between grid points, with the first grid point listed on the referenced SET1 command at the origin. For DOPT values 1, 2, or 3, the spacing between adjacent points on the abscissa is proportional to one component of the distance between their grid points. DOPT = 4 spaces the grid points equally along the abscissa.

Chapter

4 Method of Solution

- *Introduction to Solution Methods*
- *Nonlinear Iteration Scheme*
- *Steady State Analysis*
- *Transient Analysis*

4.1 Introduction to Solution Methods

This chapter describes the solution methods of NX Nastran thermal analysis. Two types of heat transfer problems, steady state analysis and transient analysis, are solved by NX Nastran. The solutions of these analysis types, their respective NX Nastran solution sequences, and iteration methods are discussed in the following sections.

4.2 Nonlinear Iteration Scheme

NX Nastran applies a Newton-Raphson iteration scheme to solve thermal (and structural) analysis problems. In finite element analysis, the general equilibrium equation is

$$[K]\{u\} = \{F\}$$

Figure 4-1.

where:

$[K]$	=	the conduction matrix (stiffness matrix)
$\{u\}$	=	the unknown grid point temperature vector to be solved (displacement)
$\{F\}$	=	the vector of known heat flows (forces)

Applying Newton's method involves the specification of a correction vector

$$\{\psi\} = [K]\{u\} - \{F\}$$

Figure 4-2.

and the approximation of the vanished correction vector at the (i + 1)-th iteration, i.e.,

$$\{\psi\}^{i+1} \approx \{\psi\}^{i} + \left[\frac{\partial\psi}{\partial u}\right]^{i}\{\Delta u\}^{i} = 0$$

Figure 4-3.

where

$$\{\Delta u\}^{i} = \{u^{i+1} - u^{i}\}$$

Figure 4-4.

is the i-th incremental displacement vector. The above equation can be rewritten as

$$[K_T]^{i}\{\Delta u\}^{i} = \{R\}^{i}$$

Figure 4-5.

where:

$[K_T] = \left[\frac{\partial\psi}{\partial u}\right]$	=	the tangential matrix which includes components related to conduction, convection advection, and radiation.
$\{R\} = -\{\psi\}$	=	the residual vector

At each iteration, the left-hand side matrix $[K_T]^{i}$ and the right-hand side vector $\{R\}^{i}$ are computed based on the temperature vector $\{u\}^{i}$. By solving the unknown vector $\{\Delta u\}^{i}$, the displacement vector at the (i + 1)-th iteration can be calculated from

$$\{u\}^{i+1} = \{u\}^{i} + \{\Delta u\}^{i}$$

Figure 4-6.

Since matrix decomposition is time consuming, NX Nastran does not update the left-hand side matrix at each iteration. The tangential matrix is updated only when the solution fails to converge or the iteration efficiency can be improved. However, the residual vector is updated at each iteration.

In concert with Newton's method, the following options are provided to improve the efficiency of the iteration:

- Tangential matrix update strategy.
- Line search method.
- Bisection of loads.
- Quasi-Newton (BFGS) updates.

These options are specified on NLPARM (steady state analysis) or TSTEPNL (transient analysis) Bulk Data entries. In general, if the solution diverges, a line search algorithm, a bisection of loads, and a quasi-Newton update are implemented in an effort to improve the solution. If the solution still fails to converge with all the above methods, the tangential stiffness is updated to resume the iteration. Refer to the *NX Nastran Handbook for Nonlinear Analysis* for detailed algorithms.

4.3 Steady State Analysis

Basic Equations

The steady state heat balance equation is

$$[K]\{u\} + [\Re]\{u + T_{abs}\}^4 = \{P\} + \{N\}$$

Figure 4-7.

where:

$[K]$	=	a heat conduction matrix
$[\Re]$	=	a radiation exchange matrix
$\{P\}$	=	a vector of applied heat loads that are independent of temperature
$\{N\}$	=	a vector of nonlinear heat loads that are temperature dependent
$\{u\}$	=	a vector of grid point temperatures
T_{abs}	=	the absolute temperature scale adjustment required for radiation heat transfer exchange or radiation boundary conditions when all other temperatures and units are specified in deg-F or deg-C.

The components of the applied heat flow vector $\{P\}$ are associated either with surface heat transfer or with heat generated inside the volume heat conduction elements. The vector of nonlinear heat flows $\{N\}$ results from boundary radiation, surface convection, and temperature-dependent thermal loads.

The equilibrium equation is solved by a Newton iteration scheme where the tangential stiffness matrix is approximated by

$$[K_T]^i \approx [K]^i + 4[\Re]^i\{u^i + T_{abs}\}^3 - \left\{ \frac{\partial N}{\partial u} \right\}^i$$

Figure 4-8.

and the residual vector is

$$\{R\}^i = \{P\} + \{N\}^i - [K]^i\{u\}^i - [\Re]^i\{u^i + T_{abs}\}^4$$

Figure 4-9.

Steady State Analysis Solution Sequence

In NX Nastran, steady state thermal analysis is solved by Solution Sequence 153. Since Solution 153 can be used for both structural (default) and thermal analyses, the user must include the command

```
ANALYSIS = HEAT
```

in the Case Control Section of the input data for thermal analysis. The input data file may then appear as:

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE
ANALYSIS = HEAT
NLPARM = 10
TEMP(INIT) = 20
.
.
BEGIN BULK
NLPARM,10,....
.
.
TEMP,20,.....
TEMPD,20,....
ENDDATA
```

The NLPARM entry is required to control the incremental and iterative solution processes. For nonlinear problems, a set of temperatures should be provided for an initial guess. These temperatures are specified on TEMP and TEMPD Bulk Data entries and are selected by a TEMP(INIT) Case Control command.

Convergence Criteria

The convergence criteria are characterized by the dimensionless error functions and the convergence tolerances. To ensure accuracy and efficiency, multiple criteria with errors measured about temperatures, loads, and energy are provided.

1. Temperature error function

   Since the error in temperatures is not known, a contraction factor q is introduced to formulate the temperature error function, which is defined as

$$q = \frac{\left\| u^{i+1} - u^i \right\|}{\left\| u^i - u^{i-1} \right\|} = \frac{\left\| \Delta u^i \right\|}{\left\| \Delta u^{i-1} \right\|}$$

Figure 4-10.

   To avoid fluctuation and ill-conditioning, an averaging scheme is applied to compute the contraction factor

$$q^i = \frac{2}{3}\frac{\|\Delta u^i\|}{\|\Delta u^{i-1}\|} + \frac{1}{3}q^{i-1}$$

Figure 4-11.

with an initial value $q^0 = 0.99$. If q is assumed to be constant with a value less than unity, the absolute error in temperatures can be estimated by

$$\begin{aligned}&\left\|u - u^{i+1}\right\| \le \left\|u - u^{i+n}\right\| + \left\|u^{i+n} - u^{i+n-1}\right\| + \ldots + \left\|u^{i+2} - u^{i+1}\right\| \\ &= \left\|\Delta u^i\right\|\left(q^n + q^{n-1} + \ldots + q\right) \\ &= \left\|\Delta u^i\right\|\frac{q}{1-q}\end{aligned}$$

Figure 4-12.

The temperature error function is formulated by introducing the weighted normalization to the above equation, i.e.,

$$E_u = \frac{q}{1-q}\frac{\|\omega \cdot \Delta u\|}{\|\omega \cdot u\|} = \frac{q}{1-q}\frac{\sum_j |\omega_j \Delta u_j|}{\sum_j |\omega_j u_j|}$$

Figure 4-13.

where the weighting function $\{\omega\}$ is defined as the square root of the diagonal terms of the tangential matrix $[K_T]$, i.e.,

$$\omega_j = \sqrt{K_{T_{jj}}}$$

Figure 4-14.

2. Load error function

   The load error function is defined as

$$E_p = \frac{\|R \cdot u\|}{\|P' \cdot u\|} = \frac{\sum_j |R_j u_j|}{\sum_j |P'_j u_j|}$$

Figure 4-15.

with

$$\{P'\} = \{|P_{ld}|\} + \{|\Delta P_{ld}|\}$$

Figure 4-16.

where $\{P_{ld}\}$ is the applied thermal load at the previous loading step, and $\{\Delta P_{ld}\}$ is the incremental load.

3. Energy error function

   The energy (or work) error function is defined as

$$E_w = \frac{\|R \cdot \Delta u\|}{\|P' \cdot u\|} \frac{\sum_j |R_j \Delta u_j|}{\sum_j |P'_j u_j|}$$

Figure 4-17.

At every iteration, error functions are computed and printed in the convergence table under the headings EUI, EPI, and EWI. The convergence test is performed by comparing the error functions with the convergence tolerances, i.e.,

$$E_u < \text{EPSU (default } = 10^{-3})$$

$$E_p < \text{EPSP (default } = 10^{-3})$$

$$E_w < \text{EPSW (default } = 10^{-7})$$

where EPSU, EPSP, and EPSW are tolerances specified on the NLPARM Bulk Data entry. The solution has converged if these tests are satisfied. However, only those criteria selected by the user (specified in the CONV field of the NLPARM entry) are checked for convergence. Note that the tolerances should not be too tight to waste iteration time or too loose to affect accuracy. It is recommended that the default values be used until better values are found through iteration experience.

Iteration Control

The incremental and iterative solution processes are controlled by the parameters specified on the NLPARM Bulk Data entry, with the data format and default values described as follows:

1	2	3	4	5	6	7	8	9	10
NLPARM	ID	NINC	DT	KMETHOD	KSTEP	MAXITER	CONV	INTOUT	
NLPARM				AUTO	5	25	PW	NO	+NP1

	EPSU	EPSP	EPSW	MAXDIV	MAXQN	MAXLS	FSTRESS	LSTOL	
+NP1	1.0E-3	1.0E-3	1.0E-7	3	MAXITER	4		0.5	+NP2

	MAXBIS				MAXR		RTOLB		
+NP2	5								

In thermal analysis, the arc-length method (specified by NLPCI command) is disabled. The DT, FSTRESS, MAXR, and RTOLB fields are also ignored and should be left blank for heat transfer.

The ID field specifies an integer selected by the Case Control request NLPARM. For each subcase, load and SPC temperature changes are processed incrementally with a number of equal subdivisions defined by the NINC value.

The KMETHOD and KSTEP fields specify the tangential matrix update strategy. Three separate options for KMETHOD may be selected.

- AUTO

  The program automatically selects the most efficient strategy based on convergence rates. At each iteration, the number of steps required to converge as well as the computing time with and without matrix update are estimated. The tangential matrix is updated if (a) the estimated number of iterations to converge exceeds MAXITER, (b) the estimated time required for convergence with current matrix exceeds the estimated time to converge with matrix update, or (c) the solution diverges. The tangential matrix is also updated on convergence if KSTEP is less than the number of steps required for convergence with the current matrix.

- SEMI

  This option is identical to the AUTO option except that the program updates the tangential matrix after the first iteration.

- ITER

  The program updates the tangential matrix at every KSTEP iteration and on convergence if KSTEP ≤MAXITER. However, the tangential matrix is never updated if KSTEP > MAXITER. Note that the Newton-Raphson method is obtained if KSTEP = 1, and the modified Newton-Raphson method is selected by setting KSTEP = MAXITER.

The number of iterations for a load increment is limited to MAXITER. If the solution does not converge in MAXITER iterations, the load increment is bisected and the analysis is repeated. If the load increment cannot be bisected (i.e., MAXBIS is reached or MAXBIS = 0) and MAXDIV is positive, the best attainable solution is computed, and the analysis is continued to the next load increment. If MAXDIV is negative, the analysis is terminated.

The convergence criteria are defined through the test flags in the CONV field and the tolerances in the EPSU, EPSP, and EPSW fields. The requested criteria (combination of temperature error U, load error P, and energy error W) are satisfied upon convergence.

The INTOUT controls the output requests for temperatures, heat fluxes, and heat flows. If the option ALL or YES is selected, the output requests specified in the Case Control Data are processed for every computed load increment. If the option is NO, the output requests are processed only for the last load step of the subcase.

The MAXDIV limits the divergence conditions allowed for each iteration. The divergence rate E^i is defined by the ratio of energy errors before and after the iteration, i.e.,

$$E^i = \frac{\{\Delta u^i\}^T\{R^i\}}{\{\Delta u^i\}^T\{R^{i-1}\}}$$

Figure 4-18.

Depending on the divergence rate, the number of diverging iterations NDIV is incremented as follows:

If $E^i \geq 1$ or $E^i < -10^{12}$, then $NDIV = NDIV + 2$

If $-10^{12} < E^i < -1$, then $NDIV = NDIV + 1$

The solution is assumed to diverge when NDIV ≥ |MAXDIV|. If the solution diverges and the load increment cannot be bisected (i.e., MAXBIS is reached or MAXBIS = 0), the tangential matrix is updated and the analysis is continued. If the solution diverges again and MAXDIV is positive, the best attainable solution is computed, and the analysis is continued to the next load increment. If MAXDIV is negative, the analysis is terminated on the second divergence.

The BFGS update is performed if MAXQN > 0. As many as MAXQN quasi-Newton vectors can be accumulated. The BFGS update with these QN vectors provides a secant modulus in the search direction. If MAXQN is reached, the tangential matrix is updated, and the accumulated QN vectors are purged. The accumulation resumes at the next iteration.

The line search is performed if MAXLS > 0. In the line search, the temperature increment is scaled to minimize the energy error. The line search is not performed if the absolute value of the relative energy error is less than the tolerance LSTOL or if the number of line searches reaches MAXLS.

The number of bisections for a load increment is limited to |MAXBIS|. Different actions are taken when the solution diverges, depending on the sign of MAXBIS. If MAXBIS is positive, the tangential matrix is updated on the first divergence, and the load is bisected on the second divergence. If MAXBIS is negative, the load is bisected every time the solution diverges until the limit on bisection is reached. If the solution does not converge after |MAXBIS| bisections, the analysis is continued or terminated depending on the sign of MAXDIV.

Iteration Output

At each iteration, the related output data is printed under the following heading:

ITERATION	Iteration count i.
EUI	Relative error in terms of temperatures.
EPI	Relative error in terms of loads.

EWI	Relative error in terms of energy.
LAMBDA	Rate of convergence.
DLMAG	Absolute norm of the residual vector ($\| R_l \|^i$.
FACTOR	Final value of the line search parameter.
E-FIRST	Divergence rate, initial error before line search.
E-FINAL	Error at the end of line search.
NQNV	Number of quasi-Newton vectors appended.
NLS	Number of line searches performed during the iteration.
ENIC	Expected number of iterations for convergence.
NDV	Number of occurrences of probable divergence during the iteration.
MDV	Number of occurrences of bisection conditions during the iteration.

The solver also prints diagnostic messages requested by DIAG 50 or 51 in the Executive Control Section. DIAG 50 only prints subcase status and NLPARM data, while DIAG 51 prints all data at each iteration. In general, the user should be cautioned against using DIAG 51, because it is used for debugging purposes and the volume of output is significant. It is recommended that DIAG 51 be used only for small test problems. The diagnostic output is summarized as follows:

For each entry into NLITER, the following is produced:

- Subcase status data
- NLPARM data
- Core statistics (ICORE, etc.)
- Problem statistics (g-size, etc.)
- File control blocks
- Input file status
- External load increment for subcase: $\{\Delta P_{ld}\}$
- Initial nonlinear force vector: $\{F_g\}$. In thermal analysis, $\{F_g\}$ is the heat flow vector associated with nonlinear conduction, convection (CONV and CONVM), and boundary radiation (RADBC), i.e.,

$$\{F_g\} = [K_g]_{nl}\{u_g\} - \{N_g\}_{CONV} - \{N_g\}_{CONVM} - \{N_g\}_{RADBC}$$

- Initial sum of nonlinear forces including follower forces: $\{F_l\}$. In heat transfer, $\{F_l\}$ is the heat flow vector associated with nonlinear conduction, convection, radiation, and nonlinear thermal loads (QBDY3, QVECT, and QVOL), i.e.,

$$\{F_l\} = [K_l]_{nl}\{u_l\} + [\Re_l](u_l + T_{abs})^4 - \{N_l\}$$

- Initial temperature vector: $\{u_l\}$

- KFSNL •DELYS: $[K_{f_s}]^T\{\Delta u_s\}$
- Initial residual vector: $\{R_l\}$

For each iteration, the following is produced:

- Temperature increment: $\{\Delta u_l\}$
- Initial energy: $\{\Delta u_l\}^T\{R_l\}$
- New temperature vector: $\{u_g\}$
- Nonlinear force vector: $\{F_g\}$
- Sum of nonlinear forces including follower forces: $\{F_l\}$
- New temperature vector: $\{u_l\}$
- New residual vector: $\{R_l\}$
- Denominator of EUI
- Denominator of EPI
- Contraction factor: q
- Remaining time

For each quasi-Newton vector set, the following is produced:

- Condition number: λ^2
- Quasi-Newton vector: δ
- Quasi-Newton vector: γ
- Energy error: z = $\dfrac{1}{\delta_j^T\gamma_j}$

For each line search, the following is produced:

- Previous line search factor: α_k
- Previous error: E_k
- New line search factor: α_{k+1}

Recommendations

The following are recommendations, designed to aid the user.

- Initial temperature estimate:

  For highly nonlinear problems, the iterative solution is sensitive to the initial temperature guess. It is recommended to overshoot (i.e., make a high initial guess) the estimated temperature vector in a radiation-dominated problem.

- Incremental load:

  Incremental loading reduces the imbalance of the equilibrium equation caused by applied loads. The single-point constraints (temperature specified by SPC in the Bulk Data) and the applied loads (specified by QBDY1, QBDY2, QBDY3, QHBDY, QVECT, and QVOL) can be incremented. If the solution takes more iterations than the default values of the maximum number of iterations allowed for convergence (MAXITER), the increment size should be decreased. For linear problems, no incremental load steps are required.

- Convergence criteria:

  At the beginning stages of a new analysis, it is recommended that the defaults be used on all options. However, the UPW option may be selected to improve the efficiency of convergence. For problems with poor convergence, the tolerances EPSU, EPSP, and EPSW can be increased within the limits of reasonable accuracy.

4.4 Transient Analysis

Basic Equations

The general equation solved in transient analysis has the form

$$[B]\{\dot{u}\} + [K]\{u\} + \{\Re\}\{u + T_{abs}\}^4 = \{P\} + \{N\}$$

Figure 4-19.

To take phase change into consideration, the heat diffusion equation is converted into

$$\{\dot{H}\} + [K]\{u\} + [\Re]\{u + T_{abs}\}^4 = \{P\} + \{N\}$$

Figure 4-20.

Note

In Figure 4-20, H represents enthalpy, not the convection heat transfer coefficient.

where:

$[B]$	=	a heat capacity matrix
$[K]$	=	a heat conduction matrix
$[\Re]$	=	a radiation exchange matrix
$\{P\}$	=	a vector of applied heat loads that are constant or functions of time, but not functions of temperature

$\{N\}$	=	a vector of nonlinear heat loads that depend on temperature
$\{H\}$	=	an enthalpy vector
$\{\dot{H}\}$	=	$\{dH/dt\}$
$\{u\}$	=	a vector of grid point temperature
$\{\dot{u}\}$	=	$\{du/dt\}$
T_{abs}	=	the absolute temperature scale adjustment required for radiation heat transfer exchange or radiation boundary conditions when all other temperatures and units are specified in deg-F or deg-C.

The equilibrium equation is solved by Newmark's method with adaptive time stepping. Based on this one-step integration scheme, the time derivative of the nodal temperatures at the $(i + 1)$-th iteration of the time step $(n + 1)$ is expressed as

$$\{\dot{u}_{n+1}\}^{i+1} = \frac{1}{\theta\Delta t}\left\{u_{n+1}^{i+1} - u_n\right\} + \left(1 - \frac{1}{\theta}\right)\{\dot{u}_n\}$$

Figure 4-21.

where

$$\{u_{n+1}\}^{i+1} = \{u_{n+1}\}^i + \{\Delta u_{n+1}\}^i$$

Figure 4-22.

and

$$\frac{1}{\theta} = 2 - 2\eta$$

Figure 4-23.

The parameter η is specified on the PARAM,NDAMP Bulk Data entry. When $\eta = 0$, $(\theta = 0.5)$, no numerical damping is requested. In this case, Newmark's method is equivalent to the Crank-Nicolson method.

For the Newton-Raphson scheme, the iteration equation is

$$\left(\frac{1}{\theta\Delta t}[B_{n+1}]^i + [K_{T_{n+1}}]^i\right)\{\Delta u_{n+1}\}^i = \{R_{n+1}\}^i$$

Figure 4-24.

The left-hand side matrices may be approximated by

$$\frac{1}{\theta\Delta t}[B_{n+1}]^i + [K_{T_{n+1}}]^i \approx \frac{1}{\theta\Delta t}[B_n] + [K_{T_n}]$$

Figure 4-25.

where $[K_{T_n}]$ is the tangential stiffness matrix evaluated at the previous time step, i.e.,

$$[K_{T_n}] \approx [K_n] + 4[\Re_n]\{u_n + T_{abs}\}^3 - \left\{\frac{\partial N_n}{\partial u_n}\right\}$$

Figure 4-26.

The residual vector is

$$\{R_{n+1}\}^i = \{P_{n+1}\} + \{N_{n+1}\}^i - [K_{n+1}]^i\{u_{n+1}\}^i - [\Re_{n+1}]^i\left\{u_{n+1}^i + T_{abs}\right\}^4$$

$$+\left(\frac{1}{\theta}-1\right)(\{P_n\} + \{N_n\} - [K_n]\{u_n\} - [\Re_n]\{u_n + T_{abs}\}^4)$$

$$-\frac{1}{\theta\Delta t}(\{H_{n+1}\}^i - \{H_n\})$$

Figure 4-27.

At the first iteration, the initial conditions are

$$\{u_{n+1}\}^0 = \{u_n\}, [K_{n+1}]^0 = [K_n], [\Re_{n+1}]^0 = [\Re_n], \text{and } [H_{n+1}]^0 = \{H_n\}$$

Figure 4-28.

Thus, the initial residual vector can be expressed as

$$\{R_{n+1}\}^0 = \{P_{n+1}\} + \{N_{n+1}\}^0 + \left(\frac{1}{\theta}-1\right)(\{P_n\} + \{N_n\})$$

$$-\frac{1}{\theta}([K_n]\{u_n\} + [\Re_n]\{u_n + T_{abs}\}^4)$$

Figure 4-29.

Transient Analysis Solution Sequence

In NX Nastran, transient thermal analysis is solved by Solution Sequence 159. Since Solution 159 can be used for both structural (default) and thermal analyses, you must include the command

```
ANALYSIS = HEAT
```

in the Case Control Section of the input data for thermal analysis. Additionally, the initial conditions (temperatures) and the time integration (solution time, time step size, convergence criteria) must be specified. The input data file may then appear as

```
ID NX NASTRAN V2
SOL 159
TIME 10
CEND
TITLE = EXAMPLE
ANALYSIS = HEAT
TSTEPNL = 10
IC = 20
.
.
BEGIN BULK
TSTEPNL,10,....
.
.
TEMP,20,.....
TEMPD,20,....
ENDDATA
```

The TSTEPNL entry is required to specify the initial time step and the iteration control. Initial temperatures are specified on TEMP and TEMPD Bulk Data entries and are selected by an "IC" Case Control command. As the solution progresses, the time steps are adjusted automatically by an adaptive time stepping scheme, which is described in the following section. It is up to the user to specify a reasonable initial time step size. A conservative estimate can be determined as follows.

Let:

$$\Delta t_o \cong \frac{\chi^2}{10 \cdot \alpha}$$

Figure 4-30.

where:

Δt_0	=	initial time step size
χ	=	smallest element dimension in the model
α	=	largest thermal diffusivity, $\alpha = k / \rho C_p$

and,

k	=	thermal conductivity,
ρ	=	density
C_p	=	specific heat

Automatic Time Stepping

NX Nastran estimates optimal time stepsize and the stepsize evolves based on the convergence condition. The time step is doubled $(\Delta t_{n+1} = 2\Delta t_n)$ as $\{\Delta u_n\} = \{u_n - u_{n-1}\}$ becomes small, i.e.,

$$\frac{\|\dot{u}_n\|}{\|\dot{u}\|_{max}} < \text{UTOL(default} = 0.1)$$

Figure 4-31.

where $\|\dot{u}\|_{max}$ is the maximum value of the norms computed from previous time steps and UTOL is a tolerance on the temperature increment specified on the TSTEPNL Bulk Data entry.

If the temperature increment exceeds the tolerance, a proper time step size can be predicted from the following calculation where ω_n is the inverse of the characteristic time.

$$\omega_n = \frac{\{\Delta u_n\}^T[K_{T_n}]\{\Delta u_n\}}{\{\Delta u_n\}^T\{\Delta H_n\}} \simeq \frac{\{\Delta u_n\}^T\{F_n - F_{n-1}\}}{\{\Delta u_n\}^T\{\Delta H_n\}}$$

Figure 4-32.

In thermal analysis, $\{F_n\}$ is the heat flow vector associated with conduction, convection (CONV and CONVM), and radiation (RADBC and RADSET), i.e.,

$$\{F_n\} = [K_n]\{u_n\} + [\Re_n]\{u_n + T_{abs}\}^4 - \{N_n\}_{CONV} - \{N_n\}_{CONVM} - \{N_n\}_{RADBC}$$

Figure 4-33.

The next time step is adjusted by

$$\Delta t_{n+1} = f(r)\Delta t_n$$

Figure 4-34.

where r is a scaling factor defined as

$$r = \frac{1}{MSTEP}\left(\frac{2\pi}{\omega_n}\right)\left(\frac{1}{\Delta t_n}\right)$$

Figure 4-35.

with

f = 0.25 for $r < 0.5 \bullet RB$
f = 0.5 for $0.5 \bullet RB \le r < RB$
f = 1.0 for $RB \le r < 2.0$
f = 2.0 for $2.0 < r \le 3.0/RB$

f = 4.0 for $r \ge 3.0/RB$

Values of MSTEP and RB are specified on the TSTEPNL Bulk Data. If MSTEP is not specified, the default value is estimated by the stiffness ratio defined as

$$\lambda = \frac{\{\Delta u_n\}^T\{F_n - F_{n-1}\}}{\{\Delta u_n\}^T[K_{T_n}]\{\Delta u_n\}}$$

Figure 4-36.

The default value of MSTEP is determined based on the following criteria:

$$\lambda^* = |\lambda| \text{ if } |\lambda| \ge 1$$

$$\lambda^* = \left|\frac{1}{\lambda}\right| \text{ if } |\lambda| < 1$$

Figure 4-37.

and

$$\text{MSTEP} = 20 \text{ for } \lambda^* < 5$$

$$\text{MSTEP} = 40 \text{ for } 5 \le \lambda^* < 1000$$

$$\text{No Adjust for } \lambda^* \ge 1000$$

Figure 4-38.

The adjusted time step size is limited to the upper and lower bounds, i.e.,

$$\text{MIN}\left(\frac{\text{DT}}{2^{\text{MAXBIS}}}, \frac{\text{DT}}{\text{MAXR}}\right) \le \Delta t \le \text{MAXR} \cdot \text{DT}$$

Figure 4-39.

where DT is the user-specified time increment and MAXR and MAXBIS are user-defined entries specified on the TSTEPNL entry. The time step is set to the limit if it falls outside the bounds.

When the time marches to a value close to the last time specified by the user, the adaptive stepping scheme stops for the current subcase. The termination criterion is

$$\sum_{n=1}^{N} \Delta t_n + \frac{\Delta t_N}{2} \leq DT \cdot NDT$$

Figure 4-40.

where $DT \bullet NDT$ is the user-specified time duration for the current subcase. The adjusted time step remains effective across the subcases.

Integration and Iteration Control

The incremental and iterative solution processes are controlled by the parameters specified on the TSTEPNL Bulk Data entry with the data format and default values described as follows:

1	2	3	4	5	6	7	8	9	10
TSTEPNL	ID	NDT	DT	NO	METHOD	KSTEP	MAXITER	CONV	
TSTEPNL				1	ADAPT	2	10	PW	+TNL1
	EPSU	EPSP	EPSW	MAXDIV	MAXQN	MAXLS	FSTRESS		
+TNL1	1.0E-2	1.0E-3	1.0E-6	2	10	2			+TNL2
	MAXBIS	ADJUST	MSTEP	RB	MAXR	UTOL	RTOLB		
+TNL2	5	5	0	0.75	16.0	0.1			

In thermal analysis, the options AUTO and TSTEP (specified in METHOD field) are disabled. The FSTRESS and RTOLB fields are also ignored and should be left blank for heat transfer.

The ID field specifies an integer selected by the Case Control command TSTEPNL. The initial time increment and the number of time steps are specified by DT and NDT. Since the time increment is adjusted during the analysis, the actual number of time steps may not be equal to NDT. However, the total time duration is close to $NDT \bullet DT$.

For printing and plotting purposes, data recovery is performed at time steps O, NO, 2 • NO, ..., and the last converged step. The Case Control command OTIME may also be used to control the output times.

Since both linear and nonlinear problems are solved by the same solution sequence, only the ADAPT option can be selected in the METHOD field for heat transfer. The ADAPT method automatically adjusts the incremental time and uses bisection. During the bisection process, the heat capacitance matrix and the tangential stiffness matrix are updated every KSTEP-th converged bisection solution.

The number of iterations for a time step is limited to MAXITER. If MAXITER is negative, the analysis is terminated on the second divergence condition during the same time step or when the solution diverges for five consecutive time steps. If MAXITER is positive, the program computes the best solution and continues the analysis until divergence occurs again. If the solution does not converge in MAXITER iterations, the process is considered divergent. Either bisection or matrix update is activated when the process diverges.

The convergence criteria are defined through the test flags in the CONV field and the tolerances in the EPSU, EPSP, and EPSW fields. The requested criteria (combination of temperature error U, load error P, and work error W) are satisfied upon convergence. Note that at least two iterations are required to check the temperature convergence criterion.

MAXDIV limits the divergence conditions allowed for each iteration. Depending on the divergence rate, the number of diverging iteration NDIV is incremented as follows:

$$\left.\begin{array}{l} NDIV = NDIV + 2 \text{ if } E_1^i \geq 1 \text{ or } E_1^i \geq -10^{12} \\ NDIV = NDIV + 1 \text{ if } -10^{12} < E_1^i \geq -1 \text{ or } \left|E_2^i\right| > 1 \end{array}\right\}$$

Figure 4-41.

where:

$$E_1^i = \frac{\{Du^i\}^T \{R^i\}}{\{Du^i\}\{R^{i-1}\}}$$

$$E_2^i = \frac{E_p^i}{E_p^{i-1}}$$

The solution is assumed to diverge when NDIV reaches MAXDIV. If the bisection option is used, the time step is bisected upon divergence. Otherwise, the left-hand side matrices are updated, and the computation for the current time step is repeated. If NDIV reaches MAXDIV again within the same time step, the analysis is terminated.

The BFGS update and the line search process are performed in the same way as in steady state analysis. Nonzero values of MAXQN and MAXLS activate the quasi-Newton update and the line search process, respectively.

The number of bisections for a load increment is limited to |MAXBIS|. Different actions are taken when the solution diverges, depending on the sign of MAXBIS. If MAXBIS is positive and the solution does not converge after MAXBIS bisections, the best solution is computed and the analysis is continued to the next time step. If MAXBIS is negative and the solution does not converge in |MAXBIS| bisections, the analysis is terminated.

ADJUST controls the automatic time stepping in the following ways:

1. If ADJUST = 0, the automatic adjustment is deactivated.

2. If ADJUST > 0, the time increment is continually adjusted for the first few steps until a good value of Δt is obtained. After this initial adjustment, the time increment is adjusted every ADJUST-th time step only.

3. If ADJUST is one order greater than NDT, the automatic adjustment is deactivated after the initial adjustment.

Parameters MSTEP and RB are used to adjust the time increment. The upper and lower bounds of time step size are defined with MAXR. If the solution approaches steady state (checked by tolerance UTOL), the time step size is doubled. Detailed computations involving these parameters are described in the previous section.

Iteration Output

At each iteration or time step, the related output data are printed under the following heading:

TIME Cumulative time for the duration of the analysis.
ITER Iteration count for each time step.
DISP Relative error in terms of temperatures defined as

$$E_u^i = \frac{\lambda^i \| u^i - u^{i-1} \|}{(1 - \lambda^i) u_{max}}$$

Figure 4-42.

where

$u_{\max} = \max(\|u_1\|, \|u_2\|, \ldots, \|u_n\|)$

$and\ \lambda^i = E_p^i / E_p^{i-1}$

.

LOAD Relative error in terms of loads defined as

$$E_p^i = \frac{\|R\|^i}{\max\left(\|F_n\|, \|P_{t_n}\|\right)}$$

Figure 4-43.

where

$\left\{P_{t_n}\right\}$ are internal heat flows and external applied heat loads, respectively.

$\{F_n\}$ and

In thermal analysis, $\{F_n\}$ is a heat flow vector defined in the Automatic Time Stepping section, and

$\left\{P_{t_n}\right\}$

is the total heat flow associated with conduction, convection, radiation, and applied loads, i.e.,

$$\left\{P_{t_n}\right\} = \{P_n\} + \{N_n\}_{ld} - \{F_n\}$$

Figure 4-44.

where $\{N_n\}_{ld} = \{N_n\}_{QBDY3} + \{N_n\}_{QVECT} + \{N_n\}_{QVOL}$

WORK Relative error in terms of work defined as

$$E_w^i = \frac{\{u^i - u^{i-1}\}^T \{R\}^i}{\max\left(\{u_n\}^T\{F_n\},\ \{u_n\}^T\left\{P_{t_n}\right\}\right)}$$

Figure 4-45.

LAMDBA(I)	Rate of convergence $\lambda^i (= E_p^i / E_p^{i-1})$.
DLMAG	Absolute norm of the residual vector ($\|R\|$) . The absolute convergence is defined using DLMAG by $\|R\| < 10^{-12}$.
FACTOR	Final value of the line search parameter.
E-FIRST	Divergence rate, initial error before line search.
E-FINAL	Error at the end of line search.
NQNV	Number of quasi-Newton vectors appended.
NLS	Number of line searches performed during the iteration.
ITR DIV	Number of occurrences of divergence detected during the adaptive iteration.
MAT DIV	Number of occurrences of bisection conditions during the iteration.
NO. BIS	Number of bisections executed for the current time interval.
ADJUST	Ratio of time step adjustment relative to DT.

Diagnostic messages are requested by DIAG 50 or 51 in the Executive Control Section. DIAG 50 only prints subcase status, TSTEPNL data, and iteration summary, while DIAG 51 prints all data at each iteration. In general, the user should be cautioned against using DIAG 51, because it is used for debugging purposes only and the volume of output is significant. It is recommended that DIAG 51 be used only for small test problems. The diagnostic output is summarized as follows:

For each entry into NLTRD2, the following is produced:

- Subcase status data.
- TSTEPNL data.
- Core statistics (ICORE, etc).
- Problem statistics (g-size, etc.).

- File control block.
- Input file status.

For each time step, the following is produced:

- NOLINi vector: $\{N_d\}$
- External load vector: $\{P_d\}$
- Load vector including follower forces and NOLINs: $\{P_{td}\}$
- Constant portion of residual vector: $\{R'_d\}$
- Total internal force: $\{F_d\}$
- Initial residual vector: $\{R_d\}$

For each iteration, the following is produced:

- Initial energy for line search: $\{\Delta u_d\}^T\{R_d\}$
- Nonlinear internal force: $\{F_g\}$, which is

$$\{F_g\} = \{K_g\}_{nl}\{u_g\} - \{N_g\}_{CONV} - \{N_g\}_{CONVM} - \{N_g\}_{RADBC}$$

Figure 4-46.

- Temperature vector: $\{u_d\}$
- Nonlinear internal force: $\{F_d\}_{nl}$, which is

$$\{F_d\}_{nl} = [K_d]_{nl}\{u_d\} + [\Re_d]\{u_d + T_{abs}\}^4 - \{N_d\}_{CONV} - \{N_d\}_{CONVM} - \{N_d\}_{RADBC}$$

Figure 4-47.

- Total internal force: $\{F_d\}$, which is

$$\{F_d\} = [K_d]_l\{u_d\} + \{F_d\}_{nl}$$

Figure 4-48.

- NOLINi vector: $\{N_d\}$
- Enthalpy vector: $\{H_d\}$
- Load vector including follower forces and NOLINs: $\{P_{td}\}$, which is

$$\{P_{td}\} = \{P_d\} + \{N_d\}_{ld} - \{F_d\}$$

Figure 4-49.

- where $$\{N_d\}_{ld} = \{N_d\}_{QBDY3} + \{N_d\}_{QVECT} + \{N_d\}_{QVOL}$$
- Residual vector: $\{R_d\}$
- Iteration summary (convergence factors, line search data, etc.)

For each quasi-Newton vector set, the following is produced:

- Condition number: λ^2
  quasi-Newton vector: δ
- quasi-Newton vector: γ
- Energy error: $$z = \frac{1}{\delta_j^T \gamma_j}$$

For each line search; the following is produced:

- Previous line search factor: α_k
- Previous error: E_k
- New line search factor: α_{k+1}

For each converged time step, the following is produced:

- Time derivative of temperature: $\{\dot{u}_d\}$

For each time step adjustment, the following is produced:

- Magnitude of the time derivative of temperature: $\{\dot{u}_n\}$
- Magnitude of the new time derivative of temperature: $\{\dot{u}_{n+1}\}$
- General conductance: DENOM1 = $\{\Delta u_n\}^T [K_{T_n}] \{\Delta u_n\}$
- General enthalpy: DENOM2 = $\{\Delta u_n\}^T \{\Delta H_n\}$
- Work: $\{\Delta u_n\}^T \{\Delta F_n\}$
- Inverse of Characteristic time: ω_n
- Conductance ratio: λ
- Number of steps for the period of dominant frequency: MSTEP

- Controlling ratio for time step adjustment: r

Recommendations

The following are recommendations designed to aid the user.

- Time step size

  To avoid inaccurate or unstable results, a proper initial time step associated with spatial mesh size is suggested. The selection criterion is

$$\Delta t = \frac{1}{n}\Delta x^2 \frac{\rho c_p}{k}$$

Figure 4-50.

  where Δt is the time step, n is the modification number of the time scale, Δx is the mesh size (smallest element dimension), ρ is the material density, c_p is the specific heat, and k is the thermal conductivity. A suggested value of n is 10. For highly nonlinear problems, a small step size is recommended.

- Numerical stability

  Numerical stability is controlled by the parameter η (specified on the PARAM,NDAMP Bulk Data entry). For linear problems, $\eta = 0$ (i.e., no numerical damping) is adequate, but for nonlinear problems a larger value of η may be advisable. Increasing the value of η improves numerical stability; however, the solution accuracy is reduced. The recommended range of values is from 0.0 to 0.1 (default value is 0.01).

- Initial temperatures and boundary temperatures

  The specification of initial temperatures and boundary condition temperatures should be consistent. For a given point, the initial temperature should be equal to the boundary condition temperature at t = 0.

- Convergence criteria

  At the beginning stages of a new analysis, it is recommended that the defaults be used on all options. However, the UPW option may be selected to improve the efficiency of convergence. For nonlinear problems with time-varying boundary conditions, the U option must be selected, because the large conductance (internally generated) affects the calculations of the PW error functions. For problems with poor convergence, the tolerances EPSU, EPSP, and EPSW can be increased within the limits of reasonable accuracy.

- Fixed time step

  If a fixed time step is desired, the adaptive time stepping can be deactivated by setting ADJUST = 0 on the TSTEPNL Bulk Data.

Chapter

5 Steady State and Transient Analysis Examples

This chapter provides several examples of steady state and transient analysis. In each case, the general "demonstrated principals" are listed at the beginning, followed by an example discussion and concluding with a description of results. Where appropriate, plots and notes are provided.

- *1a – Linear Conduction*
- *1b – Nonlinear Free Convection Relationships*
- *1c – Temperature Dependent Heat Transfer Coefficient*
- *1d – Film Nodes for Free Convection*
- *1e – Radiation Boundary Condition*
- *2a – Nonlinear Internal Heating and Free Convection*
- *2b – Nonlinear Internal Heating and Control Nodes*
- *2c – Nonlinear Internal Heating and Film Nodes*
- *3 – Axisymmetric Elements and Boundary Conditions*
- *4a – Plate in Radiative Equilibrium, Nondirectional Solar Load with Radiation Boundary Condition*
- *4b – Plate in Radiative Equilibrium, Directional Solar Load with Radiation Boundary Condition*
- *4c – Plate in Radiative Equilibrium, Directional Solar Load, Spectral Surface Behavior*
- *5a – Single Cavity Enclosure Radiation with Shadowing*
- *5b – Single Cavity Enclosure Radiation with an Ambient Element Specification*
- *5c - Multiple Cavity Enclosure Radiation*
- *6 – Forced Convection Tube Flow - Constant Property Flow*
- *7a – Transient Cool Down, Convection Boundary*
- *7b – Convection, Time Varying Ambient Temperature*
- *7c – Time Varying Loads*
- *7d – Time Varying Heat Transfer Coefficient*
- *7e – Temperature Dependent Free Convection Heat Transfer Coefficient*
- *7f – Phase Change*
- *8 – Temperature Boundary Conditions in Transient Analyses*
- *9a – Diurnal Thermal Cycles*
- *9b – Diurnal Thermal Cycles*
- *10 – Thermostat Control*
- *11 – Transient Forced Convection*

1a – Linear Conduction

Demonstrated Principles

- Specifying Grid Point Geometry

- Defining Element Connectivity
- Describing Material Properties
- Applying the “Load”
- Accessing the Results

Discussion

This simplest of examples demonstrates the organization of the NX Nastran input data file including the Executive, Case Control, and Bulk Data Sections for a typical heat transfer analysis. A complete description of all available input data is available in the *NX Nastran Quick Reference Guide*. The "Commonly Used Commands for Thermal Analysis" describes the input data most commonly applied to heat transfer problems.

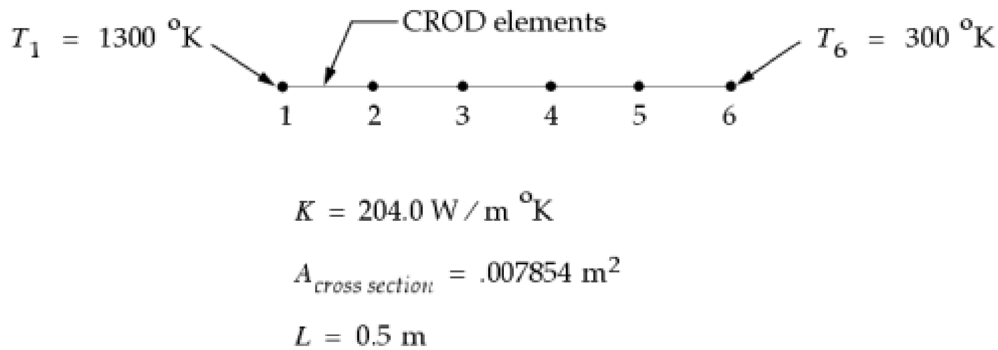


Figure 5-1. Example 1a

The NX Nastran input file is shown in Table 1.

Table 5-1. Example 1a Input File

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 1a
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
$
CROD,1,5,1,2
CROD,2,5,2,3
```

```
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,.0078540
MAT4,15,204.0
$
SPC,10,1,,1300.0
SPC,10,6,,300.0
TEMPD,20,1300.0
$
ENDDATA
```

Note

- SPC and NLPARM are requested in the Case Control Section.
- SPCs are used to set the temperature boundary condition.

Results

The abbreviated EX1A.f06 output file is shown in Table 2. A plot of temperature versus distance is shown in Figure 2.

Table 5-2. Example 1a Results File

```
EXAMPLE 1A                                                                   MAY 12, 2004 NX NASTRAN  05/12/04 PAGE    11

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      1.300000E+03   1.100000E+03   9.000000E+02   7.000000E+02   5.000000E+02   3.000000E+02
EXAMPLE 1A                                                                   May 12, 2004 NX NASTRAN  05/12/04 PAGE    12

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      3.204432E+03    .0             .0             .0             .0           -3.204432E+03
EXAMPLE 1A                                                                   MAY 12, 2004 NX NASTRAN  05/12/04 PAGE    13

LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT            X-FLUX           Y-FLUX           Z-FLUX
         1     ROD        -2.000000E+03                                           4.080000E+05
         2     ROD        -2.000000E+03                                           4.080000E+05
         3     ROD        -2.000000E+03                                           4.079999E+05
         4     ROD        -2.000000E+03                                           4.080000E+05
         5     ROD        -2.000000E+03                                           4.080001E+05
```

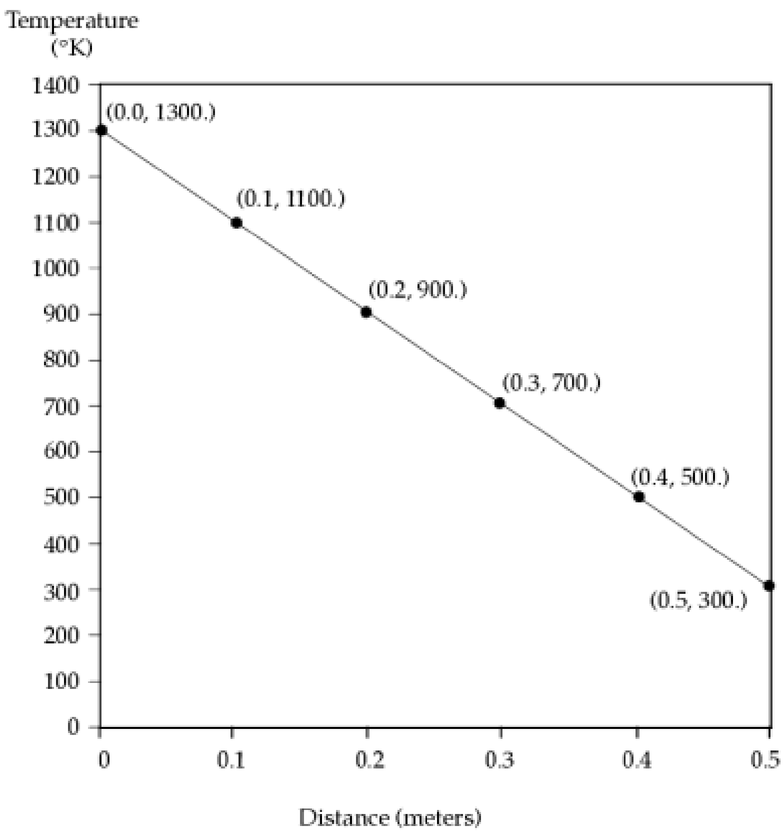


Figure 5-2. Temperature versus Distance

1b – Nonlinear Free Convection Relationships

Demonstrated Principles

- Surface Elements and Boundary Conditions
- Free Convection Forms
- Ambient Nodes

Discussion

We introduce the CHBDY surface element for the purpose of applying free convection boundary conditions along the length of the rod. The Bulk Data entry CONV defines the convection character and the ambient grid points. To take advantage of empirical relationships for this type of flow field, a hand calculation is necessary to acquire the appropriate free convection heat transfer coefficient form. To facilitate this process, we will assume a fluid film temperature of 800 degrees and use the fluid properties for air at that temperature in our calculations. In "Example 1c – Temperature Dependent Heat Transfer Coefficient" we will account for the variation of film temperature and corresponding fluid properties along the length of the rod.

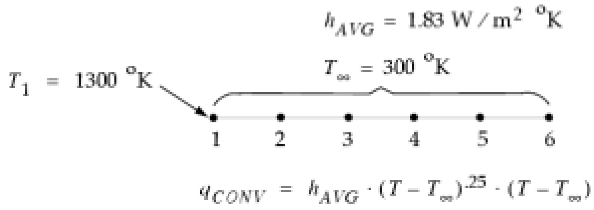


Figure 5-3. Example 1b

Calculating Heat Transfer Coefficients

First we must calculate the input coefficients and convert to NX Nastran format. The symbols used in the description of the analysis are defined herein.

C_p	Specific heat
ν	Kinematic viscosity
k	Thermal conductivity
Pr	Prandtl number
Gr	Grashof number
Nu	Nusselt number
T_w	Wall temperature
T_∞	Ambient temperature
d	Diameter
β	Volume coefficient of expansion (For an ideal gas $\beta = (1/T)$ where T is the absolute temperature of the gas)
g	Acceleration due to gravity

Assume air properties at 800×K.

C_p	=	$1.098\ \mathrm{KJ/Kg\ ^oK}$
ν	=	$.823 \times 10^{-4}\ \mathrm{m^2/s}$
k	=	$.058\ \mathrm{W/m\ ^oK}$

$$Pr = .689$$

$$Gr = \frac{g\beta d^3(T_w - T_\infty)}{\nu^2}$$

$$= \frac{9.80\ \frac{\mathrm{m}}{\mathrm{s}^2} \cdot \frac{1}{800\ {}^{\mathrm{o}}\mathrm{K}} \cdot (.10)^3\ \mathrm{m}^3 \cdot 1000\ {}^{\mathrm{o}}\mathrm{K}}{(.823 \times 10^{-4})\frac{\mathrm{m}^4}{\mathrm{s}^2}}$$

$$= 1.8 \times 10^6$$

$$Gr \cdot Pr = 1.25 \times 10^6$$

for

$$\left.\begin{matrix} 10^4 \le Gr \cdot Pr \\ \mathrm{COEFF} = .53 \end{matrix}\right\}\ )^9$$
$$m = .25$$

and for horizontal cylinders,

(see J. P. Holman, Heat Transfer)

$$Nu = \frac{hd}{k} = \mathrm{COEF}\left(\frac{g\beta d^3}{\nu^2} \cdot Pr \cdot (T - T_\infty)\right)^m$$

so

$$h = \frac{.53\ (.058)}{.10}\left\{\frac{9.80\ (1/800)(.10)^3(.689)}{(.823 \times 10^{-4})^2}\right\}^{.25}(T - T_\infty)^{.25}$$

or

Note

The equation for h is nonlinear.

therefore

$$h \cong 1.83\ (T - T_\infty)^{.25}\ \mathrm{W}/\mathrm{m}^2\ {}^{\mathrm{o}}\mathrm{K}$$

This form may be input on the PCONV and MAT4 Bulk Data entries.

The NX Nastran input file is shown in Table 1.

Table 5-3. Example 1b Input Files

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 1b
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,99,,99.0,99.0,99.0
$
CROD,1,5,1,2
CROD,2,5,2,3
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,.0078540
MAT4,15,204.0,,,1.83

$
CHBDYP,10,25,LINE,,,1,2,,+CHP10
+CHP10,,,,,0.0,1.0,0.0
CHBDYP,20,25,LINE,,,2,3,,+CHP20
+CHP20,,,,,0.0,1.0,0.0
CHBDYP,30,25,LINE,,,3,4,,+CHP30
+CHP30,,,,,0.0,1.0,0.0
CHBDYP,40,25,LINE,,,4,5,,+CHP40
+CHP40,,,,,0.0,1.0,0.0
CHBDYP,50,25,LINE,,,5,6,,+CHP50
+CHP50,,,,,0.0,1.0,0.0
PHBDY,25,.3141593
$
CONV,10,35,,,99,99
CONV,20,35,,,99,99
CONV,30,35,,,99,99
CONV,40,35,,,99,99
CONV,50,35,,,99,99
PCONV,35,15,0,0.25
$
SPC,10,1,,1300.0
SPC,10,99,,300.0
TEMPD,20,1300.0
$
ENDDATA
```

Note

- COEF is given on the MAT4 entry.
- Exponent is given on the PCONV entry.

Results

The abbreviated EX1B.f06 output file is shown in Table 2. Because this analysis is nonlinear, note the existence of numerical iteration until satifsfactory values of EPSP and EPSW (NLPARM entry defaults) have been attained. A plot of temperature versus distance is shown in Figure 2.

Table 5-4. Example 1b Results File

```
                            N O N - L I N E A R   I T E R A T I O N   M O D U L E   O U T P U T
STIFFNESS UPDATE TIME          .49 SECONDS                                                         SUBCASE
       ITERATION TIME          .01 SECONDS                                                  LOAD FACTOR    1.000
                   - - - CONVERGENCE  FACTORS - - -                      - - - LINE SEARCH DATA - - -
ITERATION     EUI         EPI         EWI        LAMBDA       DLMAG       FACTOR     E-FIRST      E-FINAL    NQNV  NLS  ENIC  ND
    1  1.0228E-13  9.7786E-02  9.9926E-17  1.0000E-01  2.9097E+02  1.0000E+00  0.0000E+00  0.0000E+00    0    0
    2  1.6730E+01  1.9848E-02  3.6841E-03  1.5149E-01  6.5130E+01  1.0000E+00 -2.4629E-01 -2.4629E-01    0    0
    3  2.7737E-02  1.3951E-04  3.4216E-06  7.9258E-02  4.3181E-01  1.0000E+00  4.7254E-03  4.7254E-03    1    0     0
    4  2.9687E-05  3.3073E-06  4.8656E-10  5.1482E-02  1.0361E-02  1.0000E+00 -6.0088E-03 -6.0088E-03    2    0    -1
*** USER    INFORMATION MESSAGE 6186,
*** SOLUTION HAS CONVERGED ***
    SUBID    1     LOADINC   1     LOOPID    1     LOAD STEP    1.000     LOAD FACTOR    1.00000
^^^ DMAP INFORMATION MESSAGE 9005 (NLSCSH) -    THE SOLUTION FOR LOOPID=            1 IS SAVED FOR RESTART
EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


LOAD STEP =  1.00000E+00
                                                T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      1.300000E+03   1.225588E+03   1.169515E+03   1.130402E+03   1.107303E+03   1.099665E+03
       99      S      3.000000E+02
EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


LOAD STEP =  1.00000E+00
                                                       L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       99      S       .0
EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      1.352363E+03    .0             .0             .0             .0             .0
       99      S     -1.352382E+03
EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION            TOTAL
                  10      0.000000E+00     -3.083314E+02      0.000000E+00      0.000000E+00     -3.083314E+02
                  20      0.000000E+00     -2.824394E+02      0.000000E+00      0.000000E+00     -2.824394E+02
                  30      0.000000E+00     -2.638446E+02      0.000000E+00      0.000000E+00     -2.638446E+02
                  40      0.000000E+00     -2.518305E+02      0.000000E+00      0.000000E+00     -2.518305E+02
                  50      0.000000E+00     -2.459362E+02      0.000000E+00      0.000000E+00     -2.459362E+02
EXAMPLE 1B                                                             NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE


LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
         1    ROD          -7.441187E+02                                      1.518002E+05
         2    ROD          -5.607344E+02                                      1.143898E+05
         3    ROD          -3.911244E+02                                      7.978937E+04
         4    ROD          -2.309877E+02                                      4.712150E+04
         5    ROD          -7.638958E+01                                      1.558347E+04
```

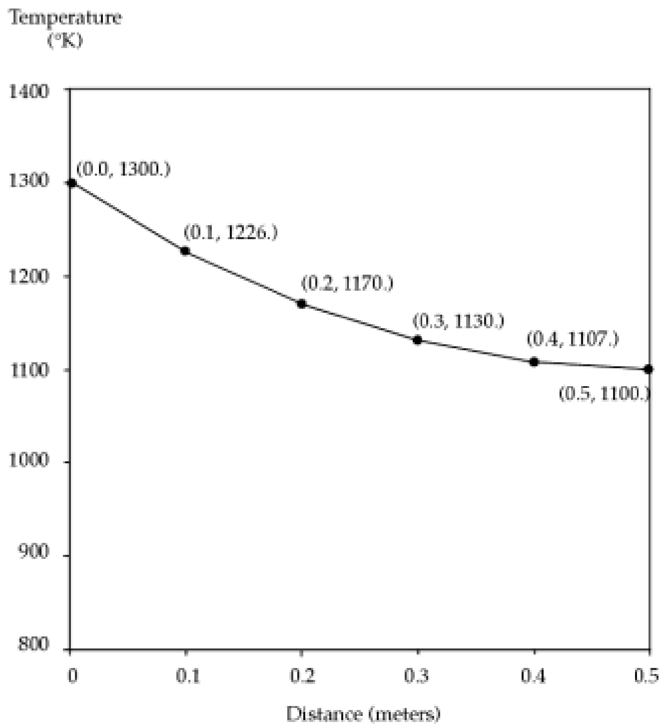


Figure 5-4. Temperature versus Distance – Example 1b

1c – Temperature Dependent Heat Transfer Coefficient

Demonstrated Principles

- Temperature dependent free convection heat transfer coefficient
- Film node

Discussion

This problem introduces the generalized method for representation of temperature dependent properties (MATT4,TABLEMi). In this case we wish to account for the fluid film temperature variation along the length of our rod and consider its effect on the local heat transfer coefficient. By default, the look-up temperature of the film node is the average temperature of the CHBDY surface and the ambient points. This temperature varies along the length of the rod.

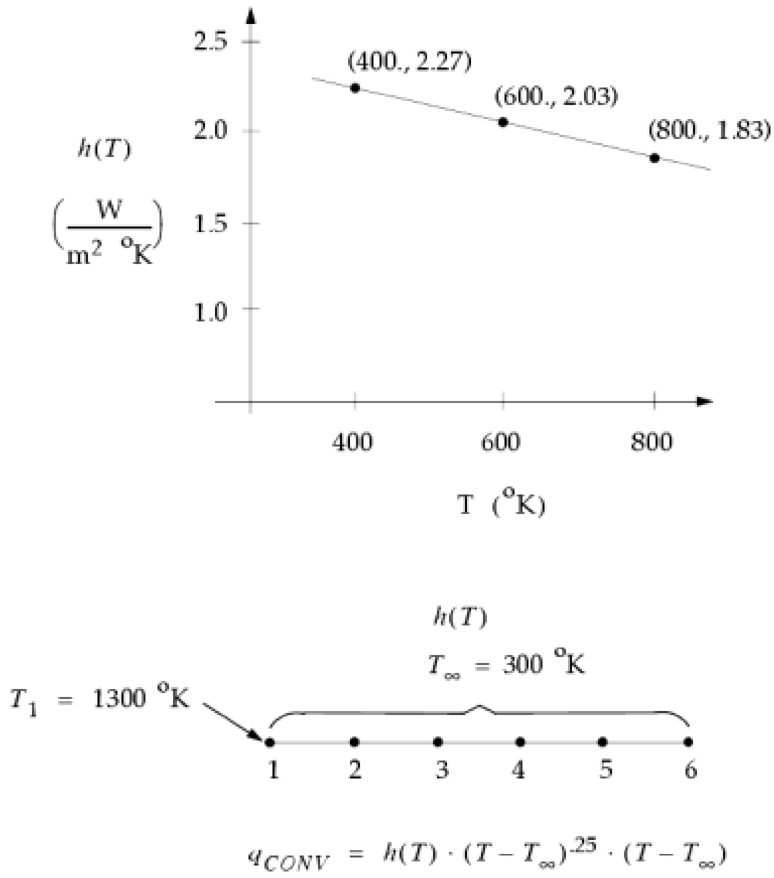


Figure 5-5. Example 1c

The NX Nastran input file is shown in Table 1.

Table 5-5. Example 1c Input File

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 1c
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,99,,99.0,99.0,99.0
```

```
$
CROD,1,5,1,2
CROD,2,5,2,3
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,.0078540
MAT4,15,204.0,,,1.0
MATT4,15,,,,40
TABLEM2,40,0.0,,,,,,,+TBM
+TBM,400.0,2.27,600.0,2.03,800.0,1.83,ENDT
$
CHBDYP,10,25,LINE,,,1,2,,+CHP10
+CHP10,,,,,0.0,1.0,0.0
CHBDYP,20,25,LINE,,,2,3,,+CHP20
+CHP20,,,,,0.0,1.0,0.0
CHBDYP,30,25,LINE,,,3,4,,+CHP30
+CHP30,,,,,0.0,1.0,0.0
CHBDYP,40,25,LINE,,,4,5,,+CHP40
+CHP40,,,,,0.0,1.0,0.0
CHBDYP,50,25,LINE,,,5,6,,+CHP50
+CHP50,,,,,0.0,1.0,0.0
PHBDY,25,.3141593
$CONV,10,35,,,99,99
CONV,20,35,,,99,99
CONV,30,35,,,99,99
CONV,40,35,,,99,99
CONV,50,35,,,99,99
PCONV,35,15,0,0.25
$
SPC,10,1,,1300.0
SPC,10,99,,300.0
TEMPD,20,1300.0
$
ENDDATA
```

Note

MAT4/MATT4/TABLEM2 supply the temperature dependence of the heat transfer coefficient.

Results

The abbreviated EX1C.f06 output file is shown in Table 2. A plot of temperature versus distance is shown in Figure 2.

Table 5-6. Example 1c Results File

```
EXAMPLE 1C                                        NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE    11

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       1      S      1.300000E+03   1.223213E+03   1.165064E+03   1.124369E+03   1.100287E+03   1.092315E+03
      99      S      3.000000E+02
EXAMPLE 1C                                                           NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
      99      S       .0
EXAMPLE 1C                                                           NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       1      S      1.392052E+03    .0             .0             .0             .0             .0
      99      S     -1.392069E+03
EXAMPLE 1C                                                           NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION    RADIATION          TOTAL
                  10      0.000000E+00    -3.110855E+02      0.000000E+00      0.000000E+00     -3.110855E+02
                  20      0.000000E+00    -2.892279E+02      0.000000E+00      0.000000E+00     -2.892279E+02
                  30      0.000000E+00    -2.729202E+02      0.000000E+00      0.000000E+00     -2.729202E+02
                  40      0.000000E+00    -2.621092E+02      0.000000E+00      0.000000E+00     -2.621092E+02
                  50      0.000000E+00    -2.567259E+02      0.000000E+00      0.000000E+00     -2.567259E+02
EXAMPLE 1C                                                           NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
         1    ROD        -7.678735E+02                                        1.566462E+05
         2    ROD        -5.814849E+02                                        1.186229E+05
         3    ROD        -4.069491E+02                                        8.301761E+04
         4    ROD        -2.408249E+02                                        4.912827E+04
         5    ROD        -7.971770E+01                                        1.626241E+04
```

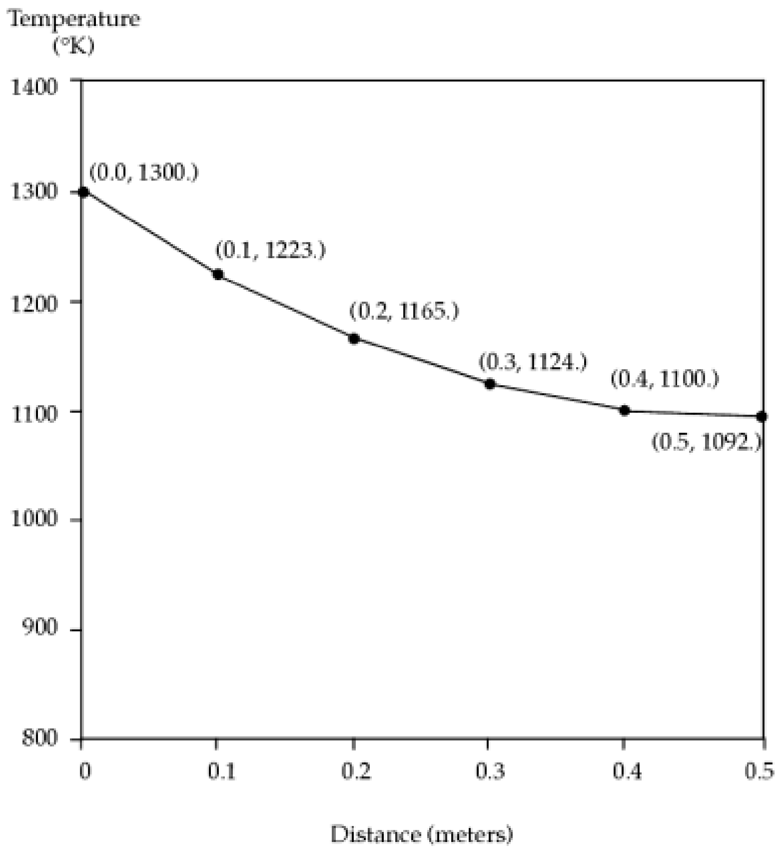


Figure 5-6. Temperature versus Distance – Example 1c

1d – Film Nodes for Free Convection

Demonstrated Principles

- Film nodes
- MPCs

Discussion

In the spirit of the previous example, we allow the free convection heat transfer coefficient to be temperature dependent; however, we extend the notion of the film node to provide a film temperature look-up value more heavily weighted toward the local surface temperatures than the ambient temperature. The MPC (multipoint constraint) relationship is available for this purpose. In this example, the film node temperatures become the average of the two CHBDY surface grid points each with a weight of 1.0, and the ambient temperature is also given a weighting of 1.0. Note that the default film node has a temperature which is the average of the average of the surface temperature and ambient point temperatures.

For example, consider the first CHBDY element:

Default calculation (see Table 1):

$$T_{FilmNode} = \left(\frac{T_1 + T_2}{2} + \frac{T_{\infty_1} + T_{\infty_2}}{2}\right) / 2$$

$$= \frac{T_1 + T_2 + 2T_\infty}{4}$$

MPC calculation:

$$T_{Film\ Node} = \frac{T_1 + T_2 + T_\infty}{3}$$

The NX Nastran input file is shown in Table 1.

Table 5-7. Example 1d Input File

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 1d
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
MPC = 30
NLPARM = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,91,,91.0,91.0,91.0
GRID,92,,92.0,92.0,92.0
GRID,93,,93.0,93.0,93.0
GRID,94,,94.0,94.0,94.0
GRID,95,,95.0,95.0,95.0
GRID,99,,99.0,99.0,99.0
```

```
$
CROD,1,5,1,2
CROD,2,5,2,3
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,.0078540
MAT4,15,204.0,,,1.0
MATT4,15,,,,40
TABLEM2,40,0.0,,,,,,,+TBM
+TBM,400.0,2.27,600.0,2.03,800.0,1.83,ENDT
$
CHBDYP,10,25,LINE,,,1,2,,+CHP10
+CHP10,,,,,0.0,1.0,0.0
CHBDYP,20,25,LINE,,,2,3,,+CHP20
+CHP20,,,,,0.0,1.0,0.0
CHBDYP,30,25,LINE,,,3,4,,+CHP30
+CHP30,,,,,0.0,1.0,0.0
CHBDYP,40,25,LINE,,,4,5,,+CHP40
+CHP40,,,,,0.0,1.0,0.0
CHBDYP,50,25,LINE,,,5,6,,+CHP50
+CHP50,,,,,0.0,1.0,0.0
PHBDY,25,.3141593
$
CONV,10,35,91,,99,99
CONV,20,35,92,,99,99
CONV,30,35,93,,99,99
CONV,40,35,94,,99,99
CONV,50,35,95,,99,99
PCONV,35,15,0,0.25

$
MPC,30,91,,3.0,1,,-1.0,,+MPC91
+MPC91,,2,,-1.0,99,,-1.0
MPC,30,92,,3.0,2,,-1.0,,+MPC92
+MPC92,,3,,-1.0,99,,-1.0
MPC,30,93,,3.0,3,,-1.0,,+MPC93
+MPC93,,4,,-1.0,99,,-1.0
MPC,30,94,,3.0,4,,-1.0,,+MPC94
+MPC94,,5,,-1.0,99,,-1.0
MPC,30,95,,3.0,5,,-1.0,,+MPC95
+MPC95,,6,,-1.0,99,,-1.0
$
SPC,10,1,,1300.0
SPC,10,99,,300.0
TEMPD,20,1299.9
$
ENDDATA
```

Note

- MPC must be requested in Case Control.
- GRID points 91-95 represent the film nodes.

Results

The abbreviated EX1D.f06 output file is shown in Table 2. A plot of temperature versus distance is shown in Figure 1.

Table 5-8. Example 1d Results File

```
EXAMPLE 1D                              NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE    15

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       1      S      1.300000E+03   1.228207E+03   1.173591E+03   1.135242E+03   1.112498E+03   1.104961E+03
      91      S      9.427355E+02   9.005992E+02   8.696109E+02   8.492465E+02   8.391531E+02
      99      S      3.000000E+02
EXAMPLE 1D                                                          NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
      91      S       .0             .0             .0             .0             .0
      99      S       .0
EXAMPLE 1D                                                          NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       1      S      1.297968E+03    .0             .0             .0             .0             .0
      91      S       .0             .0             .0             .0             .0
      99      S     -1.297969E+03
EXAMPLE 1D                                                          NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE
LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION            TOTAL
                  10      0.000000E+00     -2.847656E+02      0.000000E+00      0.000000E+00     -2.847656E+02
                  20      0.000000E+00     -2.681580E+02      0.000000E+00      0.000000E+00     -2.681580E+02
                  30      0.000000E+00     -2.554733E+02      0.000000E+00      0.000000E+00     -2.554733E+02
                  40      0.000000E+00     -2.469317E+02      0.000000E+00      0.000000E+00     -2.469317E+02
                  50      0.000000E+00     -2.426400E+02      0.000000E+00      0.000000E+00     -2.426400E+02
EXAMPLE 1D                                                          NOVEMBER   2, 1993  NX NASTRAN  11/ 1/03   PAGE
LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT        Y-GRADIENT        Z-GRADIENT         X-FLUX            Y-FLUX            Z-FLUX
         1    ROD          -7.179333E+02                                         1.464584E+05
         2    ROD          -5.461558E+02                                         1.114158E+05
         3    ROD          -3.834945E+02                                         7.823288E+04
         4    ROD          -2.274367E+02                                         4.639708E+04
```

```
   5    ROD        -7.536760E+01                                1.537499E+04
```

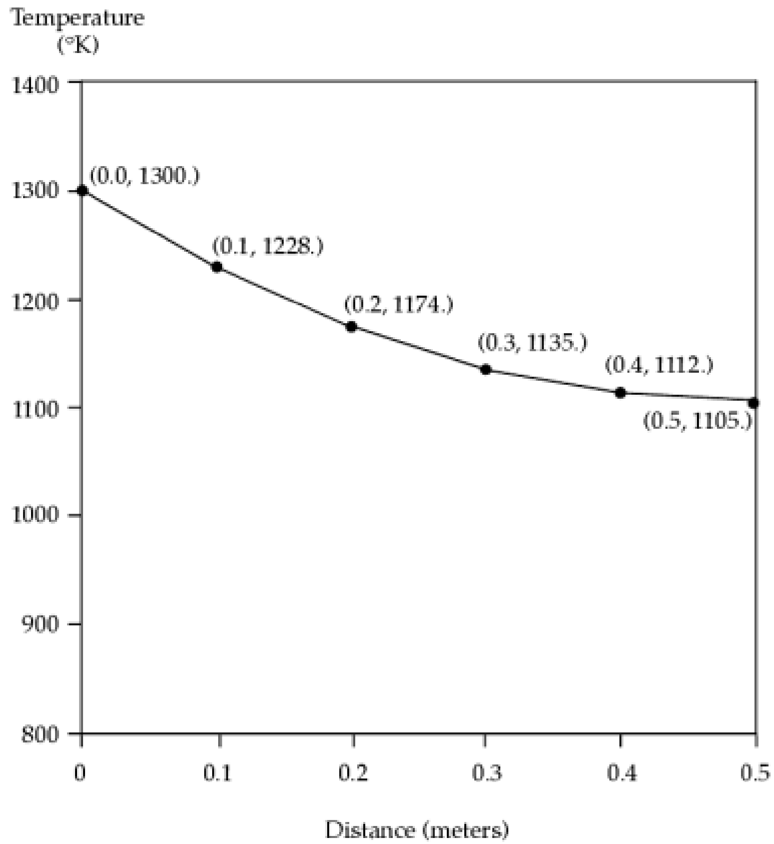


Figure 5-7. Temperature versus Distance

1e – Radiation Boundary Condition

Demonstrated Principles

- Radiation Boundary Condition
- Temperature Dependent Emissivity
- Temperature Dependent Conductivity

Discussion

Radiation heat transfer is added along the length of the rod from our previous examples. For this case we treat the problem as one in which radiant exchange occurs between the rod and an ambient environment at 300°K. This can be modeled simply with a radiation boundary condition specification. Surface emissivity variation with temperature is also accounted for. Radiation exchange from the end of the rod has been included to illustrate the POINT type CHBDY element.

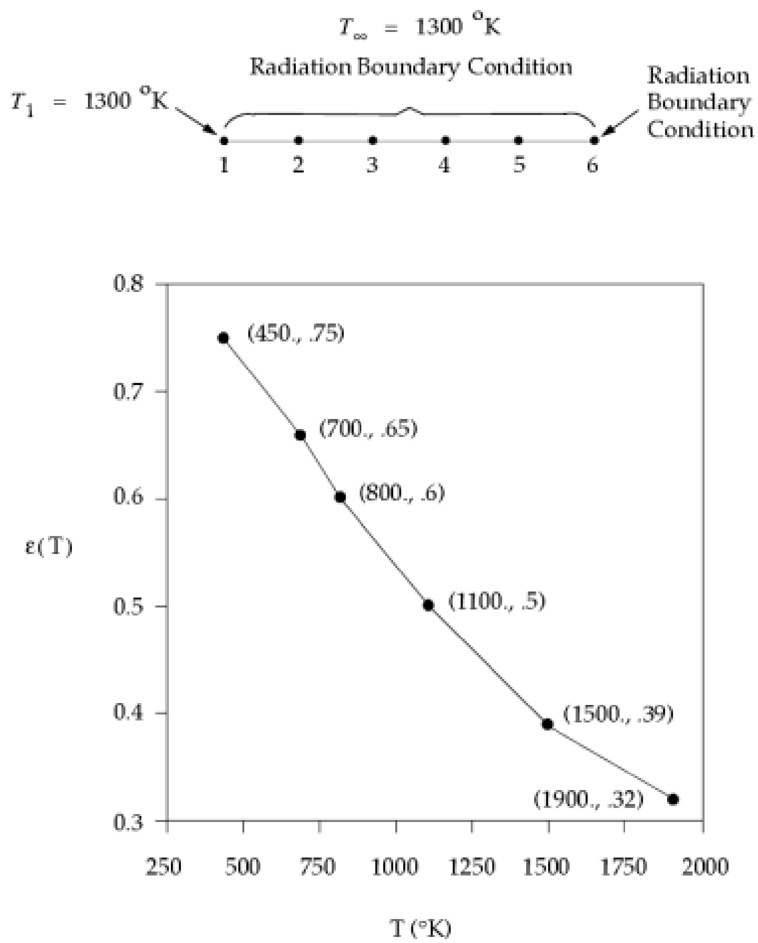


Figure 5-8. Example 1e – Emissivity as a Function of Temperature

The NX Nastran input file is shown in Table 1.

Table 5-9. Example 1e Input File

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 1e
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
NLPARM,100
PARAM,SIGMA,5.67E-8
PARAM,TABS,0.0
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
```

```
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,99,,99.0,99.0,99.0

$
CROD,1,5,1,2
CROD,2,5,2,3
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,.0078540
MAT4,15,1.0
MATT4,15,40

TABLEM2,40,0.0,,,,,,,+TBM1
+TBM1,173.16,215.0,273.16,202.0,373.16,206.0,473.16,215.0,+TBM2
+TBM2,573.16,228.0,673.16,249.0,ENDT
$
CHBDYP,10,25,LINE,,,1,2,,+CHP10
+CHP10,45,,,,0.0,1.0,0.0
CHBDYP,20,25,LINE,,,2,3,,+CHP20
+CHP20,45,,,,0.0,1.0,0.0
CHBDYP,30,25,LINE,,,3,4,,+CHP30
+CHP30,45,,,,0.0,1.0,0.0
CHBDYP,40,25,LINE,,,4,5,,+CHP40
+CHP40,45,,,,0.0,1.0,0.0
CHBDYP,50,25,LINE,,,5,6,,+CHP50
+CHP50,45,,,,0.0,1.0,0.0
CHBDYP,60,26,POINT,,,6,,,+CHP60
+CHP60,45,,,,1.0,0.0,0.0

PHBDY,25,.3141593
PHBDY,26,.0078540
$
RADBC,99,1.0,,10,THRU,60,BY,10
RADM,45,1.0,1.0
RADMT,45,41,41
TABLEM2,41,0.0,,,,,,,+TBM3
+TBM3,450.0,0.75,700.0,0.65,800.0,0.60,1100.0,0.50,+TBM4
+TBM4,1500.0,0.39,1900.0,0.32,ENDT
$
SPC,10,1,,1300.0
SPC,10,99,,300.0
TEMPD,20,1300.0
$
ENDDATA
```

Note

- Parameters SIGMA and TABS are required for any radiation problem.
- POINT type CHBDYP for radiation to space from the end of the rod.

Results

The abbreviated EX1E.f06 output file is shown in Table 2. A plot of temperature versus distance is shown in Figure 2.

Table 5-10. Example 1e Results File

```
EXAMPLE 1E                                   SEPTEMBER  24, 1993  NX NASTRAN   9/23/03   PAGE    11

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
      1      S      1.300000E+03   1.140835E+03   1.026327E+03   9.476805E+02   8.996806E+02   8.795513E+02
     99      S      3.000000E+02
EXAMPLE 1E                                                                 SEPTEMBER  24, 1993  NX NASTRAN   9/23/03   PAGE

LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
     99      S       .0
EXAMPLE 1E                                                                 SEPTEMBER  24, 1993  NX NASTRAN   9/23/03   PAGE

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
      1      S      5.468448E+03    .0             .0             .0             .0             .0
     99      S       .0
EXAMPLE 1E                                                                 SEPTEMBER  24, 1993  NX NASTRAN   9/23/03   PAGE

LOAD STEP =  1.00000E+00
                          H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION            TOTAL
                  10      0.000000E+00      0.000000E+00      0.000000E+00     -1.838179E+03     -1.838179E+03
                  20      0.000000E+00      0.000000E+00      0.000000E+00     -1.234006E+03     -1.234006E+03
                  30      0.000000E+00      0.000000E+00      0.000000E+00     -9.011517E+02     -9.011517E+02
                  40      0.000000E+00      0.000000E+00      0.000000E+00     -7.164666E+02     -7.164666E+02
                  50      0.000000E+00      0.000000E+00      0.000000E+00     -6.278596E+02     -6.278596E+02
                  60      0.000000E+00      0.000000E+00      0.000000E+00     -1.507721E+02     -1.507721E+02
EXAMPLE 1E                                                                 SEPTEMBER  24, 1993  NX NASTRAN   9/23/03   PAGE
                                                                                                      NONLINEAR
LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT        Y-GRADIENT        Z-GRADIENT        X-FLUX            Y-FLUX            Z-FLUX
         1    ROD         -1.591654E+03                                         5.792411E+05
         2    ROD         -1.145073E+03                                         3.838152E+05
         3    ROD         -7.864676E+02                                         2.476643E+05
         4    ROD         -4.799988E+02                                         1.447721E+05
         5    ROD         -2.012931E+02                                         5.927191E+04
```

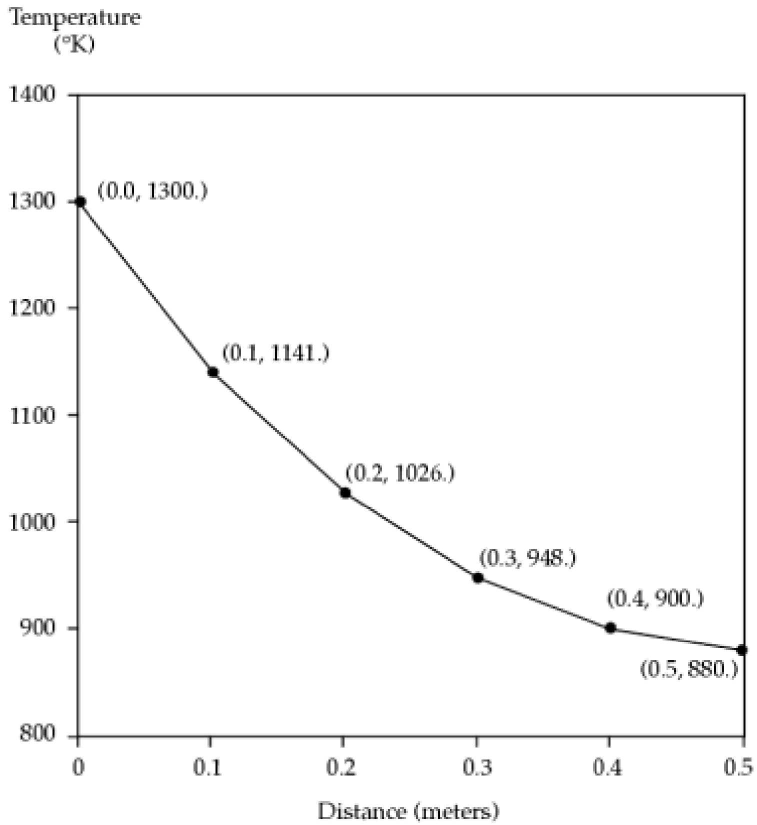


Figure 5-9. Temperature versus Distance

2a – Nonlinear Internal Heating and Free Convection

Demonstrated Principles

- Heat Transfer “Loads” and their Descriptions
- Temperature-Dependent Loads
- AREA Type CHBDYs
- Film Node
- Free Convection Exponent

Discussion

Examples 2a, 2b, and 2c describe NX Nastran heat transfer “loads”. While we tend to think of boundary conditions in regard to heat transfer, there are several surface conditions which we define as loads. In an NX Nastran sense, a load has the flexibility of being subcase selectable.

This concept, an early carryover from structural analysis, allows the load vector to vary while the stiffness matrix and its decomposition remain unchanged. This provided an economical method for evaluating the effects of multiple loading states and superposition of loads. The load set/subcase capability is less significant for heat transfer since many boundary conditions have contributions to the coefficient matrix and are fundamentally nonlinear, eliminating any potential for superposition of loads. In this series of examples, a single CHEXA element is used to demonstrate the application of internal heat generation, free convection, control nodes, film nodes, and various nonlinear effects. The temperature dependence of the heat transfer coefficient and the heat generation rate illustrated are used.

Example 2a – Nonlinear Internal Heating and Free Convection demonstrates the selection of the internal heat generation load QVOL. A control node, which is a member of the element grid point set, has been chosen to multiply the heat generation term as well as be the film node. We refer to this as local control. The free convection exponent, EXPF, is set to 0.0 (FORM = 0). The analytic expression for this example is given in Figure 2.

The basic energy balance can be expressed as:

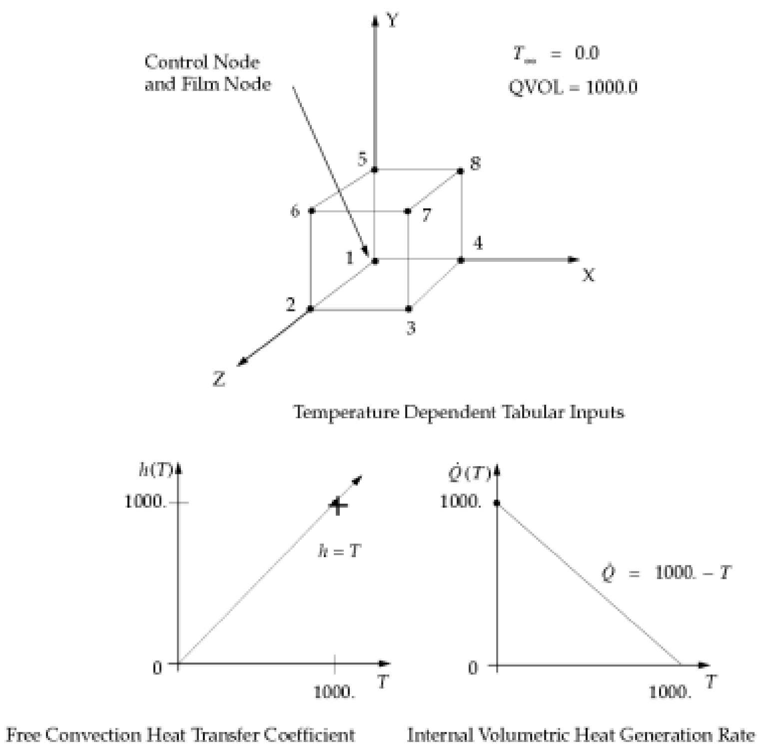


Figure 5-10. Example 2a

Analytic Solution of Example 2a

$$\left.\begin{array}{ll} QVOL \cdot U_{CN} \cdot HGEN \cdot VOLUME = h \cdot AREA \cdot (T - T_{\infty})^{EXPF} \cdot (T - T_{\infty}) & \\ \text{or,} \quad (1000. \cdot T \cdot (1000. - T) \cdot 1.0 = T \cdot 6.0 \cdot T & (EXPF = 0.0)) \\ \text{Resulting in,} & T = 994.036\ ^{\circ}\mathrm{C} \end{array}\right\}$$

Figure 5-11.

The NX Nastran input file is shown in Table 1.

Table 5-11. Example 2a Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 2a
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,,,1.0,,1.0
MATT4,15,,,,40,,41
TABLEM2,40,0.0,,,,,,,+TBM40
+TBM40,0.0,0.0,1000.0,1000.0,ENDT
TABLEM2,41,0.0,,,,,,,+TBM41
+TBM41,0.0,1000.0,1000.0,0.0,ENDT
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
```

```
$
CONV,10,35,1,,99
CONV,20,35,1,,99
CONV,30,35,1,,99
CONV,40,35,1,,99
CONV,50,35,1,,99
CONV,60,35,1,,99
PCONV,35,15,0,0.0
$
QVOL,200,1000.0,1,1
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Note

The load, in this case QVOL, must be requested in Case Control.

The temperature dependence on internal heat generation is requested through HGEN on the MAT4/MATT4 entries.

Results

The abbreviated EX2A.f06 output file is shown in Table 2.

Table 5-12. Example 2a Results File

```
LOAD STEP =  1.00000E+00
                                           T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      9.940355E+02   9.940355E+02   9.940355E+02   9.940355E+02   9.940355E+02   9.940355E+02
        7      S      9.940355E+02   9.940355E+02
       99      S       .0
EXAMPLE 2A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    12

LOAD STEP =  1.00000E+00
                                                  L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0                .0
       99      S       .0
EXAMPLE 2A                                                    SSEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    13

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0                .0
       99      S     -5.928640E+06
EXAMPLE 2A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    14

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION           TOTAL
                  10      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
                  20      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
                  30      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
                  40      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
                  50      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
                  60      0.000000E+00     -9.881066E+05      0.000000E+00      0.000000E+00     -9.881066E+05
EXAMPLE 2A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    15

LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX          Y-FLUX           Z-FLUX
         1    HEXA       -1.136868E-13     1.136868E-13     5.684342E-14     2.319211E-11    -2.319211E-11    -1.159606E-11
```

2b – Nonlinear Internal Heating and Control Nodes

Demonstrated Principles

- Control Node Applied to Loads and Convection Boundaries
- Free Convection Forms

Discussion of Variation 1

This problem extends Example 2a – Nonlinear Internal Heating and Free Convection in the implementation of local control for the internal heat generation control node and the film node for convection. However, the same control node is now used to multiply the convection heat transfer coefficient. The free convection exponent EXPF remains at 0.0 (FORM = 0).

The basic energy balance can be expressed as:

$$\left.\begin{array}{ll} QVOL \cdot U_{CN} \cdot HGEN \cdot VOLUME = h \cdot AREA \cdot (T - T_{\infty}) \cdot (T - T_{\infty})^{EXPF} \cdot U_{CN} & \\ \text{or,} \qquad (1000 \cdot T \cdot (1000 - T) \cdot 1.0 = T \cdot 6.0 \cdot (T - T_{\infty}) \cdot T) & \\ \text{Resulting in,} \qquad T = 333.33\ ^{\circ}\text{C} & \end{array}\right\}$$

Figure 5-12.

The NX Nastran input file for Variation 1 is shown in Table 1.

Table 5-13. Example 2b1 Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE2b1
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0

GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,,,1.0,,1.0
MATT4,15,,,,40,,41
TABLEM2,40,0.0,,,,,,,+TBM40
+TBM40,0.0,0.0,1000.0,1000.0,ENDT
TABLEM2,41,0.0,,,,,,,+TBM41
+TBM41,0.0,1000.0,1000.0,0.0,ENDT
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,1,1,99
CONV,20,35,1,1,99
CONV,30,35,1,1,99
CONV,40,35,1,1,99
CONV,50,35,1,1,99
CONV,60,35,1,1,99
PCONV,35,15,0,0.0
$
QVOL,200,1000.0,1,1
```

```
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Results of Variation 1

The abbreviated EX2B1.f06 output file is shown in Table 2.

Table 5-14. Example 2b1 Results File

```
EXAMPLE 2B1                              SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    11

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S     3.333339E+02   3.333339E+02   3.333339E+02   3.333339E+02   3.333339E+02   3.333339E+02
        7      S     3.333339E+02   3.333339E+02
       99      S      .0
EXAMPLE 2B1                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    12

LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S      .0              .0
       99      S      .0
EXAMPLE 2B1                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    13

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S      .0              .0
       99      S    -2.222233E+08
EXAMPLE 2B1                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    14

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                  10      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
                  20      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
                  30      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
                  40      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
                  50      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
                  60      0.000000E+00     -3.703721E+07      0.000000E+00      0.000000E+00     -3.703721E+07
EXAMPLE 2B1                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    15

LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE      X-GRADIENT       Y-GRADIENT       Z-GRADIENT       X-FLUX           Y-FLUX           Z-FLUX
         1    HEXA        0.000000E+00     0.000000E+00    -2.842171E-14     0.000000E+00     0.000000E+00     5.798029E-12
```

Discussion of Variation 2

A slight variation of Example 2a – Nonlinear Internal Heating and Free Convection is depicted in Figure 2. The free convection relationship has been altered by introducing an EXPF value of 1.0 (FORM = 0).

The basic energy balance can be written as:

$$\left.\begin{array}{ll}
QVOL \cdot U_{CN} \cdot HGEN \cdot VOLUME = h \cdot AREA \cdot (T - T_{\infty})^{EXPF} \cdot (T - T_{\infty}) \cdot U_{CN} & \\
\text{or,} \qquad (1000 \cdot T \cdot (1000 - T) \cdot 1.0 = T \cdot 6.0 \cdot (T - T_{\infty}) \cdot (T - T_{\infty}) \cdot T) & \\
\text{Resulting in,} \qquad\qquad T = 54.02 &
\end{array}\right\}$$

Figure 5-13.

The NX Nastran input file for Variation 2 is shown in Table 3.

Table 5-15. Example 2b2 Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 2b2
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,,,1.0,,1.0
MATT4,15,,,,40,,41
TABLEM2,40,0.0,,,,,,,+TBM40
+TBM40,0.0,0.0,1000.0,1000.0,ENDT
TABLEM2,41,0.0,,,,,,,+TBM41
+TBM41,0.0,1000.0,1000.0,0.0,ENDT
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
$
CONV,10,35,1,1,99
CONV,20,35,1,1,99
CONV,30,35,1,1,99
CONV,40,35,1,1,99
CONV,50,35,1,1,99
CONV,60,35,1,1,99
PCONV,35,15,0,1.0
$
QVOL,200,1000.0,1,1
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Results of Variation 2

The abbreviated EX2b2.f06 output file is shown in Table 4.

Table 5-16. Example 2b2 Results File

```
EXAMPLE 2B2                             SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    11

LOAD STEP =  1.00000E+00
                                        T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      5.402279E+01   5.402279E+01   5.402279E+01   5.402279E+01   5.402279E+01   5.402279E+01
        7      S      5.402279E+01   5.402279E+01
       99      S       .0
EXAMPLE 2B2                                                    SEPTEMBER  24, 2004 NX ASTRAN 9/24/04 PAGE    12

LOAD STEP =  1.00000E+00
                                               L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0             .0
       99      S       .0
EXAMPLE 2B2                                                    SEPTEMBER  24, 2004 NX NASTRAN 9/24/04 PAGE    13

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0             .0
       99      S     -5.110450E+07
EXAMPLE 2B2                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    14

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION            TOTAL
                  10      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
                  20      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
                  30      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
                  40      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
                  50      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
                  60      0.000000E+00     -8.517416E+06      0.000000E+00      0.000000E+00     -8.517416E+06
EXAMPLE 2B2                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    15

LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT       X-FLUX           Y-FLUX           Z-FLUX
         1    HEXA        0.000000E+00     5.329071E-15     8.881784E-15     0.000000E+00    -1.087130E-12    -1.811884E-12
```

2c – Nonlinear Internal Heating and Film Nodes

Demonstrated Principles

- Free Convection Film Nodes
- Free Convection Forms

Discussion of Variation 1

This problem provides another example of the use of film nodes. In our previous examples, the film node was chosen to be an element grid point, meaning that the TABLEM look-up temperature for the temperature dependent heat transfer coefficient was the actual body temperature. More often than not, the look-up temperature should be some weighted average of the surface temperature and ambient temperature. In this case, the default value (a blank entry) for the film node depicts that the average of the CHBDY surface element and the associated ambient point temperatures provide the TABLEM look up temperature (FORM = 0). The analytic expression for this case is given in Figure 1:

The basic energy balance can be expressed as:

$$\left.\begin{array}{ll} QVOL \cdot U_{CN} \cdot HGEN \cdot VOLUME = h \cdot AREA \cdot (T - T_{\infty}) \cdot U_{CN} & \\ \text{or,} \quad \left(1000 \cdot T \cdot (1000 - T) = \left(\frac{T}{2}\right) \cdot 6.0 \cdot (T - T_{\infty}) \cdot T\right) & \\ \text{Resulting in,} \quad T = 434.26\ ^{\circ}\mathrm{C} & \end{array}\right\}$$

Figure 5-14.

The NX Nastran input file for Variation 1 is shown in Table 1.

Table 5-17. Example 2c1 Input File

```
ID NX NASTRAN V2
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 2c1
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,,,1.0,,1.0
MATT4,15,,,,40,,41
TABLEM2,40,0.0,,,,,,,+TBM40
+TBM40,0.0,0.0,1000.0,1000.0,ENDT
TABLEM2,41,0.0,,,,,,,+TBM41
+TBM41,0.0,1000.0,1000.0,0.0,ENDT
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,1,99
CONV,20,35,,1,99
```

```
CONV,30,35,,1,99
CONV,40,35,,1,99
CONV,50,35,,1,99
CONV,60,35,,1,99
PCONV,35,15,0,0.0
$
QVOL,200,1000.0,1,1
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Results for Variation 1

The abbreviated EX2C1.f06 output file for Variation 1 is shown in Table 2.

Table 5-18. Example 2c1 Results File

```
EXAMPLE 2C1                          SEPTEMBER  24, 2004 NX NASTRAN 9/24/04 PAGE    11

LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1     S      4.342588E+02   4.342588E+02   4.342588E+02   4.342588E+02   4.342588E+02   4.342588E+02
        7     S      4.342588E+02   4.342588E+02
       99     S       .0
EXAMPLE 2C1                                                      SEPTEMBER  24, 2004 NX NASTRAN 9/24/04 PAGE    12

LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7     S       .0              .0
       99     S       .0
EXAMPLE 2C1                                                      SEPTEMBER  24, 2004 NX NASTRAN 9/24/04 PAGE    13

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7     S       .0              .0
       99     S     -2.456784E+08
EXAMPLE 2C1                                                      SEPTEMBER  24, 2004 NX NASTRAN 9/24/04 PAGE    14

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION           TOTAL
                  10      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
                  20      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
                  30      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
                  40      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
                  50      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
                  60      0.000000E+00     -4.094640E+07      0.000000E+00      0.000000E+00     -4.094640E+07
EXAMPLE 2C1                                                      SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    15

LOAD STEP =  1.00000E+00
             F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
         1    HEXA        0.000000E+00     0.000000E+00    -2.842171E-14     0.000000E+00     0.000000E+00     5.798029E
```

Discussion of Variation 2

Figure 1 describes a variation of this problem which has the control nodes removed and the value of 0.2 introduced for EXPF (FORM = 0). It should be noted that the elimination of the control nodes alone would have no effect on the analysis since they would have cancelled out of the prior equations.

The basic energy balance can be expressed as:

$$
\left.\begin{array}{ll}
QVOL \cdot HGEN \cdot VOLUME = h \cdot AREA \cdot (T - T_\infty)^{.20} \cdot (T - T_\infty) & \\
\text{or,} \quad \left(\qquad 1000 \cdot (1000 - T) = \left(\frac{T}{2}\right) \cdot 6.0 \cdot (T)^{.20} \cdot (T)\right) & \\
\text{Resulting in,} \qquad T = 280.\ ^{\circ}C &
\end{array}\right\}
$$

Figure 5-15.

The NX Nastran input file for Variation 2 is shown in Table 3.

Table 5-19. Example 2c2 Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 2c2
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,,,1.0,,1.0
MATT4,15,,,,40,,41
TABLEM2,40,0.0,,,,,,,+TBM40
+TBM40,0.0,0.0,1000.0,1000.0,ENDT
TABLEM2,41,0.0,,,,,,,+TBM41
+TBM41,0.0,1000.0,1000.0,0.0,ENDT
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,1,99
CONV,20,35,,1,99
```

```
CONV,30,35,,1,99
CONV,40,35,,1,99

CONV,50,35,,1,99
CONV,60,35,,1,99
PCONV,35,15,0,0.2
$
QVOL,200,1000.0,1,1
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Results of Variation 2

The abbreviated EX2c2.f06 output file for Variation 2 is shown in Table 4.

Table 5-20. Example 2c2 Results File

```
EXAMPLE 2C2                                 SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    11


LOAD STEP =  1.00000E+00
                                          T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S     2.791197E+02   2.791197E+02   2.791197E+02   2.791197E+02   2.791197E+02   2.791197E+02
        7      S     2.791197E+02   2.791197E+02
       99      S       .0
EXAMPLE 2C2                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    12


LOAD STEP =  1.00000E+00
                                                 L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0              .0
       99      S       .0
EXAMPLE 2C2                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    13


LOAD STEP =  1.00000E+00
                         F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0              .0
       99      S    -2.012106E+08
EXAMPLE 2C2                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    14


LOAD STEP =  1.00000E+00
                          H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                  10      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
                  20      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
                  30      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
                  40      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
                  50      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
                  60      0.000000E+00     -3.353510E+07      0.000000E+00      0.000000E+00     -3.353510E+07
EXAMPLE 2C2                                                         SEPTEMBER  24, 2004 NX NASTRAN   9/24/04 PAGE    15


LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT       X-FLUX           Y-FLUX           Z-FLUX
         1    HEXA        0.000000E+00     0.000000E+00    -2.842171E-14     0.000000E+00     0.000000E+00     5.798029E-12
```

3 – Axisymmetric Elements and Boundary Conditions

Demonstrated Principles

- Axisymmetric Modeling
- Axisymmetric Surface Elements

Discussion

Axisymmetric geometric models may be constructed using the CTRAX3, CTRAX4, CTRAX6, CTRAX8, and CTRIAX6 elements. For this element, the grid point locations are input as

R,THETA,Z where the axis of symmetry is the Z axis. The grid points lie in the RZ plane (THETA = 0.0). In this example we demonstrate the CHBDYE statement for identifying the surface element to which the boundary condition is to be applied. The surface type is automatically accounted for with this specification. If the CHBDYG had been used, a TYPE field of REV would be specified. For reference, any applied loads of a flux nature have a total load applied to the structure that is calculated based on the entire circumferential surface area.

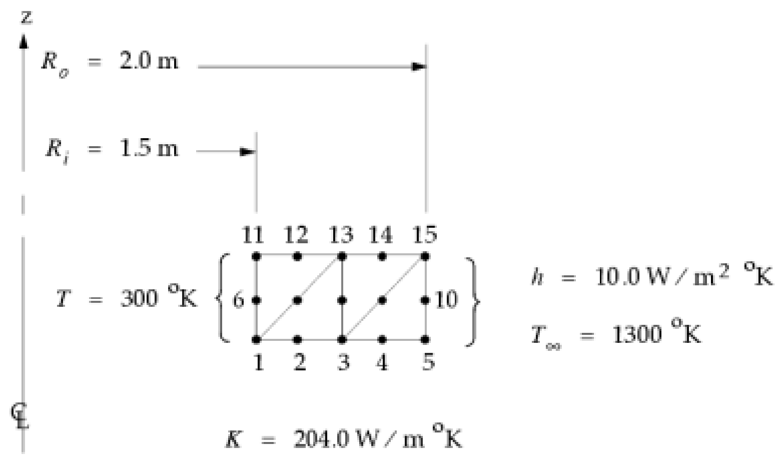


Figure 5-16. Example 3

The NX Nastran input file is shown in Table 1.

Table 5-21. Example 3 Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 3
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM  = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,1.500,0.0,0.0
GRID,2,,1.625,0.0,0.0
GRID,3,,1.750,0.0,0.0
GRID,4,,1.875,0.0,0.0
GRID,5,,2.000,0.0,0.0
GRID,6,,1.500,0.0,0.125
GRID,7,,1.625,0.0,0.125
GRID,8,,1.750,0.0,0.125
GRID,9,,1.875,0.0,0.125
GRID,10,,2.000,0.0,0.125
GRID,11,,1.500,0.0,0.250
GRID,12,,1.625,0.0,0.250
GRID,13,,1.750,0.0,0.250
GRID,14,,1.875,0.0,0.250
GRID,15,,2.000,0.0,0.250
GRID,99,,99.0,99.0,99.0
$
CTRIAX6,1,15,1,2,3,8,13,7
CTRIAX6,2,15,11,12,13,7,1,6
CTRIAX6,3,15,3,4,5,10,15,9
CTRIAX6,4,15,13,14,15,9,3,8
MAT4,15,204.0,,,10.0
$
CHBDYE,10,3,2
CONV,10,35,,,99
PCONV,35,15,0,0.0
$
SPC,10,99,,1300.0
```

```
SPC,10,1,,300.0,6,,300.0
SPC,10,11,,300.0
TEMP,20,99,1300.0
TEMPD,20,300.0
$
ENDDATA
```

Results

The abbreviated EX3.f06 output file is shown in Table 2.

Table 5-22. Example 3 Results File

```
EXAMPLE 3                      NOVEMBER   2, 2004 NX NASTRAN  11/ 1/04 PAGE    11


LOAD STEP =  1.00000E+00
                                         T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1     S      3.000000E+02   3.076283E+02   3.147016E+02   3.212750E+02   3.274322E+02   3.000000E+02
        7     S      3.076319E+02   3.146983E+02   3.212766E+02   3.274309E+02   3.000000E+02   3.076353E+02
       13     S      3.146945E+02   3.212776E+02   3.274268E+02
       99     S      1.300000E+03
EXAMPLE 3                                                  NOVEMBER   2, 2004 NX NASTRAN  11/ 1/04 PAGE    12


LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
       13     S       .0             .0             .0
       99     S       .0
EXAMPLE 3                                                  NOVEMBER   2, 2004 NX NASTRAN  11/ 1/04 PAGE    13


LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1     S     -5.102459E+03    .0             .0             .0             .0          -2.036143E+04
        7     S       .0             .0             .0             .0          -5.090287E+03    .0
       13     S       .0             .0             .0
       99     S      3.055418E+04
EXAMPLE 3                                                  NOVEMBER   2, 2004 NX NASTRAN  11/ 1/04 PAGE    14


LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION           TOTAL
                  10      0.000000E+00      3.055420E+04      0.000000E+00      0.000000E+00      3.055420E+04
EXAMPLE 3                                                  NOVEMBER   2, 2004 NX NASTRAN  11/ 1/04 PAGE    15


LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
         1    TRIAX6       5.728976E+01     0.000000E+00     9.583211E-03    -1.168711E+04     0.000000E+00    -1.954975E+00
         2    TRIAX6       6.029604E+01     0.000000E+00     1.792225E-02    -1.230039E+04     0.000000E+00    -3.656140E+00
         3    TRIAX6       4.979697E+01     0.000000E+00     1.273317E-03    -1.015858E+04     0.000000E+00    -2.597566E-01
         4    TRIAX6       5.206061E+01     0.000000E+00    -4.323532E-03    -1.062036E+04     0.000000E+00     8.820006E-01
```

4a – Plate in Radiative Equilibrium, Nondirectional Solar Load with Radiation Boundary Condition

Demonstrated Principles

- Flux Load Application
- Radiation to Space

Discussion

This series of radiative equilibrium problems illustrates various methods of flux load application and radiation exchange with space. The first example uses a nondirectional heat flux load to represent a solar source. A simple radiation boundary condition to space represents the loss mechanism. A blackbody surface is initially presumed.

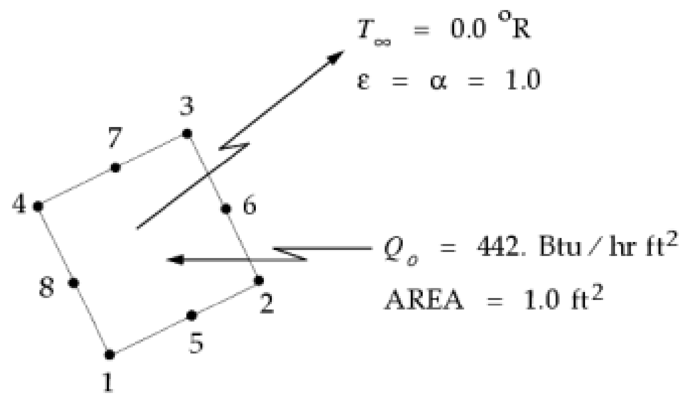


Figure 5-17. Example 4a

The basic energy balance can be expressed as:

$$Q = \sigma A \varepsilon F(T_e^4 - T_\infty^4)$$

$$\text{or,}\qquad 442.\ \mathrm{Btu/hr} = .1714 \times 10^{-8}\ \mathrm{Btu/hr\ ft^2}\ ^oR^4 \cdot 1.0\ \mathrm{ft^2} \cdot 1.0 \cdot 1.0\ (T_e^4 - (460.)^4)$$

$$\text{Resulting in,}\qquad T_e \cong 281.7\ ^oF$$

Figure 5-18.

The NX Nastran input file is shown in Table 1.

Table 5-23. Example 4a Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 4a
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
PARAM,TABS,459.67
PARAM,SIGMA,.1714E-8
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,0.0,0.5
GRID,6,,0.5,0.0,1.0
GRID,7,,1.0,0.0,0.5
```

```
GRID,8,,0.5,0.0,0.0
GRID,99,,99.0,99.0,99.0
$
CQUAD8,1,5,1,2,3,4,5,6,+CQD8
+CQD8,7,8
PSHELL,5,15,0.1
MAT4,15,204.0
$
CHBDYG,10,,AREA8,,,45,,,+CHG10
+CHG10,1,2,3,4,5,6,7,8
$
RADM,45,1.0,1.0
RADBC,99,1.0,,10
$
QHBDY,200,AREA8,442.0,,1,2,3,4,+QHBDY
+QHBDY,5,6,7,8
$
SPC,10,99,,0.0
TEMPD,20,0.0
$
ENDDATA
```

Results

The abbreviated EX4a.f06 output file is shown in Table 2

Table 5-24. Example 4a Results File

```
EXAMPLE 4A                  SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    11

LOAD STEP =  1.00000E+00
                                       T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      2.819637E+02   2.819637E+02   2.819637E+02   2.819637E+02   2.819637E+02   2.819637E+02
        7      S      2.819637E+02   2.819637E+02
       99      S       .0
EXAMPLE 4A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    12

LOAD STEP =  1.00000E+00
                                               L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S     -3.683333E+01  -3.683333E+01  -3.683334E+01  -3.683333E+01   1.473333E+02   1.473333E+02
        7      S      1.473333E+02   1.473333E+02
       99      S       .0
EXAMPLE 4A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    13

LOAD STEP =  1.00000E+00
                          F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        7      S       .0             .0
       99      S       .0
EXAMPLE 4A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    14

LOAD STEP =  1.00000E+00
                           H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION           TOTAL
                  10      0.000000E+00      0.000000E+00      0.000000E+00     -4.420000E+02     -4.420000E+02
EXAMPLE 4A                                                    SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    15

LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX          Y-FLUX          Z-FLUX
         1    QUAD8       -5.454024E-08     7.243386E-09                     1.112621E-05    -1.477651E-06
```

4b – Plate in Radiative Equilibrium, Directional Solar Load with Radiation Boundary Condition

Demonstrated Principle

- Directional Solar Heat Flux Loads

Discussion

Heat loads from a distant source can be treated in a directional sense with the QVECT Bulk Data entry. The absorptivity is made available from a RADM Bulk Data entry. In this case, the radiation boundary condition also uses this absorptivity in its exchange relationship. For illustrative purposes, the angle of incidence was varied to create a plot of equilibrium temperature versus θ .

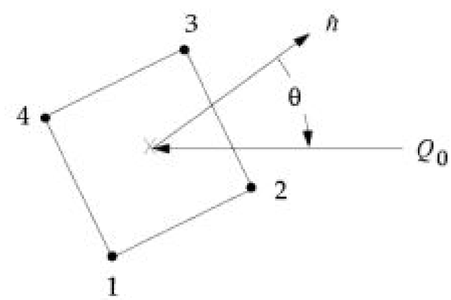


Figure 5-19. Example 4b

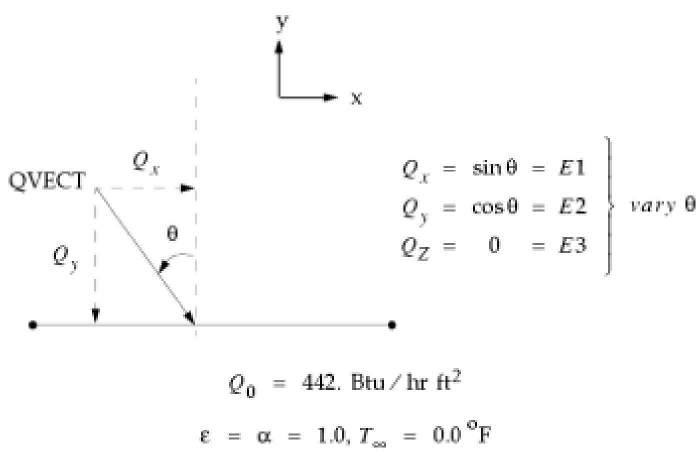


Figure 5-20.

Table 5-25. Equilibrium Temperature versus Angle of Incident Radiation

		Direction Cosines	
θ(deg)	*T* plate (×F)	E1	E2

0	282.0	0.0	-1.0
10	279.6	0.173648	-0.984808
20	272.2	0.342020	-0.939693
30	259.8	0.5	-0.866025
40	241.8	0.642788	-0.766044
50	217.6	0.766044	-0.642788
60	185.8	0.866025	-0.5
70	144.1	0.939693	-0.342020
80	87.2	0.984808	-0.173648
90	0.0	1.0	0.0

Note

$\theta = 80°$ case is illustrated in the input file listing.

The NX Nastran input file is shown in Table 2.

Table 5-26. Example 4b Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 4b
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
PARAM,TABS,459.67
PARAM,SIGMA,.1714E-8
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,99,,99.0,99.0,99.0
$
CQUAD4,1,5,1,2,3,4
PSHELL,5,15,0.1
MAT4,15,204.0
RADM,45,1.0,1.0
$
CHBDYG,10,,AREA4,,,45,,,+CHG10
+CHG10,1,2,3,4
QVECT,200,442.0,,,.984808,-.173648,0.0,,+QVCT1
+QVCT1,10
RADBC,99,1.0,,10
$
SPC,10,99,,0.0
TEMPD,20,0.0
$
ENDDATA
```

Results

The abbreviated EX4b.f06 output file is shown in Table 3. Figure 3 describes equilibrium temperature versus angle of incident radiation.

Table 5-27. Example 4b Results File

```
EXAMPLE 4B                                                          SEPTEMBER  24, 2004 NX NASTRAN 9/23/04 PAGE    11

LOAD STEP =  1.00000E+00
                                          T E M P E R A T U R E   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      8.717700E+01   8.717700E+01   8.717700E+01   8.717700E+01
       99      S       .0
EXAMPLE 4B                                                          SEPTEMBER  24, 2004 NX NASTRAN 9/23/04 PAGE    12

LOAD STEP =  1.00000E+00
                                                 L O A D   V E C T O R
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S      1.918810E+01   1.918810E+01   1.918810E+01   1.918810E+01
       99      S       .0
EXAMPLE 4B                                                          SEPTEMBER  24, 2004 NX NASTRAN 9/23/04 PAGE    13

LOAD STEP =  1.00000E+00
                        F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
 POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
        1      S       .0             .0             .0             .0
       99      S       .0
EXAMPLE 4B                                                          SEPTEMBER  24, 2004 NX NASTRAN 9/23/04 PAGE    14

LOAD STEP =  1.00000E+00
                         H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
          ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                  10      7.675242E+01      0.000000E+00      0.000000E+00     -7.675240E+01      2.288818E-05
EXAMPLE 4B                                                          SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    15

LOAD STEP =  1.00000E+00
              F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
ELEMENT-ID   EL-TYPE        X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
         1    QUAD4       -7.105427E-15     7.105427E-15                     1.449507E-12    -1.449507E-12
```

```
DIENT X-FLUX Y-FLUX Z-FLUX  1 QUAD4 -7.105427E-15 7.105427E-15 1.449507E-12 -1.449507E-12
```

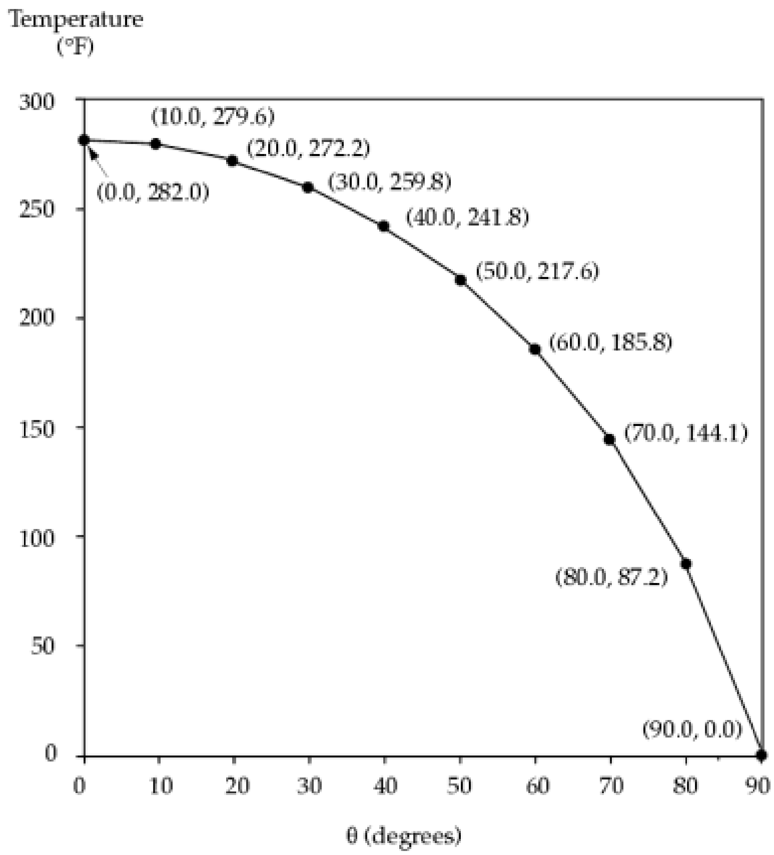


Figure 5-21. Temperature versus Angle of Incident Radiation

4c – Plate in Radiative Equilibrium, Directional Solar Load, Spectral Surface Behavior

Demonstrated Principles

- Solar Loads
- Spectral Radiation Surface Behavior

Discussion

Wavelength dependent surface properties can be incorporated in the radiation boundary condition or any radiation enclosure. For this simple radiative equilibrium problem, we demonstrate the principles by using a perfectly selective surface-a surface that behaves like a perfect blackbody (e = 1.0) below some finite cutoff wavelength and does not participate above that wavelength. Appendix G describes the mathematics underlying the waveband approximation to spectral radiation exchange. The RADBND Bulk Data entry supplies the wavelength break points and the RADM Bulk Data entry provides the band emissivities. The solar source (QVECT) for the analysis is treated as a blackbody at a temperature of 10400 ×R.

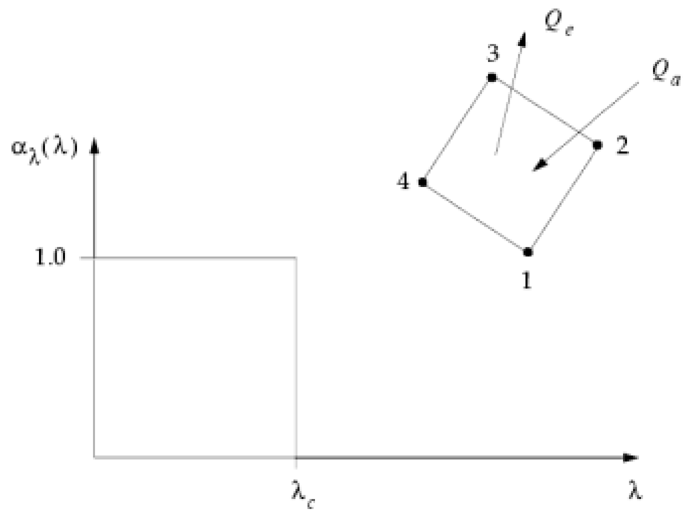


Figure 5-22. Surface Absorptivity versus Wavelength – Example 4c

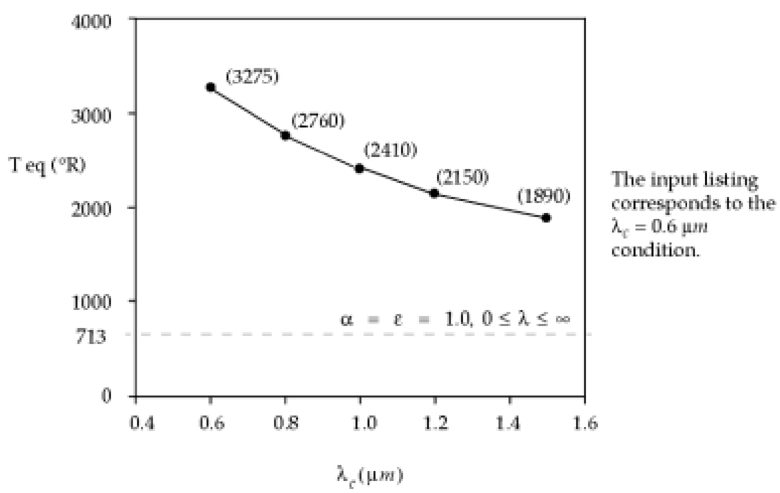


Figure 5-23. Radiative Equilibrium Temperature versus Cutoff Wavelength

The NX Nastran input file is shown in Table 1.

Table 5-28. Example 4c Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 4c
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
OLOAD = ALL
SPCF = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
LOAD = 200
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,.1714E-8
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,1.0,0.0,0.0
GRID,3,,1.0,1.0,0.0
GRID,4,,0.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CQUAD4,1,5,1,2,3,4
PSHELL,5,15,0.1
MAT4,15,204.0
$
CHBDYG,10,,AREA4,,,45,,,+CHG10
+CHG10,1,2,3,4
$
RADM,45,1.0,1.0,0.0
RADBND,3,25898.0,0.6,0.6
RADBC,99,1.0,,10
$
QVECT,200,442.0,10400.0,,0.0,0.0,-1.0,0,+QVECT
+QVECT,10
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,2500.0
$
ENDDATA
```

Note

Only one RADBND may exist in any analysis.

Results

The abbreviated EX4c.f06 output file is shown in Table 2.

Table 5-29. Example 4c Results File

```
EXAMPLE 4C                    DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE     8

    LOAD STEP =  1.00000E+00
                                        T E M P E R A T U R E   V E C T O R
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      3.275139E+03   3.275139E+03   3.275139E+03   3.275139E+03
           99      S      .0
    EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE     9

    LOAD STEP =  1.00000E+00
                                                L O A D   V E C T O R
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      4.153704E+01   4.153704E+01   4.153704E+01   4.153704E+01
           99      S      .0
EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE    10

    LOAD STEP =  1.00000E+00
                           F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      .0             .0             .0             .0
           99      S      .0
    EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE    11

    LOAD STEP =  1.00000E+00
                            H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
               ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                      10      1.661482E+02      0.000000E+00      0.000000E+00    -1.661480E+02      1.678467E-04
    EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE    12

    LOAD STEP =  1.00000E+00
                  F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
   ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT       X-FLUX           Y-FLUX           Z-FLUX
            1    QUAD4        0.000000E+00     0.000000E+00                     0.000000E+00     0.000000E+00
    EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE    13

    EXAMPLE 4C                                                  DECEMBER  10, 2004 NX NASTRAN  12/ 9/04 PAGE    14
```

5a – Single Cavity Enclosure Radiation with Shadowing

Demonstrated Principles

- Surface to Surface Radiation Exchange
- Radiation Cavity / Enclosure
- View Factor Calculation with Shadowing

Discussion

A simple geometry composed of four plate elements is used to demonstrate radiant exchange in an enclosure. Every surface to participate in the exchange is identified with an CHBDYi Bulk Data entry surface element, in this case providing five surface elements. Only one RADCAV Bulk Data entry is defined in this example indicating that a single enclosure cavity has been defined. For this configuration, shadowing must be considered when calculating the view factors.

The statements essential to the radiation solution process are described as follows:

RADSET	Requests which cavities are to be included as radiation enclosures for the thermal analysis.
RADLST / RADMTX	Provides the view factors required for generation of the radiation matrix. Since they are not provided by the user in this example, they are determined by use of the view module in the course of the analysis.
RADCAV	Provides various global controls used for the calculation of view factors within the identified cavity.
VIEW	Provides the connection between a surface element and its assigned cavity and requests that view factors be calculated among those surface elements assigned to the same cavity.

VIEW3D	Requests that the view factors be calculated using the adaptive gaussian integration view factor routine as opposed to the default finite difference calculation.
CHBDYi	Describes the surface elements used in the enclosure, and associates them with the VIEW and RADM Bulk Data entries.
RADM	Provides the radiative surface properties (emissivity), in this case a constant value of 1.0.

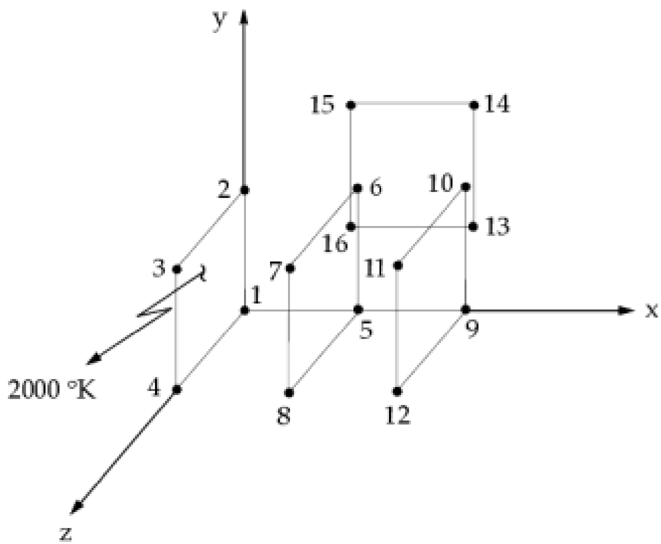


Figure 5-24. Example 5a.

The NX Nastran input file is shown in Table 1.

Table 5-30. Example 5a Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 5a
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10

TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
PARAM,TABS,0.0
```

```
PARAM,SIGMA,5.67E-08
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,1.0,0.0
GRID,3,,0.0,1.0,1.0
GRID,4,,0.0,0.0,1.0
GRID,5,,1.0,0.0,0.0
GRID,6,,1.0,1.0,0.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,0.0,1.0
GRID,9,,2.0,0.0,0.0
GRID,10,,2.0,1.0,0.0
GRID,11,,2.0,1.0,1.0
GRID,12,,2.0,0.0,1.0
GRID,13,,1.5,0.0,-1.0
GRID,14,,1.5,1.0,-1.0
GRID,15,,0.5,1.0,-1.0
GRID,16,,0.5,0.0,-1.0
$

CQUAD4,1,5,1,2,3,4
CQUAD4,2,5,5,6,7,8
CQUAD4,3,5,9,12,11,10
CQUAD4,4,5,13,14,15,16
PSHELL,5,15,0.1
MAT4,15,204.0
$
CHBDYG,10,,AREA4,55,,45,,,+CHG10
+CHG10,1,2,3,4

CHBDYG,20,,AREA4,56,,45,,,+CHG20
+CHG20,5,6,7,8
CHBDYG,21,,AREA4,56,,45,,,+CHG21
+CHG21,5,8,7,6
CHBDYG,30,,AREA4,55,,45,,,+CHG30
+CHG30,9,12,11,10
CHBDYG,40,,AREA4,57,,45,,,+CHG40
+CHG40,13,14,15,16
$
RADM,45,1.0,1.0
RADSET,65
RADCAV,65,,YES
VIEW,55,65,KBSHD
VIEW,56,65,KSHD
VIEW,57,65,NONE
VIEW3D,65,,,,,,,3
$
SPC,10,1,,2000.0,2,,2000.0
SPC,10,3,,2000.0,4,,2000.0
TEMPD,20,2000.0
$
ENDDATA
```

Note

The CQUAD4 element with an EID = 2 has two surface elements associated with it.

The direction of the CHBDYG surface normals are important for any radiation exchange.

Shadowing flags can save vast amounts of computation time for large problems.

Results

The abbreviated EX5a.f06 output file is shown in Table 2. Included in this output is a tabulation of the view factor calculation. The details of this output are discussed in"View Factor Calculation Methods". Because the view factor summations are less than 1.0, there is considerable energy lost to space. The punch file of radiation view factors is shown in Table 3.

Table 5-31. Example 5a Results File

```
EXAMPLE 5A                SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE     6


         *** VIEW FACTOR MODULE *** OUTPUT DATA *** CAVITY ID =      65 ***
                          ELEMENT TO ELEMENT VIEW FACTORS   C*   PARTIAL
  SURF-I   SURF-J   AREA-I      AI*FIJ        FIJ         ERROR  SHADING ERROR  SCALE
     10 -     21   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
     10       30   1.0000E+00  6.84135E-02  6.84135E-02  7.3895E-02   NO    NO
     10       40   1.0000E+00  4.08547E-02  4.08547E-02  6.6278E-02   NO    NO
     10       30   1.0000E+00  0.00000E+00  0.00000E+00     0/256
     10       21   1.0000E+00  1.99944E-01  1.99944E-01
     10 -SUM OF                2.40799E-01  2.40799E-01
     20 -     30   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
     20       40   1.0000E+00  1.31841E-02  1.31841E-02  2.0133E-02  YES    NO
     20       40   1.0000E+00  1.16713E-02  1.16713E-02
     20       30   1.0000E+00  1.99944E-01  1.99944E-01
     20 -SUM OF                2.11616E-01  2.11616E-01
     21 -     40   1.0000E+00  1.31841E-02  1.31841E-02  2.0133E-02  YES    NO
     21       40   1.0000E+00  1.16713E-02  1.16713E-02
     21 -SUM OF                2.11616E-01  2.11616E-01
     30 -     40   1.0000E+00  4.08547E-02  4.08547E-02  6.6278E-02   NO    NO
     30 -SUM OF                2.40799E-01  2.40799E-01
     40 -SUM OF                1.05052E-01  1.05052E-01
^^^ DMAP INFORMATION MESSAGE 9048 (NLSCSH) - LINEAR ELEMENTS   ARE CONNECTED TO THE ANALYSIS SET (A-SET).
*** USER INFORMATION MESSAGE 4534,    5 ELEMENTS HAVE A TOTAL VIEW FACTOR (FA/A) LESS THAN 0.99, ENERGY MAY BE LOST TO SPACE.
    LOAD STEP =  1.00000E+00
                                            T E M P E R A T U R E   V E C T O R
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      2.000000E+03   2.000000E+03   2.000000E+03   2.000000E+03   1.132229E+03   1.132229E+03
            7      S      1.132229E+03   1.132229E+03   7.732046E+02   7.732046E+02   7.732046E+02   7.732046E+02
           13      S      9.168311E+02   9.168311E+02   9.168311E+02   9.168311E+02
   EXAMPLE 5A                                                           SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    24


   LOAD STEP =  1.00000E+00
                                                   L O A D   V E C T O R
    POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
          13      S       .0              .0             .0             .0
   EXAMPLE 5A                                                           SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    25


   LOAD STEP =  1.00000E+00
                              F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
    POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
           1      S     2.217105E+05   2.217105E+05   2.217105E+05   2.217105E+05    .0             .0
          13      S       .0              .0             .0             .0
   EXAMPLE 5A                                                           SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    26


   LOAD STEP =  1.00000E+00
                               H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
            ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION           TOTAL
                    10      0.000000E+00      0.000000E+00      0.000000E+00     -8.868420E+05     -8.868420E+05
                    20      0.000000E+00      0.000000E+00      0.000000E+00     -8.865096E+04     -8.865096E+04
                    21      0.000000E+00      0.000000E+00      0.000000E+00      8.865097E+04      8.865097E+04
                    30      0.000000E+00      0.000000E+00      0.000000E+00     -3.671037E-04     -3.671037E-04
                    40      0.000000E+00      0.000000E+00      0.000000E+00      6.051011E-03      6.051011E-03
 EXAMPLE 5A                                                SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    27


   LOAD STEP =  1.00000E+00
                  F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
  ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT        X-FLUX           Y-FLUX           Z-FLUX
           1    QUAD4       0.000000E+00     0.000000E+00                      0.000000E+00     0.000000E+00
           2    QUAD4       2.273737E-13     1.136868E-13                     -4.638423E-11    -2.319211E-11
           3    QUAD4       0.000000E+00     0.000000E+00                      0.000000E+00     0.000000E+00
           4    QUAD4      -5.684342E-14     0.000000E+00                      1.159606E-11     0.000000E+00
```

Table 5-32. Example 5a Punch File (EX5a.pch)

```
RADMTX        65        1   0.0      0.0    .199944   0.0    .040855
RADMTX        65        2   0.0      0.0    .199944 .011671
RADMTX        65        3   0.0      0.0    .011671
RADMTX        65        4   0.0    .040855
RADMTX        65        5   0.0
RADLST        65        1      10       20       21       30       40
```

5b – Single Cavity Enclosure Radiation with an Ambient Element Specification

Demonstrated Principles

- Enclosure Radiation Exchange
- Radiation Ambient Element

Discussion

Example 5a involves four plates in radiative equilibrium which exhibit considerable energy loss to space since there is no defined exchange mechanism between them and their environment. This undefined environment behaves mathematically the same as blackbody space at a temperature of absolute zero. A convenient method for introducing an ambient environment into the problem capitalizes on the use of the ambient element as selected on the RADCAV Bulk Data entry. For any group of surface elements we wish to consider as a partial enclosure, we can define a single unique ambient element which will mathematically complete the enclosure. This surface element must have a specified temperature boundary condition.

The ambient element concept relies on our knowledge that the individual elemental view factors must add up to a value of 1.0 for a complete enclosure. Any elemental surfaces which have a view factor sum of less than 1.0 as determined by the view module will automatically have the remainder assigned to the ambient element. This environmental view factor is not listed in the view module output, but is identified in the generated RADLST/RADMTX punch files. If the ambient element is to model space, it should be made appropriately large relative to the other elements in the enclosure. As discussed in "View Factor Calculation Methods", whenever an ambient element is requested for a cavity, a symmetric conservative radiation matrix is generated.

The NX Nastran input file is shown in Table 1.

Table 5-33. Example 5b Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 5b
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-08
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,1.0,0.0
GRID,3,,0.0,1.0,1.0
GRID,4,,0.0,0.0,1.0
GRID,5,,1.0,0.0,0.0
GRID,6,,1.0,1.0,0.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,0.0,1.0
GRID,9,,2.0,0.0,0.0
GRID,10,,2.0,1.0,0.0
GRID,11,,2.0,1.0,1.0
GRID,12,,2.0,0.0,1.0
GRID,13,,1.5,0.0,-1.0
GRID,14,,1.5,1.0,-1.0
GRID,15,,0.5,1.0,-1.0
GRID,16,,0.5,0.0,-1.0
GRID,17,,0.0,100.0,0.0
```

```
GRID,18,,100.0,100.0,0.0
GRID,19,,100.0,100.0,100.0
GRID,20,,0.0,100.0,100.0
$
CQUAD4,1,5,1,2,3,4
CQUAD4,2,5,5,6,7,8
CQUAD4,3,5,9,12,11,10
CQUAD4,4,5,13,14,15,16
CQUAD4,5,5,17,18,19,20
PSHELL,5,15,0.1
MAT4,15,204.0
$

CHBDYG,10,,AREA4,55,,45,,,+CHG10
+CHG10,1,2,3,4
CHBDYG,20,,AREA4,56,,45,,,+CHG20
+CHG20,5,6,7,8
CHBDYG,21,,AREA4,56,,45,,,+CHG21
+CHG21,5,8,7,6
CHBDYG,30,,AREA4,55,,45,,,+CHG30
+CHG30,9,12,11,10
CHBDYG,40,,AREA4,57,,45,,,+CHG40
+CHG40,13,14,15,16
CHBDYG,99,,AREA4,,,45,,,+CHG99
+CHG99,17,18,19,20
$
RADM,45,1.0,1.0
RADSET,65
RADCAV,65,99,YES
VIEW,55,65,KBSHD
VIEW,56,65,KSHD
VIEW,57,65,NONE
VIEW3D,65,,,,,,,3
$
SPC,10,1,,2000.0,2,,2000.0
SPC,10,3,,2000.0,4,,2000.0
SPC,10,17,,500.0,18,,500.0
SPC,10,19,,500.0,20,,500.0
TEMPD,20,2000.0
$
ENDDATA
```

Note

Ambient element EID = 99 is defined with a large area to represent space.

Results

The abbreviated EX5b.f06 output file is shown in Table 2. Note that the ambient element does not appear in the view factor .f06 output. The punch file is shown in 3, and does include the ambient element.

Table 5-34. Example 5b Results File

```
 EXAMPLE 5B                                   FEBRUARY  14, 2004 NX NASTRAN   2/14/04 PAGE     7


          *** VIEW FACTOR MODULE *** OUTPUT DATA *** CAVITY ID =      65 ***
                          ELEMENT TO ELEMENT VIEW FACTORS   C*   PARTIAL
  SURF-I   SURF-J   AREA-I      AI*FIJ        FIJ          ERROR  SHADING ERROR  SCALE
     10 -      21   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
     10        30   1.0000E+00  6.84135E-02  6.84135E-02  7.3895E-02   NO    NO
     10        40   1.0000E+00  4.08547E-02  4.08547E-02  6.6278E-02   NO    NO
     10        30   1.0000E+00  0.00000E+00  0.00000E+00     0/256
     10        21   1.0000E+00  1.99944E-01  1.99944E-01
     10 -SUM OF                 2.40799E-01  2.40799E-01
     20 -      30   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
     20        40   1.0000E+00  1.31841E-02  1.31841E-02  2.0133E-02  YES    NO
     20        40   1.0000E+00  1.16713E-02  1.16713E-02
     20        30   1.0000E+00  1.99944E-01  1.99944E-01
     20 -SUM OF                 2.11616E-01  2.11616E-01
     21 -      40   1.0000E+00  1.31841E-02  1.31841E-02  2.0133E-02  YES    NO
     21        40   1.0000E+00  1.16713E-02  1.16713E-02
     21 -SUM OF                 2.11616E-01  2.11616E-01
     30 -      40   1.0000E+00  4.08547E-02  4.08547E-02  6.6278E-02   NO    NO
     30 -SUM OF                 2.40799E-01  2.40799E-01
     40 -SUM OF                 1.05052E-01  1.05052E-01
    LOAD STEP =  1.00000E+00
                                              T E M P E R A T U R E   V E C T O R
     POINT ID.   TYPE      ID   VALUE      ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      2.000000E+03   2.000000E+03   2.000000E+03   2.000000E+03   1.141790E+03   1.141790E+03
            7      S      1.141790E+03   1.141790E+03   8.044109E+02   8.044109E+02   8.044109E+02   8.044109E+02
           13      S      9.356503E+02   9.356503E+02   9.356503E+02   9.356503E+02   5.000000E+02   5.000000E+02
           19      S      5.000000E+02   5.000000E+02
   EXAMPLE 5B                                                           FEBRUARY  14, 2004 NX NASTRAN   2/14/04   PAGE    11


    LOAD STEP =  1.00000E+00
                                                    L O A D   V E C T O R
     POINT ID.   TYPE      ID   VALUE      ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
           19      S      .0             .0
   EXAMPLE 5B                                                           FEBRUARY  14, 2004 NX NASTRAN   2/14/04   PAGE    12
```

```
    LOAD STEP =  1.00000E+00
                                F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
           1      S      2.208269E+05   2.208269E+05   2.208269E+05   2.208269E+05    .0             .0
          13      S       .0             .0             .0             .0            -2.208285E+05  -2.208285E+05
          19      S     -2.208285E+05  -2.208285E+05
EXAMPLE 5B                                                          FEBRUARY  14, 2004 NX NASTRAN   2/14/04   PAGE    13

LOAD STEP =  1.00000E+00
                                 H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
              ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                      10      0.000000E+00      0.000000E+00      0.000000E+00     -8.833074E+05     -8.833074E+05
                      20      0.000000E+00      0.000000E+00      0.000000E+00     -8.830299E+04     -8.830299E+04
                      21      0.000000E+00      0.000000E+00      0.000000E+00      8.830428E+04      8.830428E+04
                      30      0.000000E+00      0.000000E+00      0.000000E+00     -7.230929E+00     -7.230929E+00
                      40      0.000000E+00      0.000000E+00      0.000000E+00     -5.820249E-01     -5.820249E-01
                      99      0.000000E+00      0.000000E+00      0.000000E+00      8.833141E+05      8.833141E+05

EXAMPLE 5B                                 FEBRUARY  14, 2004 NX NASTRAN   2/14/04 PAGE    14


    LOAD STEP =  1.00000E+00
                      F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
   ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT       X-FLUX          Y-FLUX            Z-FLUX
            1    QUAD4        0.000000E+00     0.000000E+00                      0.000000E+00    0.000000E+00
            2    QUAD4        0.000000E+00     0.000000E+00                      0.000000E+00    0.000000E+00
            3    QUAD4       -5.684342E-14    -1.136868E-13                      1.159606E-11    2.319211E-11
            4    QUAD4        0.000000E+00     0.000000E+00                      0.000000E+00    0.000000E+00
            5    QUAD4       -5.204170E-17     5.204170E-17                      1.061651E-14   -1.061651E-14
```

Table 5-35. Example 5b Punch File (EX5b.pch)

```
RADMTX         65        1    0.0      0.0    .199944   0.0   .040855 .759201
RADMTX         65        2    0.0      0.0    .199944 .011671 .788384
RADMTX         65        3    0.0      0.0    .011671 .788384
RADMTX         65        4    0.0    .040855 .759201
RADMTX         65        5    0.0    .894948
RADMTX         65        6    0.0
RADLST         65        4       10       20       21       30       40       99
```

5c - Multiple Cavity Enclosure Radiation

Demonstrated Principles

- Multiple Radiation Cavities
- View Factor Calculation for Multiple Cavities

Discussion

The concept of multiple radiation cavities is investigated in this problem. The primary use of this capability is to reduce the computation time associated with the identification and calculation of view factors when total separation exists between regions. If defined as a single enclosure, this problem would involve third body shadowing calculations, the most laborious and expensive part of any view factor calculation. As a three cavity problem, these calculations are eliminated.

RADSET selects three cavities and the RADCAV entry for SHADOW is denoted as NO indicating that no third body shadowing calculations are to be performed within the individual cavities. The fields on the VIEW Bulk Data entry concerning SHADE are ignored when SHADOW is set to NO on the RADCAV Bulk Data entry. When hundreds or thousands of surfaces are involved, the savings may be crucial to the economics of the total analysis.

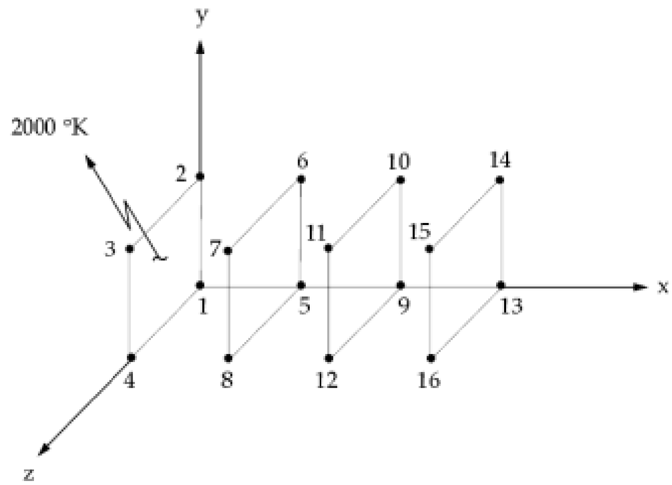


Figure 5-25. Example 5c

The NX Nastran input file is shown in Table 1.

Table 5-36. Example 5c Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 5c
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100

$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,1.0,0.0
GRID,3,,0.0,1.0,1.0
GRID,4,,0.0,0.0,1.0
GRID,5,,1.0,0.0,0.0
GRID,6,,1.0,1.0,0.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,0.0,1.0
GRID,9,,2.0,0.0,0.0
GRID,10,,2.0,1.0,0.0
GRID,11,,2.0,1.0,1.0
GRID,12,,2.0,0.0,1.0
GRID,13,,3.0,0.0,0.0
GRID,14,,3.0,1.0,0.0
GRID,15,,3.0,1.0,1.0
GRID,16,,3.0,0.0,1.0
$
```

```
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-08
NLPARM,100
CQUAD4,1,5,1,2,3,4
CQUAD4,2,5,5,6,7,8
CQUAD4,3,5,9,10,11,12
CQUAD4,4,5,13,16,15,14
PSHELL,5,15,0.1
MAT4,15,204.0
$
CHBDYG,10,,AREA4,55,,45,,,+CHG10
+CHG10,1,2,3,4
CHBDYG,20,,AREA4,55,,45,,,+CHG20
+CHG20,5,8,7,6
CHBDYG,30,,AREA4,56,,45,,,+CHG30
+CHG30,5,6,7,8
CHBDYG,40,,AREA4,56,,45,,,+CHG40
+CHG40,9,12,11,10
CHBDYG,50,,AREA4,57,,45,,,+CHG50
+CHG50,9,10,11,12
CHBDYG,60,,AREA4,57,,45,,,+CHG60
+CHG60,13,16,15,14

$
RADM,45,1.0,1.0
RADSET,65,75,85
RADCAV,65,,NO
RADCAV,75,,NO
RADCAV,85,,NO
VIEW,55,65
VIEW,56,75
VIEW,57,85
VIEW3D,65,,,,,,,3

VIEW3D,75,,,,,,,3
VIEW3D,85,,,,,,,3
$
SPC,10,1,,2000.0,2,,2000.0
SPC,10,3,,2000.0,4,,2000.0
TEMPD,20,2000.0
$
ENDDATA
```

Results

The abbreviated EX5c.f06 output file is shown in Table 2. The punch file is shown in Table 3. Note the multiple cavity information.

Table 5-37. Example 5c Results File

```
EXAMPLE 5C                                           SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE     7
*** VIEW FACTOR MODULE *** OUTPUT DATA *** CAVITY ID =       65 ***
                                  ELEMENT TO ELEMENT VIEW FACTORS   C*   PARTIAL
   SURF-I   SURF-J   AREA-I     AI*FIJ       FIJ          ERROR  SHADING ERROR  SCALE
      10 -     20   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
      10       20   1.0000E+00  1.99944E-01  1.99944E-01
      10 -SUM OF                1.99944E-01  1.99944E-01
      20 -SUM OF                1.99944E-01  1.99944E-01
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE     8

            *** VIEW FACTOR MODULE *** OUTPUT DATA *** CAVITY ID =       75 ***
                                  ELEMENT TO ELEMENT VIEW FACTORS   C*   PARTIAL
   SURF-I   SURF-J   AREA-I     AI*FIJ       FIJ          ERROR  SHADING ERROR  SCALE
      30 -     40   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
      30       40   1.0000E+00  1.99944E-01  1.99944E-01
      30 -SUM OF                1.99944E-01  1.99944E-01
      40 -SUM OF                1.99944E-01  1.99944E-01
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE     9

            *** VIEW FACTOR MODULE *** OUTPUT DATA *** CAVITY ID =       85 ***
                                  ELEMENT TO ELEMENT VIEW FACTORS   C*   PARTIAL
   SURF-I   SURF-J   AREA-I     AI*FIJ       FIJ          ERROR  SHADING ERROR  SCALE
      50 -     60   1.0000E+00  1.97750E-01  1.97750E-01  2.5529E-01   NO   YES
      50       60   1.0000E+00  1.99944E-01  1.99944E-01
      50 -SUM OF                1.99944E-01  1.99944E-01
      60 -SUM OF                1.99944E-01  1.99944E-01
^^^ DMAP INFORMATION MESSAGE 9048 (NLSCSH) - LINEAR ELEMENTS   ARE CONNECTED TO THE ANALYSIS SET (A-SET).
*** USER INFORMATION MESSAGE 4534,    2 ELEMENTS HAVE A TOTAL VIEW FACTOR (FA/A) LESS THAN 0.99, ENERGY MAY BE LOST TO SPACE.
    LOAD STEP =  1.00000E+00
                                                      T E M P E R A T U R E   V E C T O R
      POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      2.000000E+03   2.000000E+03   2.000000E+03   2.000000E+03   1.127462E+03   1.127462E+03
            7      S      1.127462E+03   1.127462E+03   6.371667E+02   6.371667E+02   6.371667E+02   6.371667E+02
           13      S      4.260592E+02   4.260592E+02   4.260592E+02   4.260592E+02
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    43

     LOAD STEP =  1.00000E+00
                                                             L O A D   V E C T O R
      POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
           13      S       .0             .0             .0             .0
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    44


 LOAD STEP =  1.00000E+00
                                F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
      POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      2.221976E+05   2.221976E+05   2.221976E+05   2.221976E+05    .0             .0
           13      S       .0             .0             .0             .0
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    45

     LOAD STEP =  1.00000E+00
                                 H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
               ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION     RADIATION          TOTAL
                       10      0.000000E+00     0.000000E+00      0.000000E+00     -8.887904E+05     -8.887904E+05
                       20      0.000000E+00     0.000000E+00      0.000000E+00      8.974247E+04      8.974247E+04
                       30      0.000000E+00     0.000000E+00      0.000000E+00     -8.974246E+04     -8.974246E+04
                       40      0.000000E+00     0.000000E+00      0.000000E+00      8.970887E+03      8.970887E+03
                       50      0.000000E+00     0.000000E+00      0.000000E+00     -8.970880E+03     -8.970880E+03
                       60      0.000000E+00     0.000000E+00      0.000000E+00     -5.437486E-04     -5.437486E-04
EXAMPLE 5C                                                             SEPTEMBER  24, 2004 NX NASTRAN   9/23/04 PAGE    46

     LOAD STEP =  1.00000E+00
                    F I N I T E   E L E M E N T   T E M P E R A T U R E   G R A D I E N T S   A N D   F L U X E S
    ELEMENT-ID   EL-TYPE       X-GRADIENT       Y-GRADIENT       Z-GRADIENT         X-FLUX           Y-FLUX           Z-FLUX
             1    QUAD4       0.000000E+00     0.000000E+00                       0.000000E+00     0.000000E+00
             2    QUAD4       0.000000E+00     0.000000E+00                       0.000000E+00     0.000000E+00
             3    QUAD4       0.000000E+00     0.000000E+00                       0.000000E+00     0.000000E+00
             4    QUAD4       0.000000E+00     0.000000E+00                       0.000000E+00     0.000000E+00
```

Table 5-38. Example 5c Punch File

```
RADMTX        65       1   0.0   .199944
RADMTX        65       2   0.0
RADLST        65       1      10       20
RADMTX        75       1   0.0   .199944
RADMTX        75       2   0.0
RADLST        75       1      30       40
RADMTX        85       1   0.0   .199944
RADMTX        85       2   0.0
RADLST        85       1      50       60
```

6 – Forced Convection Tube Flow - Constant Property Flow

Demonstrated Principles

- Forced Convection Fluid Elements
- Control Node for Mass Flow Rate
- Relationships for Tube Flows

- Film Nodes for Forced Convection
- Constant Heat Transfer Coefficient

Discussion

A forced convection element (CONVM) is available for the simulation of 1-D fluid flow networks. The formulation takes into account conduction and convection in the streamwise direction as well as the convection resistance between the fluid and the adjoining structure or environment. The mass flow rate is specified by the value of the control node (CNTMDOT). Fluid properties which vary with temperature are available through the MAT4/MATT4 entries for conductivity, specific heat, and dynamic viscosity. In this example, the forced convection heat transfer coefficient has been input at a constant value of 200. W/m2 °C. For tube flow, the heat transfer coefficient could easily have been calculated internally based on the relationships available through the CONVM/PCONVM.

It may be desirable to consider a fluid flow problem in an evolutionary sense. This allows for a much broader interpretation of load incrementing through time stepping, as well introducing the stabilizing effects associated with heat capacitance and implicit time integration. The steady state solution may then be likened to the long time solution from a transient analysis.

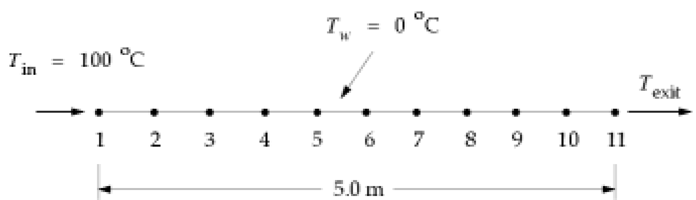


Figure 5-26. Example 6

Working Fluid = Water:

K	=	$.065\ W/m\ ^oC$
C_p	=	$4200.\ J/kg\ ^oC$
ρ	=	$1000.\ kg/m^3$
μ	=	$1.0 \times 10^{-3}\ kg/m\ sec$
h	=	$200.\ W/m^2\ ^oC = \text{constant}$
$\dot{m}$	=	$0.1\ kg/sec$
DIA	=	.05 m

The NX Nastran input file is shown in Table 1.

Table 5-39. Example 6 Input File

```
ID NX NASTRAN V3
SOL 153
TIME 10
CEND
TITLE = EXAMPLE 6
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
TEMP(INIT) = 20
NLPARM = 100
BEGIN BULK
NLPARM,100
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.5,0.0,0.0
GRID,3,,1.0,0.0,0.0
GRID,4,,1.5,0.0,0.0
GRID,5,,2.0,0.0,0.0
GRID,6,,2.5,0.0,0.0
GRID,7,,3.0,0.0,0.0
GRID,8,,3.5,0.0,0.0
GRID,9,,4.0,0.0,0.0
GRID,10,,4.5,0.0,0.0
GRID,11,,5.0,0.0,0.0
GRID,50,,50.0,50.0,50.0
GRID,99,,99.0,99.0,99.0
$
CHBDYP,10,25,FTUBE,,,1,2
CHBDYP,20,25,FTUBE,,,2,3
CHBDYP,30,25,FTUBE,,,3,4
CHBDYP,40,25,FTUBE,,,4,5
CHBDYP,50,25,FTUBE,,,5,6
CHBDYP,60,25,FTUBE,,,6,7
CHBDYP,70,25,FTUBE,,,7,8
CHBDYP,80,25,FTUBE,,,8,9
CHBDYP,90,25,FTUBE,,,9,10
CHBDYP,100,25,FTUBE,,,10,11
PHBDY,25,,0.05,0.05
$
CONVM,10,95,,50,99
CONVM,20,95,,50,99
CONVM,30,95,,50,99
CONVM,40,95,,50,99
CONVM,50,95,,50,99
CONVM,60,95,,50,99
CONVM,70,95,,50,99
CONVM,80,95,,50,99
CONVM,90,95,,50,99
CONVM,100,95,,50,99
$
PCONVM,95,15,0,1,200.0,0.0,0.0,0.0
MAT4,15,0.65,4200.0,1000.0,,1.0E-03
$
SPC,10,1,,100.0
SPC,10,99,,0.0
SPC,10,50,,0.1
$
TEMP,20,1,100.0
TEMP,20,99,0.0
TEMP,20,50,0.1
TEMPD,20,100.0
$
```

```
ENDDATA
```

Note

The input file reflects a mass flow rate of $\dot{m}$ = .10 kg/sec.

Results

The abbreviated EX6.f06 output file is shown in Table 2. A plot of temperature versus mass flow rate is shown in Figure 2.

Table 5-40. Example 6 Results File

```
EXAMPLE 6                            DECEMBER   3, 2004 NX NASTRAN  12/ 2/04 PAGE     8

    LOAD STEP =  1.00000E+00
                                               T E M P E R A T U R E   V E C T O R
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            1      S      1.000000E+02   9.639484E+01   9.291965E+01   8.956976E+01   8.634062E+01   8.322791E+01
            7      S      8.022740E+01   7.733508E+01   7.454703E+01   7.185950E+01   6.926884E+01
           50      S      1.000000E-01
           99      S       .0
EXAMPLE 6                                                         DECEMBER   3, 2004 NX NASTRAN  12/ 2/04 PAGE     9

    LOAD STEP =  1.00000E+00
                                                      L O A D   V E C T O R
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            7      S       .0             .0             .0             .0             .0
           50      S       .0
           99      S       .0
   EXAMPLE 6                                                         DECEMBER   3, 2004 NX NASTRAN  12/ 2/04 PAGE    10

    LOAD STEP =  1.00000E+00
                                 F O R C E S   O F   S I N G L E - P O I N T   C O N S T R A I N T
     POINT ID.   TYPE      ID   VALUE     ID+1 VALUE     ID+2 VALUE     ID+3 VALUE     ID+4 VALUE     ID+5 VALUE
            7      S       .0             .0             .0             .0             .0
           50      S       .0
           99      S     -1.338981E+04
   EXAMPLE 6                                                         DECEMBER   3, 2004 NX NASTRAN  12/ 2/04 PAGE    11

    LOAD STEP =  1.00000E+00
                                  H E A T   F L O W   I N T O   H B D Y   E L E M E N T S   (CHBDY)
              ELEMENT-ID      APPLIED-LOAD   FREE-CONVECTION   FORCED-CONVECTION    RADIATION          TOTAL
                     10      0.000000E+00      0.000000E+00     -1.542481E+03      0.000000E+00     -1.542481E+03
                     20      0.000000E+00      0.000000E+00     -1.486873E+03      0.000000E+00     -1.486873E+03
                     30      0.000000E+00      0.000000E+00     -1.433269E+03      0.000000E+00     -1.433269E+03
                     40      0.000000E+00      0.000000E+00     -1.381597E+03      0.000000E+00     -1.381597E+03
                     50      0.000000E+00      0.000000E+00     -1.331788E+03      0.000000E+00     -1.331788E+03
                     60      0.000000E+00      0.000000E+00     -1.283775E+03      0.000000E+00     -1.283775E+03
                     70      0.000000E+00      0.000000E+00     -1.237493E+03      0.000000E+00     -1.237493E+03
                     80      0.000000E+00      0.000000E+00     -1.192879E+03      0.000000E+00     -1.192879E+03
                     90      0.000000E+00      0.000000E+00     -1.149874E+03      0.000000E+00     -1.149874E+03
                    100      0.000000E+00      0.000000E+00     -1.108419E+03      0.000000E+00     -1.108419E+03
```

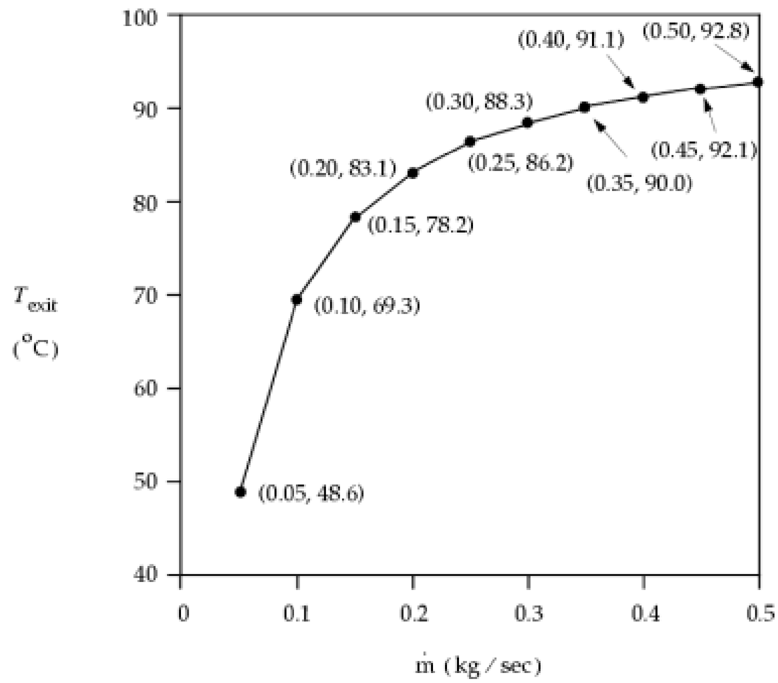


Figure 5-27. Exit Temperature versus Mass Flow Rate

7a – Transient Cool Down, Convection Boundary

Demonstrated Principles

- Transient Solution Sequence
- Transient Solution Control
- Transient Temperature Specification
- Initial Conditions
- Transient Plots

Discussion

This example demonstrates the simplest of transient thermal responses. A single CHEXA element at an initial temperature of 1000. ×C is exposed to a free convection environment maintained at 0.0 ×C. Transient analysis involves the time-dependent storage as well as transport of thermal energy. Therefore, relative to steady state analysis, the heat capacitance (storage) must be accounted for as well as any time dependencies on loads and boundary conditions. A starting point or initial condition is required and a solution duration is specified.

There are various techniques available for specifying temperature boundary conditions or ambient node temperatures for transient analyses. If the temperature is to remain constant throughout the analysis, an SPC should be used to set the boundary condition just as in steady state analysis.

Fundamental NX Nastran X-Y plotting is demonstrated here for simple transient plots. "Interface and File Communication" discusses this capability in more detail.

The NX Nastran input file is shown in Table 1.

Table 5-41. Example 7a Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 7A
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = TEMPERATURE DEGREES CELSIUS
TCURVE = TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
TSTEPNL,100,1500,100.0,1
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,896.0,2707.0,10.0
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,1000.0
$
ENDDATA
```

Note

TSTEPNL is identified in the Case Control Section, as are the NASPLT plot requests.

TSTEPNL provides the solution timing information in the Bulk Data Section.

MAT4 must have density and specific heat field data for transient analysis.

Results

Figure 1 shows an X-Y plot of temperature versus time. These plots were examined by typing NASPLT EX7A.plt subsequent to the analysis. The EX7A.f06 file has large lists of temperature vs. time for each grid point, and has been omitted here for brevity.

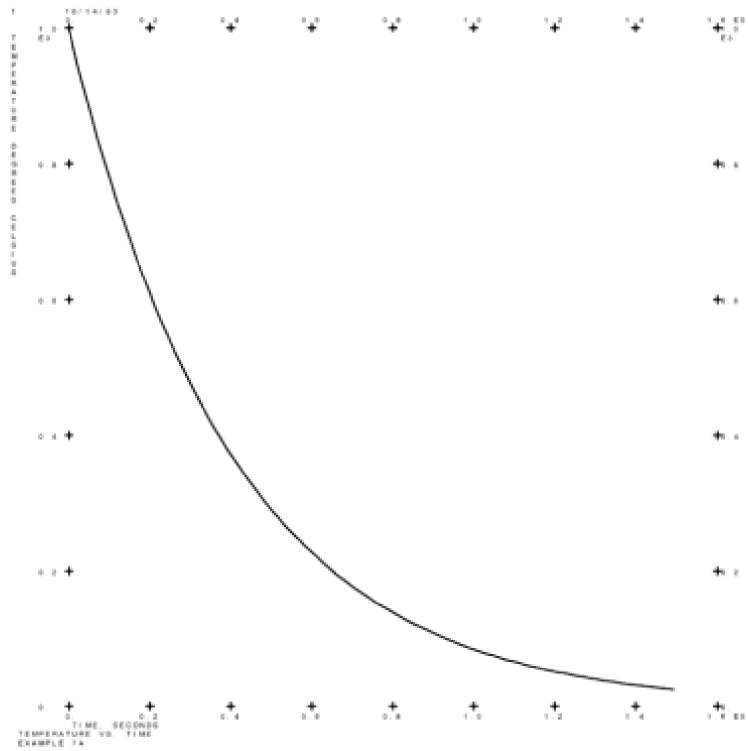


Figure 5-28. Temperature versus Time

7b – Convection, Time Varying Ambient Temperature

Demonstrated Principles

- General Time Varying Methodology
- Time-Varying Ambient Temperature

Discussion

The simple CHEXA element example is extended to illustrate convection with a time-varying ambient temperature. In this case, the nonconstant temperature disallows the use of an SPC for this specification. The transient form of the TEMPBC Bulk Data entry is demonstrated. The TEMPBC is treated with the same methodology as a thermal load for transient analysis (see Figure 1 for input schematic). Note the Case Control request for DLOAD = SID.

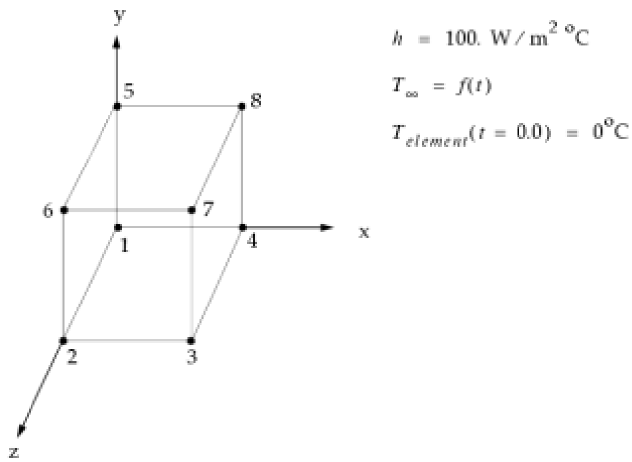


Figure 5-29. Example 7b

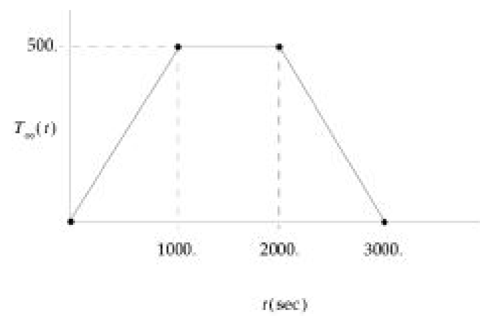


Figure 5-30. T $_\infty$ versus Time

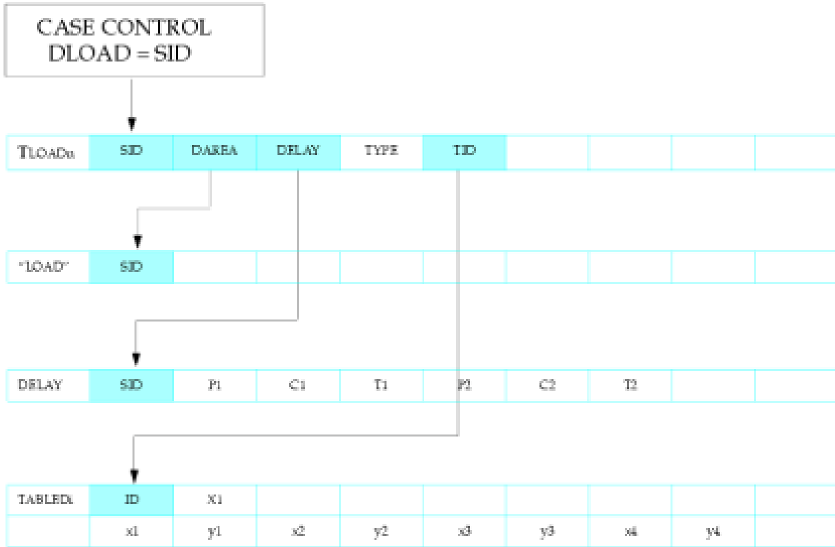


Figure 5-31. General Transient Load Methodology

The NX Nastran input file is shown in Table 1.

Table 5-42. Example 7b Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 7B
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
IC = 20
TSTEPNL  = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
XTITLE = TIME, SECONDS
YTITLE = AMBIENT TEMPERATURE DEGREES CELSIUS
TCURVE = AMBIENT TEMPERATURE VS. TIME
XYPLOT TEMP/99(T1)
BEGIN BULK
TSTEPNL,100,7500,1.0,1,,,,U
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
```

```
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,896.0,2707.0,100.0
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
TLOAD1,200,300,,,400
TABLED1,400,,,,,,,,+TBD1
+TBD1,0.0,0.0,1000.0,1.0,2000.0,1.0,3000.0,0.0,+TBD2
+TBD2,4000.0,0.0,ENDT
TEMPBC,300,TRAN,500.0,99
TEMP,20,99,0.0
TEMPD,20,0.0
$
ENDDATA
```

Results

Figure 4 shows an X-Y plot of ambient temperature versus time. Figure 5 shows an X-Y plot of grid 1 temperature versus time.

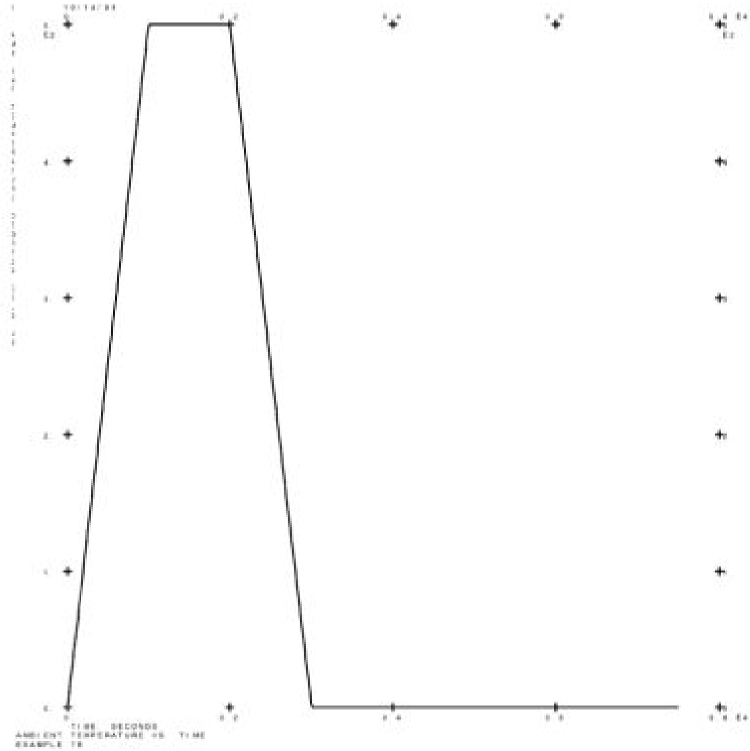


Figure 5-32. Ambient Temperature versus Time

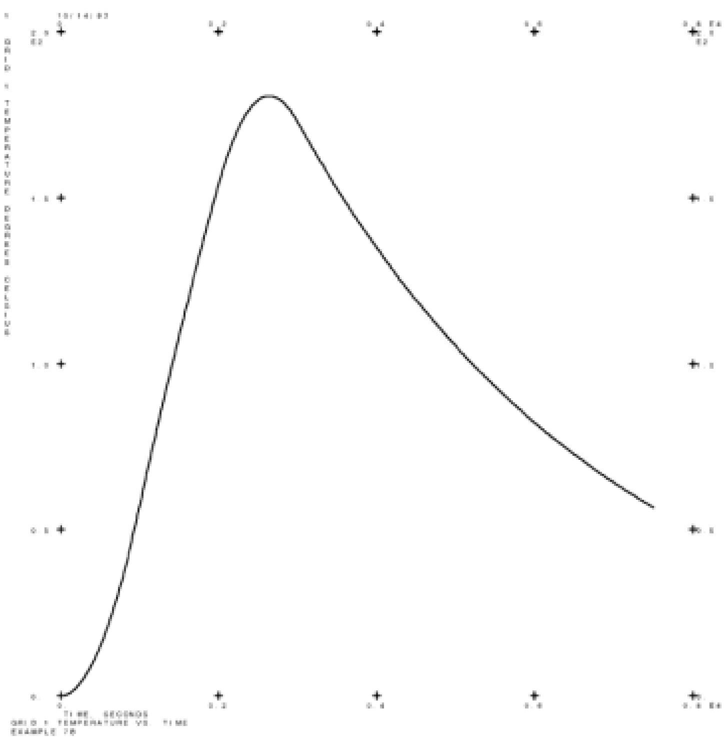


Figure 5-33. Grid 1 Temperature versus Time

7c – Time Varying Loads

Demonstrated Principle

- Time-Varying Loads

Discussion

As discussed in regard to steady state analysis (see "Thermal Loads"), internal heat generation is considered to be a thermal load and as such is Case Control selectable. In a transient analysis, this allows for using the time loading scheme illustrated in the previous example (see Figure 3). This methodology can be applied to any SID selectable load.

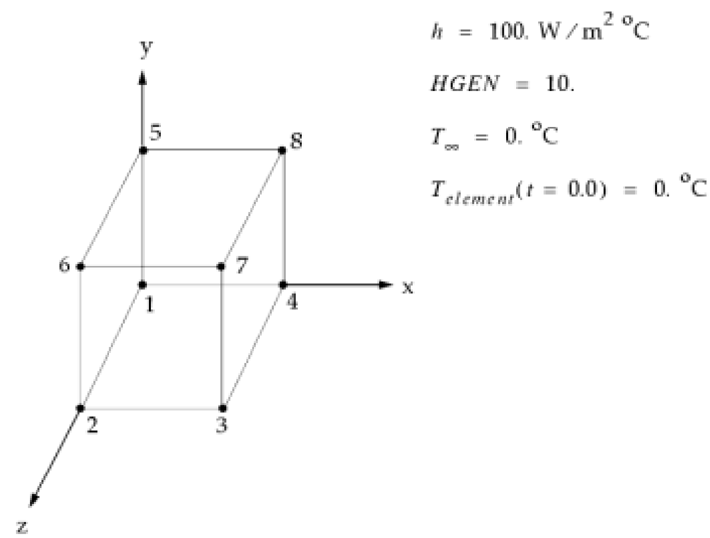


Figure 5-34. Example 7c

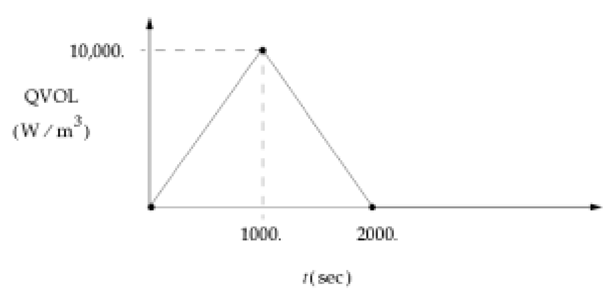


Figure 5-35. Internal Heat Generation Rate versus Time

The NX Nastran input file is shown in Table 1.

Table 5-43. Example 7c Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 7C
ANALYSIS = HEAT
THERMAL = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
TSTEPNL,100,5900,1.0,1
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$
 CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,896.0,2707.0,100.0,,10.0
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
TLOAD1,200,300,,,400
TABLED1,400,,,,,,,,+TBD1
+TBD1,0.0,0.0,1000.0,1.0,2000.0,0.0,3000.0,0.0,+TBD2
+TBD2,ENDT
QVOL,300,10000.0,,1
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,0.0
$
ENDDATA
```

Note

HGEN field on MAT4 is 10.0. It multiplies the QVOL entry.

Results

Figure 3 shows an X-Y plot of grid 1 temperature versus time..

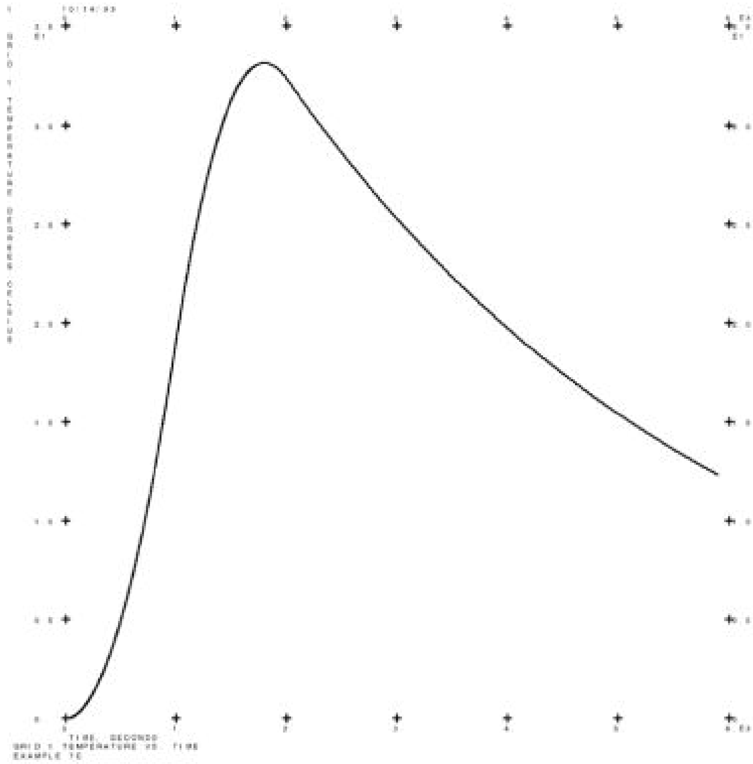


Figure 5-36. Grid 1 Temperature versus Time

7d – Time Varying Heat Transfer Coefficient

Demonstrated Principles

- Specification of Multiple Loads.

Discussion

There are a number of boundary conditions which are not defined as loads (“Thermal Capabilities”) and as a result cannot be made time varying in the same fashion as described in “Example 7c – Time Varying Loads”. In most cases, transient behavior can be introduced into the boundary condition (convection or radiation) through specification of a control node. The control node can be a simple free grid point, an SPOINT, or an active degree of freedom in the system. In this example we drive the value of the control node explicitly via TEMPBC and related TLOAD1 and TABLED1 statements to produce a free convection heat transfer coefficient which varies with time. We also demonstrate the use of the DLOAD statement in the Bulk Data for applying more than one TLOADi in the same analysis.

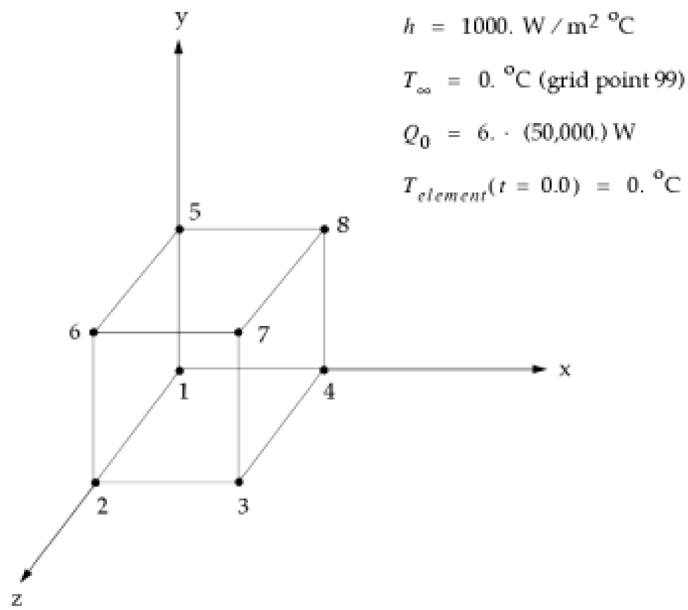


Figure 5-37. Example 7d

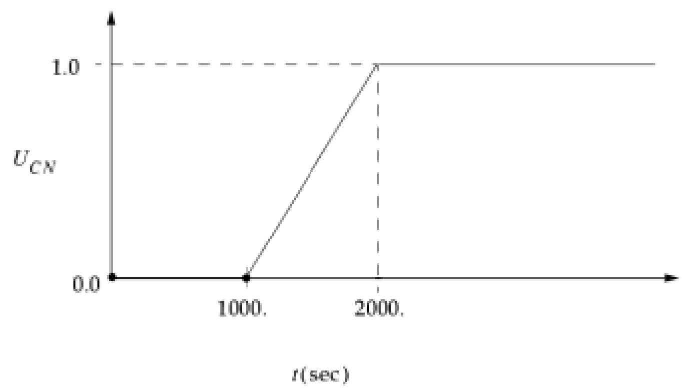


Figure 5-38. Control Node (Grid Point 50) for Free Convection Boundary Condition

The NX Nastran input file is shown in Table 1.

Table 5-44. Example 7d Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 7D
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
XTITLE = TIME, SECONDS
YTITLE = GRID 50 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 50 TEMPERATURE VS. TIME
XYPLOT TEMP/50(T1)
BEGIN BULK
TSTEPNL,100,490,10.0,,,,U
$GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,50,,50.0,50.0,50.0
GRID,99,,99.0,99.0,99.0

$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,896.0,2707.0,1000.0
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,50,99
CONV,20,35,,50,99
CONV,30,35,,50,99
CONV,40,35,,50,99
CONV,50,35,,50,99
CONV,60,35,,50,99
PCONV,35,15,0,0.0
$
DLOAD,200,1.0,1.0,300,1.0,400
$
TLOAD1,300,500,,,700
TABLED1,700,,,,,,,,+TBD700
+TBD700,0.0,1.0,1000.0,1.0,ENDT
QBDY3,500,50000.0,,10,THRU,60,BY,10
$
TLOAD1,400,600,,,800
TABLED1,800,,,,,,,,+TBD800
+TBD800,0.0,0.0,1000.0,0.0,2000.0,1.0,5000.0,1.0,+TBD801
```

```
+TBD801,ENDT
TEMPBC,600,TRAN,1.0,50
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,0.0
$
ENDDATA
```

Results

An NX Nastran X-Y plot of the control node, grid point 50, temperature versus time is shown in Figure 3. An NX Nastran X-Y plot of grid point 1 temperature versus time is shown in Figure 4.

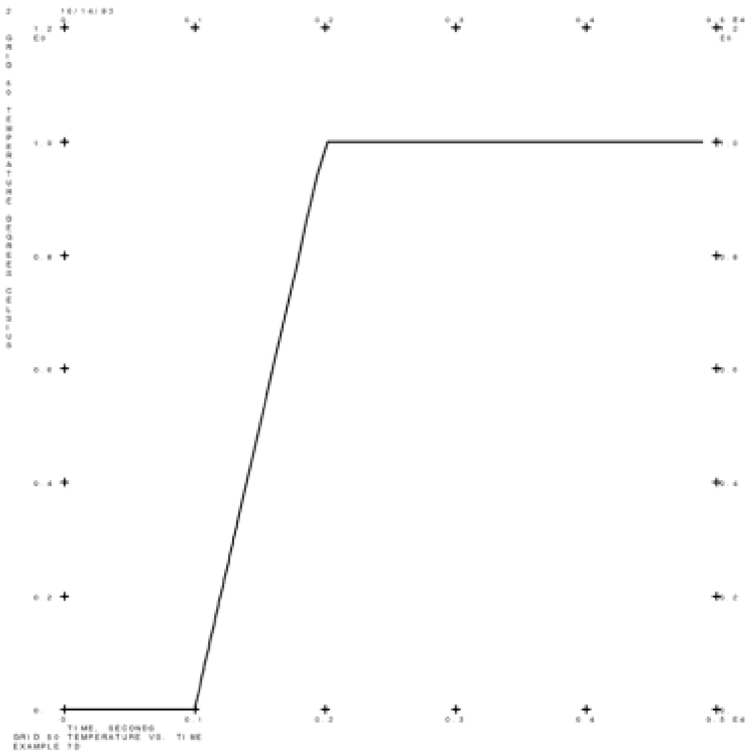


Figure 5-39. Grid 50 Temperature versus Time

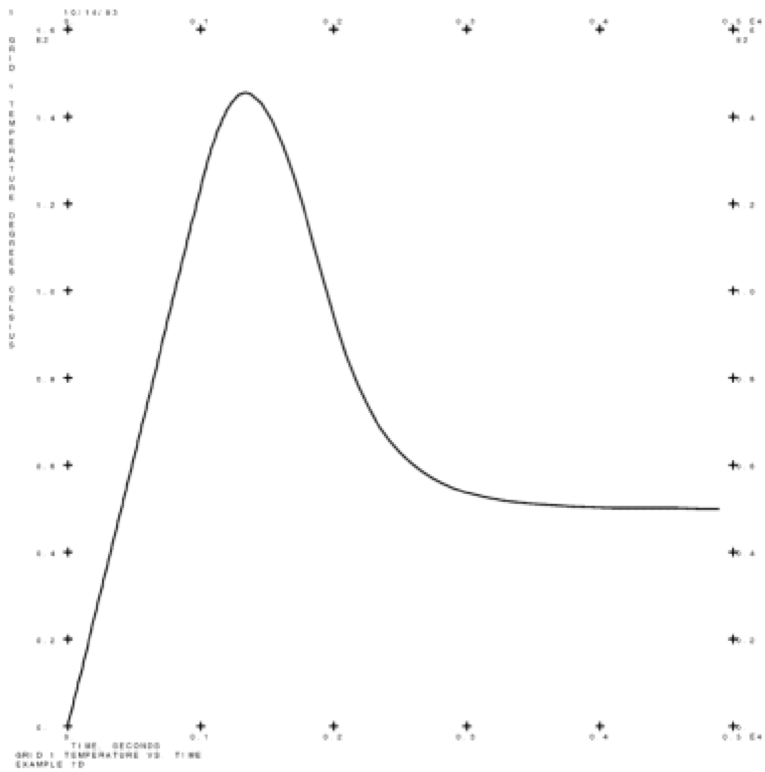


Figure 5-40. Grid 1 Temperature versus Time Examples

7e – Temperature Dependent Free Convection Heat Transfer Coefficient

Demonstrated Principle

- Temperature Dependent Heat Transfer Coefficient

Discussion

The extension of the temperature dependent free convection heat transfer coefficient is demonstrated for transient analysis. The user specification of this capability is treated the same as in the steady state case, but due to the evolutionary nature of the transient problem, the heat transfer coefficient becomes an implicit function of time.

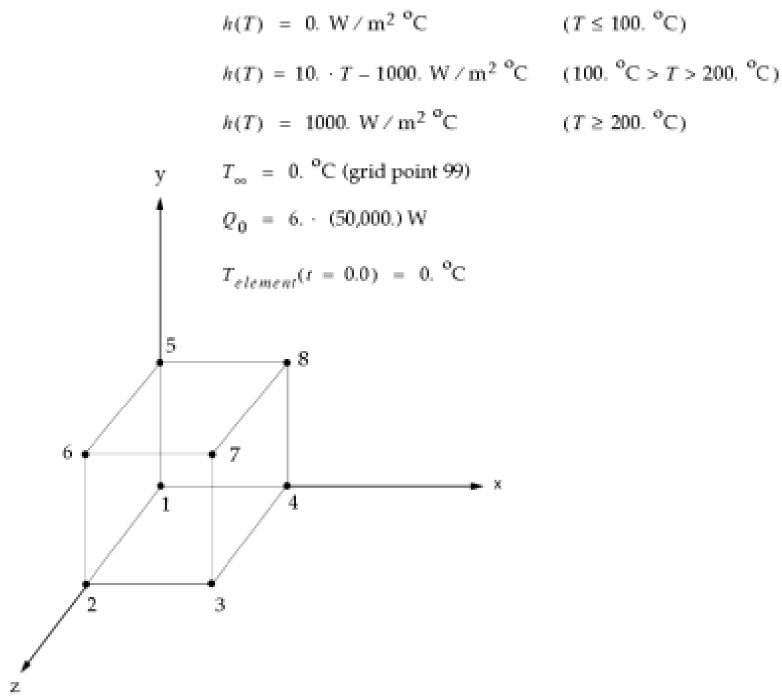


Figure 5-41. Example 7e

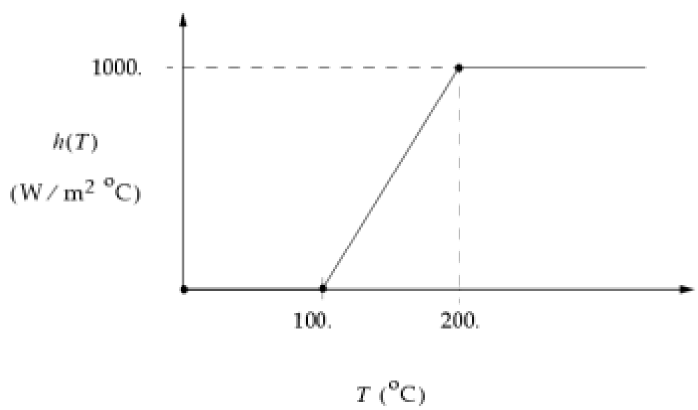


Figure 5-42. h(T) versus T

The NX Nastran input file is shown in Table 1.

Table 5-45. Example 7e Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 7E
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
DLOAD = 300
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
TSTEPNL,100,390,10.0,1
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,1.0
GRID,3,,1.0,0.0,1.0
GRID,4,,1.0,0.0,0.0
GRID,5,,0.0,1.0,0.0
GRID,6,,0.0,1.0,1.0
GRID,7,,1.0,1.0,1.0
GRID,8,,1.0,1.0,0.0
GRID,99,,99.0,99.0,99.0
$

CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,204.0,896.0,2707.0,1000.0
MATT4,15,,,,40
TABLEM2,40,0.0,,,,,,,+TBM1
+TBM1,0.0,0.0,100.0,0.0,200.0,1.0,1000.0,1.0,+TBM2
+TBM2,ENDT
$

CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$

CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
```

```
TLOAD1,300,500,,,700
TABLED1,700,,,,,,,,+TBD700
+TBD700,0.0,1.0,1000.0,1.0,ENDT
QBDY3,500,50000.0,,10,THRU,60,BY,10
$
SPC,10,99,,0.0
TEMP,20,99,0.0
TEMPD,20,0.0
$
ENDDATA
```

Results

An NX Nastran X-Y plot of grid 1 temperature versus time is shown in Figure 3.

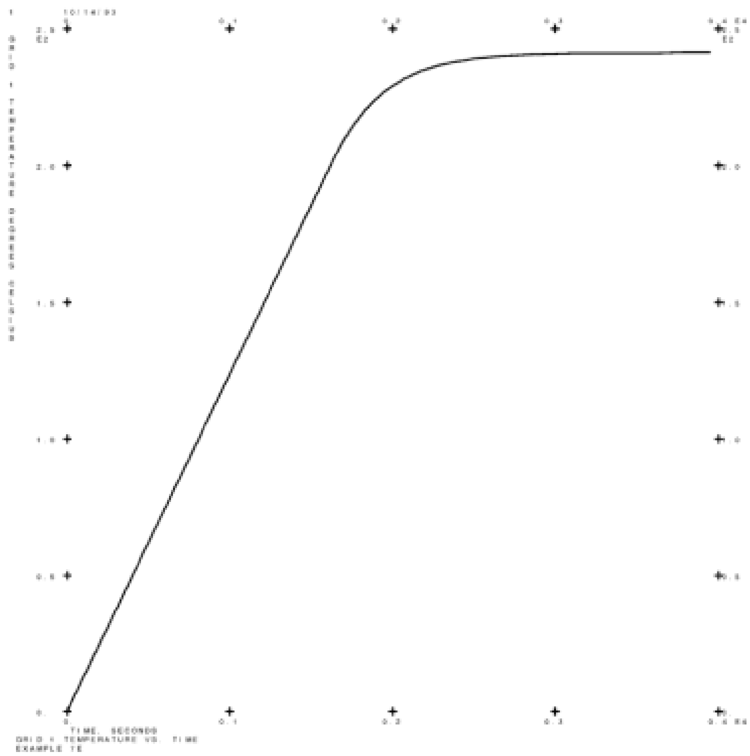


Figure 5-43. Grid 1 Temperature versus Time

7f – Phase Change

Demonstrated Principles

- Capturing Latent Heat Effects
- Appropriate Convergence Criteria
- Numerical Damping
- Consistent Units

- Enthalpy

Discussion

Latent heat effects can be captured by specifying phase change material properties on the MAT4 Bulk Data entry. The information required includes the latent heat and a finite temperature range over which the phase change is to occur. For pure materials, this range can physically be quite small whereas for solutions or alloys the range can be quite large. Numerically, the wider the range the better. It is not recommended to make this range less than a few degrees.

Phase change involves the release of considerable amounts of heat while the temperature remains nearly constant. In this case, it is beneficial to consider the change in enthalpy as illustrated in Figure 1. The calculated enthalpies are available with the use of DIAG 50, 51, or by the Case Control command ENTHALPY = ALL. The solution sequence for the phase change specific algorithm is discussed in "Method of Solution".

In the cases that follow, the first variation illustrates freezing. Variation 2 demonstrates melting.

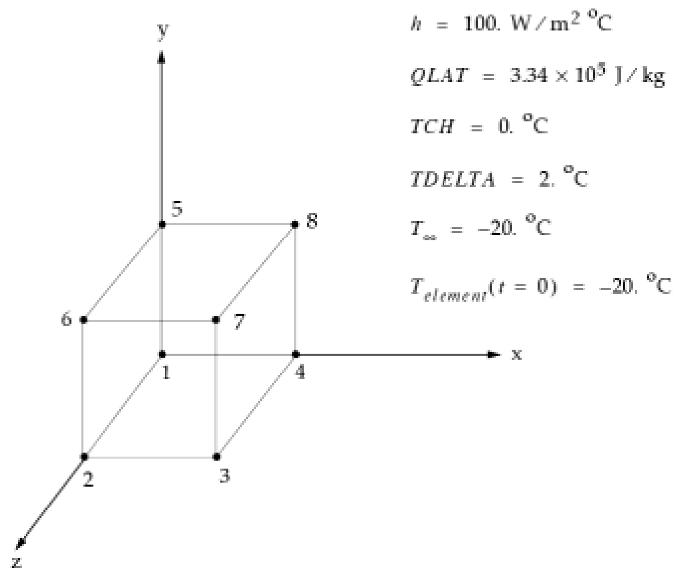


Figure 5-44. Example 7f1 Variation 1

The NX Nastran input file is shown in Table 1.

Table 5-46. Example 7f1 Variation 1 Input File

```
ID NX NASTRAN V3
SOL 159
DIAG 51
TIME 10
CEND
$
TITLE = EXAMPLE 7F1
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
ENTHALPY = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS

YTITLE = TEMPERATURE DEGREES CELSIUS
TCURVE = TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,NDAMP,0.1
TSTEPNL,100,980,5.0,1,,,,,+TSTP
+TSTP,0.001
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,0.1
GRID,3,,0.1,0.0,0.1
GRID,4,,0.1,0.0,0.0
GRID,5,,0.0,0.1,0.0
GRID,6,,0.0,0.1,0.1
GRID,7,,0.1,0.1,0.1
GRID,8,,0.1,0.1,0.0
GRID,99,,99.0,99.0,99.0
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,0.569,4217.0,1000.0,100.0,,,0.0,+MAT4
+MAT4,0.0,2.0,3.34E5
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
SPC,10,99,,-20.0
TEMP,20,99,-20.0
TEMPD,20,20.0
$
ENDDATA
```

Note

NDAMP provides numerical damping for the phase change phenomenon.

Results – Variation 1

An NX Nastran X-Y plot of temperature versus time is shown in Figure 2.

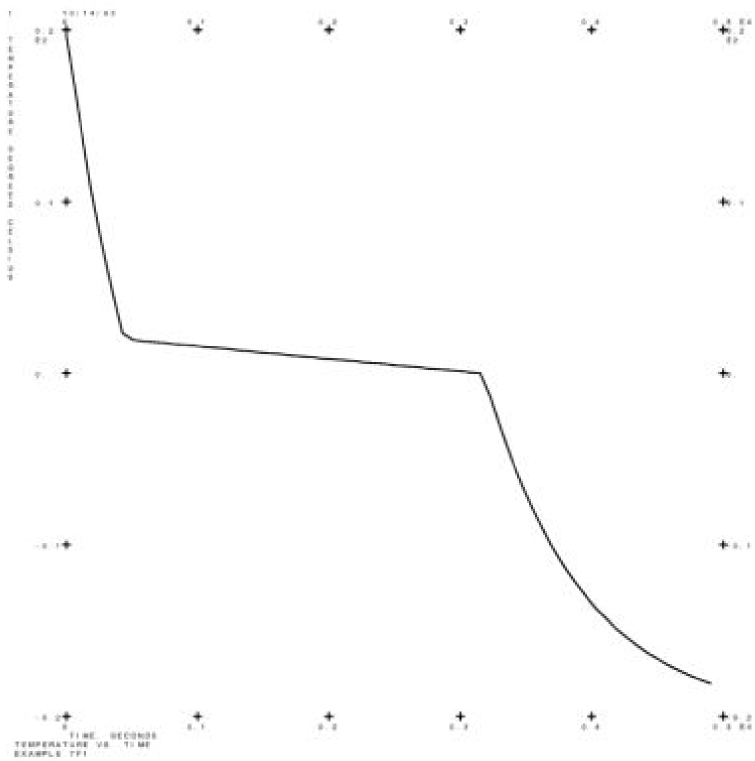


Figure 5-45. Temperature versus Time (Variation 1)

Variation 2

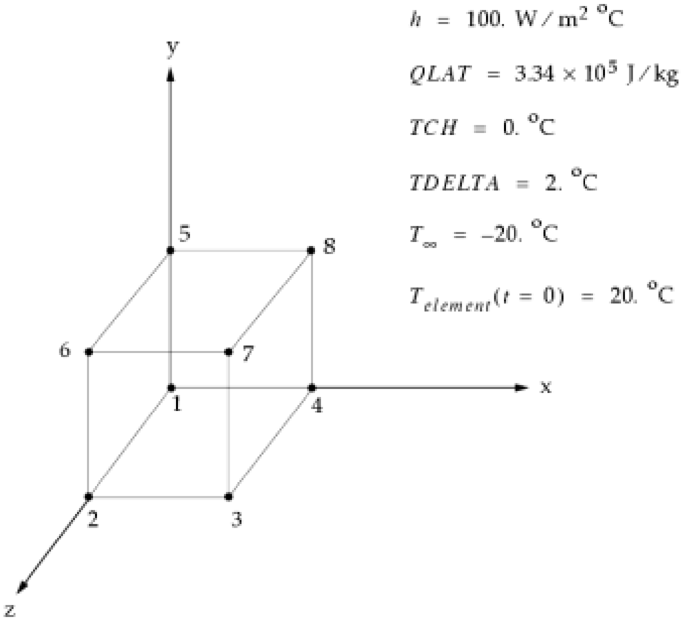


Figure 5-46. Example 7f2 Variation 2

Table 5-47. Example 7f2 Variation 2 Input File

```
ID NX NASTRAN V3
SOL 159
DIAG 51
TIME 10
CEND
$
TITLE = EXAMPLE 7F2
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = TEMPERATURE DEGREES CELSIUS
TCURVE = TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,NDAMP,0.1
TSTEPNL,100,980,5.0,1,,,,U,+TSTP
+TSTP,0.001
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.0,0.0,0.1
GRID,3,,0.1,0.0,0.1
GRID,4,,0.1,0.0,0.0
GRID,5,,0.0,0.1,0.0
GRID,6,,0.0,0.1,0.1
GRID,7,,0.1,0.1,0.1
GRID,8,,0.1,0.1,0.0
GRID,99,,99.0,99.0,99.0
```

```
$
CHEXA,1,5,1,2,3,4,5,6,+CHX1
+CHX1,7,8
PSOLID,5,15
MAT4,15,1.88,2040.0,920.0,100.0,,,0.0,+MAT4
+MAT4,0.0,2.0,3.34E5
$
CHBDYE,10,1,1
CHBDYE,20,1,2
CHBDYE,30,1,3
CHBDYE,40,1,4
CHBDYE,50,1,5
CHBDYE,60,1,6
$
CONV,10,35,,,99
CONV,20,35,,,99
CONV,30,35,,,99
CONV,40,35,,,99
CONV,50,35,,,99
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
SPC,10,99,,20.0
TEMP,20,99,20.0
TEMPD,20,-20.0
$
ENDDATA
```

Results - Variation 2

An NX Nastran X-Y plot of temperature versus time is shown in Figure 4.

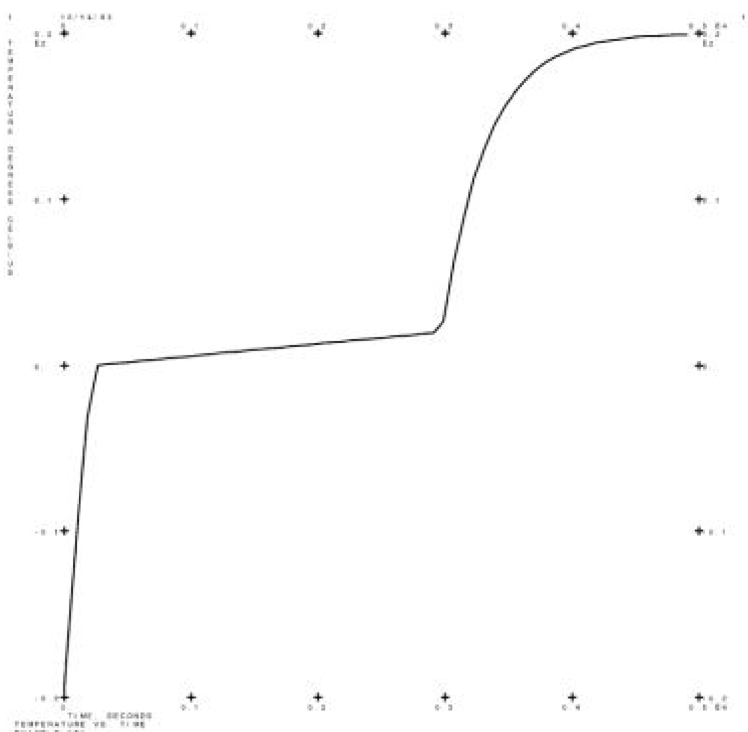


Figure 5-47. Temperature versus Time (Variation 2)

8 – Temperature Boundary Conditions in Transient Analyses

Demonstrated Principles

- SPC for Transient Analysis
- TEMPBC for Transient Analysis
- SLOAD and CELASi for Transient Analysis
- Nodal Lumped Heat Capacitance
- POINT type CHBDYi

Discussion

A radiative equilibrium analysis is used to demonstrate different methods of temperature specification for transient analyses. As discussed in “Thermal Capabilities”, an SPC is used when the temperature is to remain constant for the duration of the analysis (Variation 1). To vary the temperature during the analysis, you can use either:

- a TEMPBC of type TRAN, or
- a CELASi with applied SLOAD

When a TEMPBC is implemented (Variation 2), a thermal conductivity matrix element of magnitude of 1.0E+10 is imposed internally in the form of a penalty method. For many problems this will be adequate for maintaining the grid point temperature while facilitating convergence. In some cases, however, the size of this conductance can be overwhelming with respect to those of the rest of the model. In such a case, it may be difficult to satisfy the convergence criteria due to the dominance of one matrix conductance value.

Alternatively, you can also use a CELASi element and specify a consistent conductance or stiffness value for the model in question (Variation 3). The QHBDY power level can be adjusted to maintain the desired temperature.

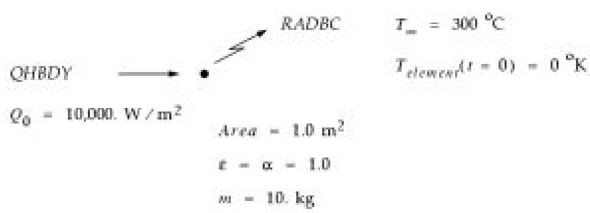


Figure 5-48. Example 8

The NX Nastran input file is shown in Table 1.

Table 5-48. Example 8a Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 8A
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL  = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE KELVIN
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-8
TSTEPNL,100,1500,1.0,1

$
GRID,1,,0.0,0.0,0.0
GRID,99,,99.0,99.0,99.0
$
CDAMP5,1,5,1
PDAMP5,5,15,10.0
MAT4,15,204.0,896.0
$
CHBDYP,10,25,POINT,,,1,,,+CHP10
+CHP10,45,,,,1.0,0.0,0.0
PHBDY,25,1.0
$
RADM,45,1.0,1.0
RADBC,99,1.0,,10
$
TLOAD1,200,300,,,400
TABLED1,400,,,,,,,,+TBD400
+TBD400,0.0,1.0,1000.0,1.0,ENDT
QHBDY,300,POINT,10000.0,1.0,1
$
SPC,10,99,,300.0
TEMP,20,99,300.0
TEMPD,20,0.0
$
ENDDATA
```

An NX Nastran X-Y plot of grid 1 temperature versus time is shown in Figure 2.

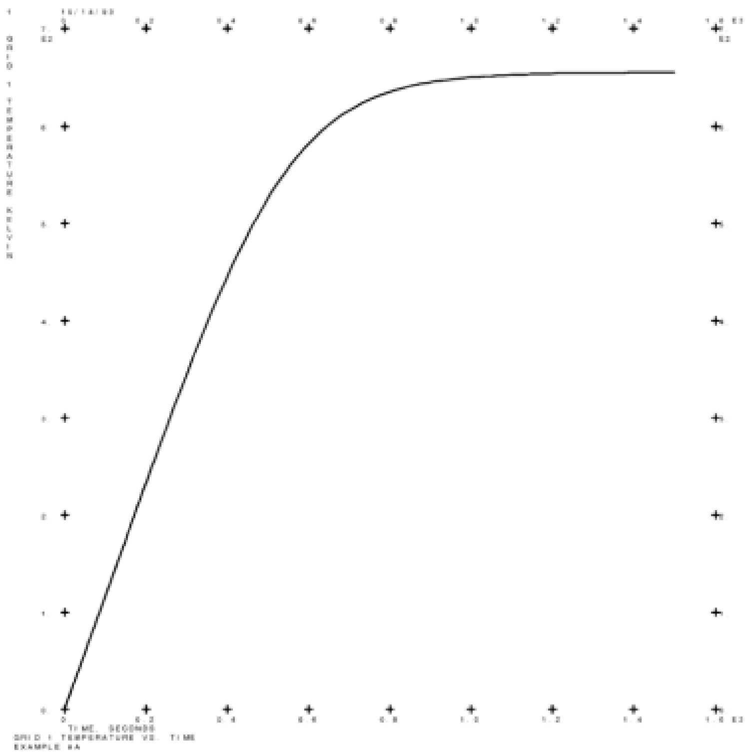


Figure 5-49. Grid 1 Temperature versus Time

Table 5-49. Example 8b Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 8B
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
IC = 20
TSTEPNL  = 100
DLOAD = 700
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE KELVIN
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-8
TSTEPNL,100,1500,1.0,1,,,,U
```

```
$
GRID,1,,0.0,0.0,0.0
GRID,99,,99.0,99.0,99.0
$
CDAMP5,1,5,1
PDAMP5,5,15,10.0
MAT4,15,204.0,896.0
$
CHBDYP,10,25,POINT,,,1,,,+CHP10
+CHP10,45,,,,1.0,0.0,0.0
PHBDY,25,1.0
$
RADM,45,1.0,1.0
RADBC,99,1.0,,10
$
DLOAD,700,1.0,1.0,200,1.0,500
TABLED1,400,,,,,,,,+TBD400
+TBD400,0.0,1.0,1000.0,1.0,ENDT
$
TLOAD1,200,300,,,400
QHBDY,300,POINT,10000.0,1.0,1
$
TLOAD1,500,600,,,400
TEMPBC,600,TRAN,300.0,99
TEMP,20,99,300.0
TEMPD,20,0.0
$
ENDDATA
```

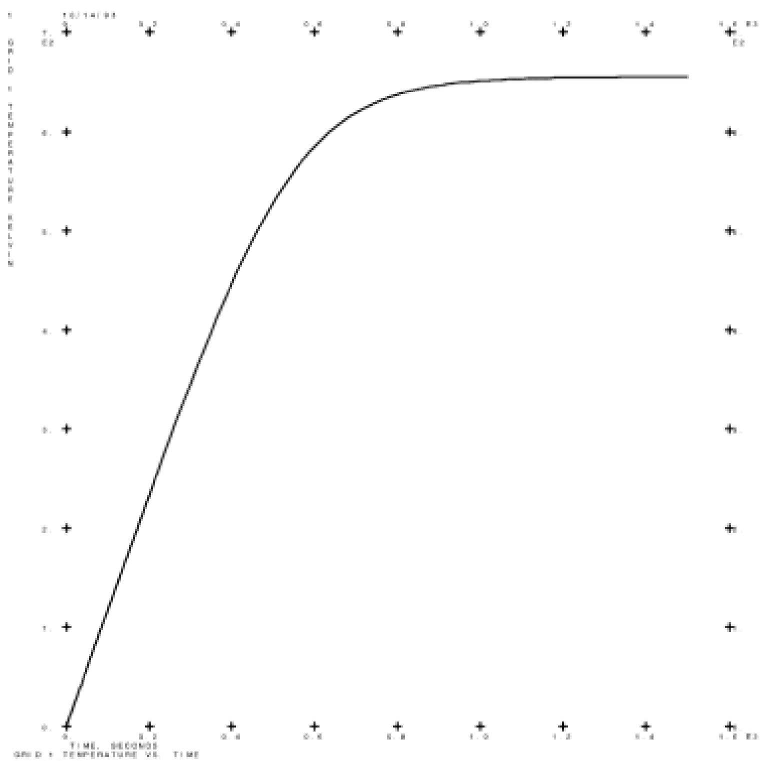


Figure 5-50. Grid 1 Temperature versus Time

Table 5-50. Example 8c Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 8C
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
IC = 20
TSTEPNL  = 100
DLOAD = 700
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE KELVIN
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-8
TSTEPNL,100,1500,1.0,1
$
GRID,1,,0.0,0.0,0.0
GRID,99,,99.0,99.0,99.0

$
CDAMP5,1,5,1
PDAMP5,5,15,10.0
MAT4,15,204.0,896.0
$
CHBDYP,10,25,POINT,,,1,,,+CHP10
+CHP10,45,,,,1.0,0.0,0.0
PHBDY,25,1.0
$
RADM,45,1.0,1.0
RADBC,99,1.0,,10
$
DLOAD,700,1.0,1.0,200,1.0,500
TABLED1,400,,,,,,,,+TBD400
+TBD400,0.0,1.0,1000.0,1.0,ENDT
$
TLOAD1,200,300,,,400
QHBDY,300,POINT,10000.0,1.0,1
$
TLOAD1,500,600,,,400
CELAS2,999,1.0E5,99,1
SLOAD,600,99,300.0E5
TEMP,20,99,300.0
TEMPD,20,0.0
$
ENDDATA
```

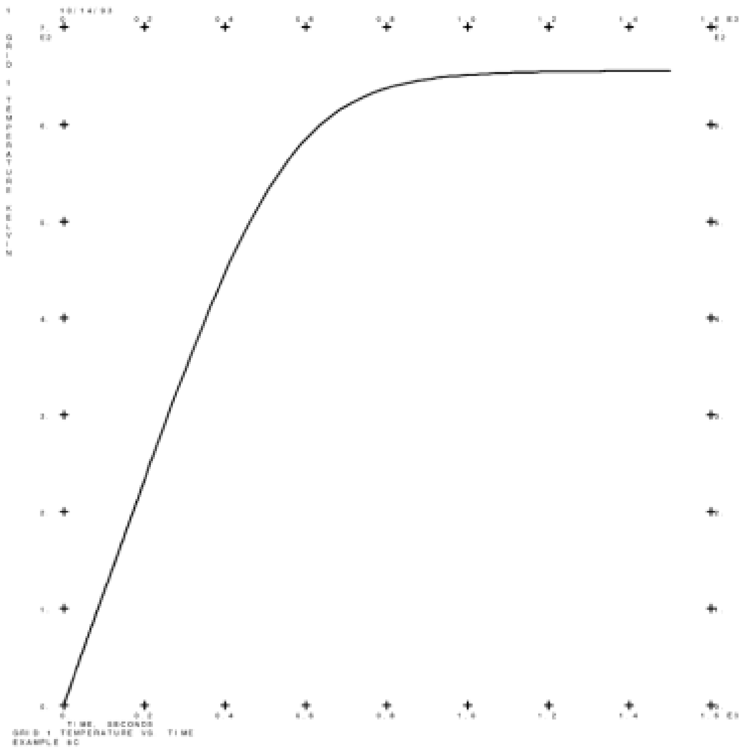


Figure 5-51. Grid 1 Temperature versus Time

9a – Diurnal Thermal Cycles

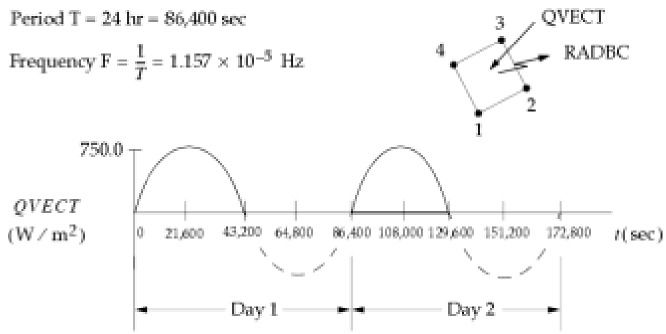
Demonstrated Principles

- Diurnal Heat Loads
- Multiple Loads / Multiple CHBDYi's

Discussion

A diurnal heat transfer analysis is performed over a two day cycle. The TLOAD2 Bulk Data entry is used to specify the load function (QVECT) in convenient sinusoidal format. A radiation boundary condition provides the heat loss mechanism to an ambient environment at 300 degrees. In Example 9a, the absorptivity and emissivity are constant and the loading is a function of time based on the load magnitude which reflects a projected area without treating the QVECT as a vector load.

In "Example 9b – Diurnal Thermal Cycles", the variation of absorptivity with respect to time is added to the problem.



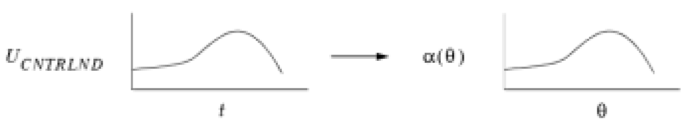
	Day 1	Day 2
Sunrise	t = 0	t = 86,400
Noon	t = 21,600	t = 108,000
Sunset	t = 43,200	t = 129,600
Night	43,200 < t < 86,400	129,600 < t < 172,800

Figure 5-52. Example 9a

- Sun heating aluminum plate over two days.
- Solar flux = 750 W/m2 at noon. Plate is one square meter and 0.005 meters thick. Ambient temperature is 300°K.
- Solar flux magnitude varies sinusoidally with an amplitude of 750.0 W/m2, and a period of one day.
- CHBDYG 10 absorbs heat for the first day.
- CHBDYG 20 absorbs heat for the second day.
- CHBDYG 30 radiates heat both days.

Example 9b only:

- Grid 50 is the control node on the QVECT entry. It is forced to vary with time as absorptivity (a) varies with the “attack” angle of the sun, i.e.,



- So the value of $U_{CNTRLND}$ equals α(θ) at any given time (or any given angle: 180°→12 hr = 43,200 sec, 1°→240 sec).
- Absorptivity is set to 1.0 on the RADM card so that $U_{CNTRLND}$ will act as absorptivity:

$$P_{in} = \underbrace{\alpha}_{1.0}[\vec{e}(t) \cdot \vec{n}]\ F(t-\tau)\ Q_0\ \underbrace{U_{CNTRLND}}_{\alpha(\theta)}$$

- $$P_{in} = \alpha[\vec{e}(t) \cdot \vec{n}]\ F(t-\tau)\ Q_0\ \alpha(\theta)$$
- Ex9a. – α= constant
- Ex9b. – α= $f(\theta)$

The NX Nastran input file is shown in Table 1.

Table 5-51. Example 9a Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 9A
ANALYSIS = HEAT
THERMAL = ALL
FLUX = ALL
SPCF = ALL
OLOAD = ALL
SPC = 10
IC = 20
TSTEPNL = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = PLATE TEMPERATURE KELVIN
TCURVE = PLATE TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-08
TSTEPNL,100,1728,100.0,1,,,,U

QVECT,2000,750.0,,,0.0,0.0,-1.0,,+QVCT2
+QVCT2,20
RADM,45,0.6,0.6
RADBC,99,1.0,,30
$
SPC,10,99,,300.0
TEMPD,20,300.0
$
ENDDATA
```

Results

An NX Nastran X-Y plot of plate temperature versus time is shown in Figure 2.

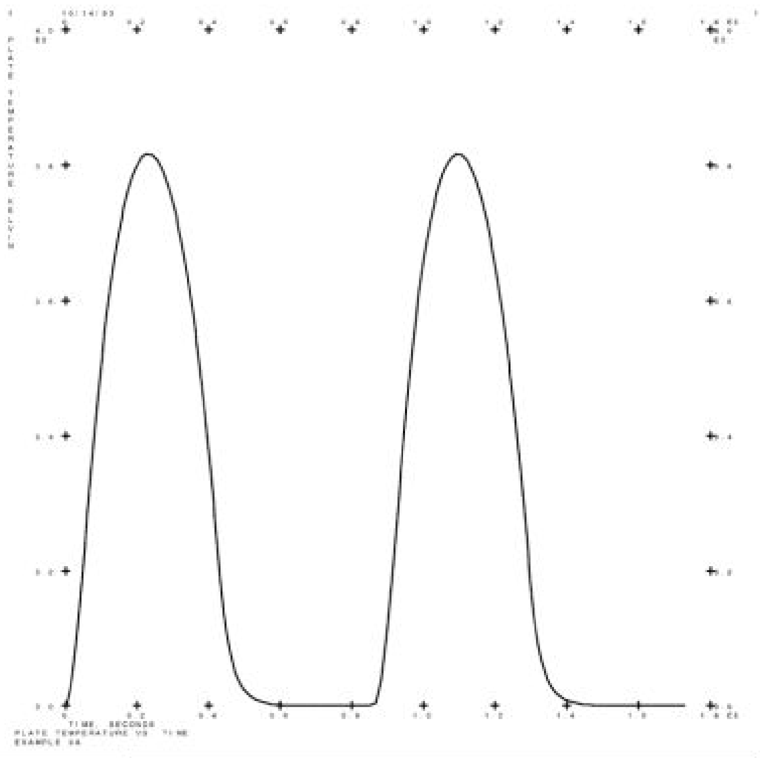


Figure 5-53. Plate Temperature versus Time

9b – Diurnal Thermal Cycles

Demonstrated Principles

- Diurnal Heat Loads
- Multiple Loads / Multiple CHBDYi's
- Control Node for Directionally Dependent Radiation Surface Properties

Discussion

The loading pattern is substantially unchanged from the previous example; however, the effect of variation of surface absorptivity with angle of incident solar radiation is taken into account implicitly via the control node. As in the previous example, we provide independent CHBDY surface elements for each load and boundary condition specification resulting in a total of three surface elements attached to the conduction element. This can sometimes be convenient for postprocessing if we wish to isolate applied load segments of the same type.

The NX Nastran input file is shown in Table 1.

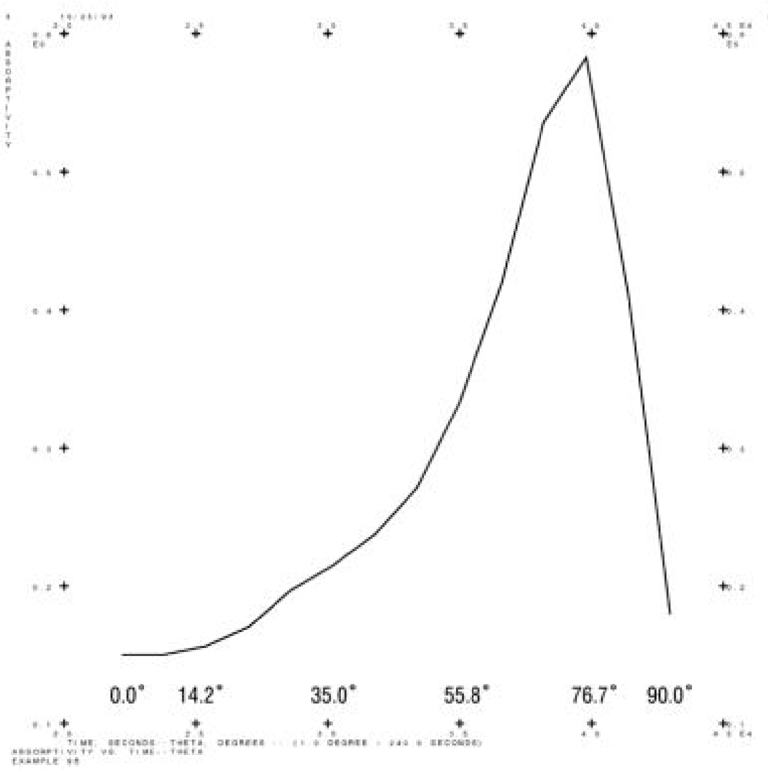
Table 5-52. Example 9b Input File

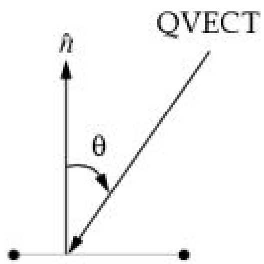
```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 9B
ANALYSIS = HEAT
THERMAL = ALL
SPC = 10
IC = 20
TSTEPNL = 100
DLOAD = 200
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = PLATE TEMPERATURE KELVIN
TCURVE = PLATE TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
XTITLE = TIME, SECONDS--THETA, DEGREES -- (1.0 DEGREE = 240.0 SECONDS)
YTITLE = ABSORPTIVITY
TCURVE = ABSORPTIVITY VS. TIME--THETA
XYPLOT TEMP/50(T1)
XTITLE = TIME, SECONDS--THETA, DEGREES -- (1.0 DEGREE = 240.0 SECONDS)
YTITLE = ABSORPTIVITY
TCURVE = ABSORPTIVITY VS. TIME--THETA
XMIN = 21600.0
XMAX = 43200.0
XYPLOT TEMP/50(T1)
BEGIN BULK
PARAM,TABS,0.0
PARAM,SIGMA,5.67E-08
TSTEPNL,100,1728,100.0,1,,,,U
$
GRID,1,,0.0,0.0,0.0
GRID,2,,1.0,0.0,0.0
GRID,3,,1.0,1.0,0.0
GRID,4,,0.0,1.0,0.0
GRID,50,,50.0,50.0,50.0
GRID,99,,99.0,99.0,99.0
$
CQUAD4,1,5,1,2,3,4
PSHELL,5,15,0.005
MAT4,15,204.0,896.0,2707.0
RADM,45,1.0,0.6
RADM,46,0.6,0.6
$
CHBDYG,10,,AREA4,,,45,,,+CHG10
+CHG10,1,2,3,4
CHBDYG,20,,AREA4,,,45,,,+CHG20
+CHG20,1,2,3,4
CHBDYG,30,,AREA4,,,46,,,+CHG30
+CHG30,4,3,2,1
DLOAD,200,1.0,1.0,300,1.0,400,1.0,500
TLOAD2,300,1000,,,0.0,43200.0,1.157E-5,-90.0,+TLD300
+TLD300,0.0,0.0
TLOAD2,400,2000,,,86400.0,129600.0,1.157E-5,-90.0,+TLD400
+TLD400,0.0,0.0
QVECT,1000,750.0,,,0.0,0.0,-1.0,50,+QVCT1
+QVCT1,10
QVECT,2000,750.0,,,0.0,0.0,-1.0,50,+QVCT2
+QVCT2,20
RADBC,99,1.0,,30
$
TLOAD1,500,600,,,700
TABLED1,700,,,,,,,,+TBD1
+TBD1,0.0,0.15,2400.0,0.50,3600.0,0.60,4800.0,0.55,+TBD2
+TBD2,7200.0,0.375,9600.0,0.275,12000.0,0.225,14400.0,0.20,+TBD3
+TBD3,16800.0,0.16,19200.0,0.15,21600.0,0.15,24000.0,0.15,+TBD4
+TBD4,26400.0,0.16,28800.0,0.20,31200.0,0.225,33600.0,0.275,+TBD5
```

```
+TBD5,36000.0,0.375,38400.0,0.55,39600.0,0.60,40800.0,0.50,+TBD6
+TBD6,43200.0,0.15,86400.0,0.15,88800.0,0.50,90000.0,0.60,+TBD7
+TBD7,91200.0,0.55,93600.0,0.375,96000.0,0.275,98400.0,0.225,+TBD8
+TBD8,100800.0,0.20,103200.0,0.16,105600.0,0.15,108000.0,0.15,+TBD9
+TBD9,110400.0,0.15,112800.0,0.16,115200.0,0.20,117600.0,0.225,+TBD10
+TBD10,120000.0,0.275,122400.0,0.375,124800.0,0.55,126000.0,0.60,+TBD11
+TBD11,127200.0,0.50,129600.0,0.15,172800.0,0.15,ENDT
TEMPBC,600,TRAN,1.0,50
$
SPC,10,99,,300.0
TEMP,20,50,0.15
TEMPD,20,300.0
$
ENDDATA
```

Results

NX Nastran X-Y plots showing absorptivity versus time are shown in Figure 1 and Figure 2. Plate temperature versus time is shown in Figure 3.





$\alpha(\theta)$ **versus** θ

Figure 5-54.

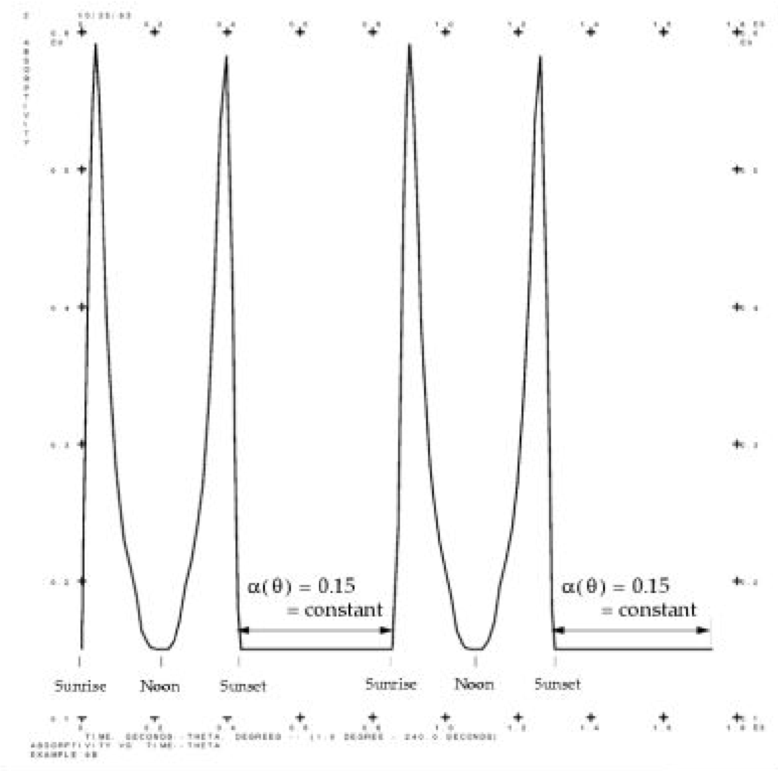


Figure 5-55. $\alpha(\theta)$ **versus** θ

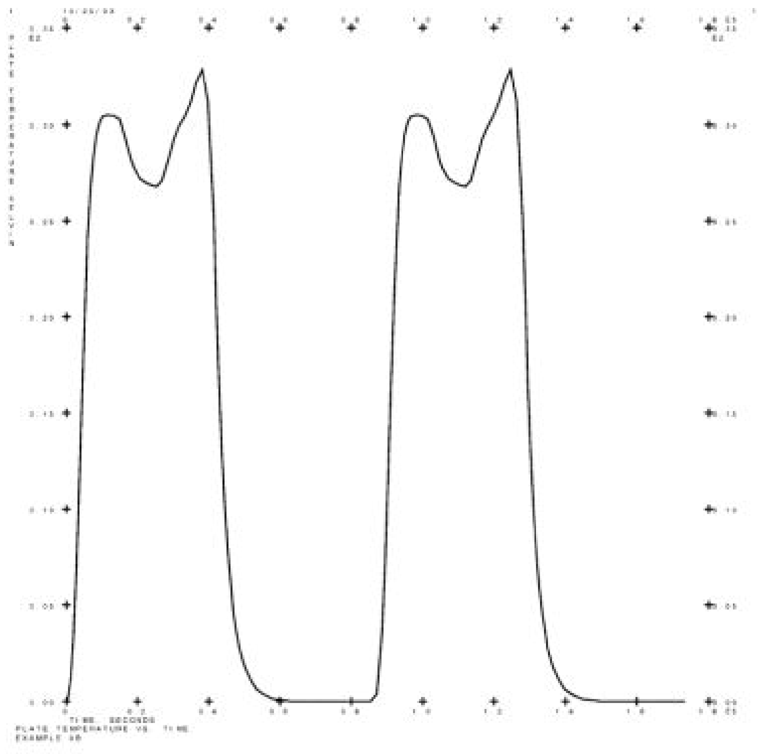


Figure 5-56. Plate Temperature versus Time

10 – Thermostat Control

Demonstrated Principles

- NOLINs and MPCs
- Thermostat Control

Discussion

A thermostat is modeled using the nonlinear transient forcing function (NOLIN3) as a heating element and the multi-point constraint (MPC) relationship to provide the thermostat connections. One end of the rod element structure has the thermocouple attached to it and is subject to convective losses to the ambient environment at 0.0 ×C. When this local temperature drops below 100.0 ×C, heating occurs at the opposite end of the structure at a constant rate. Conversely, when the thermocouple temperature exceeds 100.0 ×C, the heat load is removed. There is an inherent delay in this system associated with the distance between the thermocouple and the point of application of the heat load as well as the delay generated as a result of the thermal diffusivity of the material.

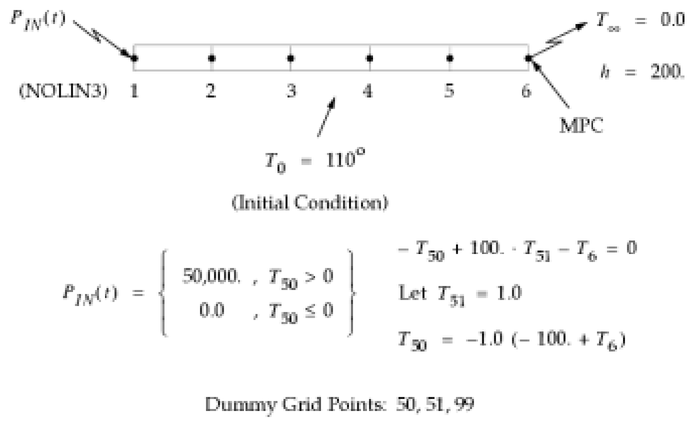


Figure 5-57. Example 10

The NX Nastran input file is shown in Table 1.

Table 5-53. Example 10 Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 10
ANALYSIS = HEAT
THERMAL = ALL
SPC = 10
IC = 20
MPC = 30
TSTEPNL  = 100
NONLINEAR = 300
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = GRID 1 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 1 TEMPERATURE VS. TIME
XYPLOT TEMP/1(T1)
XTITLE = TIME, SECONDS
YTITLE = GRID 6 TEMPERATURE DEGREES CELSIUS
TCURVE = GRID 6 TEMPERATURE VS. TIME
XYPLOT TEMP/6(T1)
BEGIN BULK
TSTEPNL,100,30000,1.0,1
$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,50,,50.0,50.0,50.0
GRID,51,,51.0,51.0,51.0
GRID,99,,99.0,99.0,99.0
$
CROD,1,5,1,2
CROD,2,5,2,3
CROD,3,5,3,4
CROD,4,5,4,5
CROD,5,5,5,6
PROD,5,15,1.0
MAT4,15,204.0,896.0,2707.0,200.0
$
```

```
CHBDYE,60,5,3
$
CONV,60,35,,,99
PCONV,35,15,0,0.0
$
NOLIN3,300,1,,50000.0,50,1,0.0
SPC,10,51,,1.0
SPC,10,99,,0.0
TEMP,20,51,1.0
$
MPC,30,6,,-1.0,50,,-1.0,,+MPC
+MPC,,51,,100.0
$
TEMP,20,99,0.0
TEMP,20,50,-10.0
TEMPD,20,110.0
$
ENDDATA
```

Results

Figure 2 shows an NX Nastran X-Y plot of grid 1 temperature versus time. Figure 3 shows an NX Nastran X-Y plot of grid 6 temperature versus time.

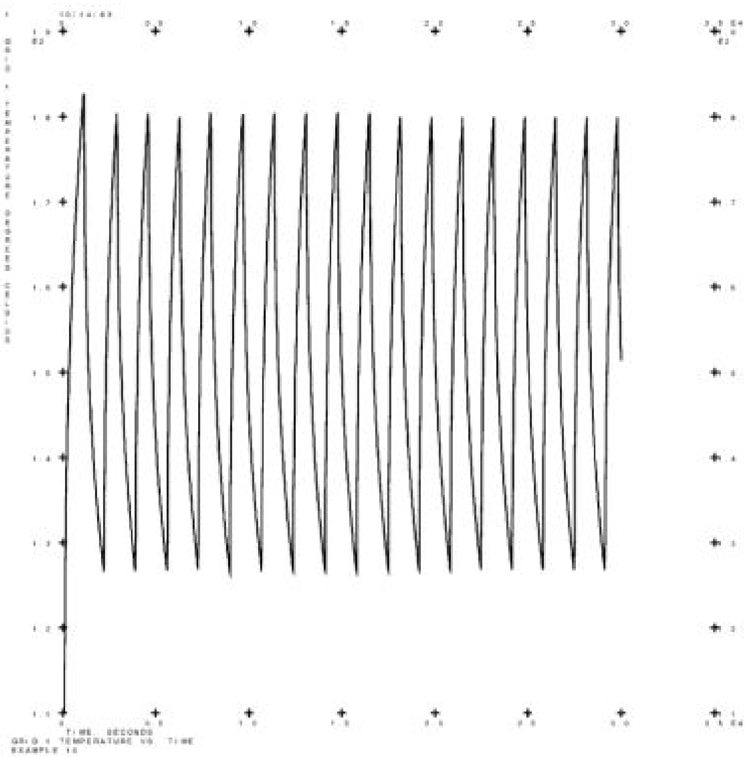


Figure 5-58. Grid 1 Temperature versus Time

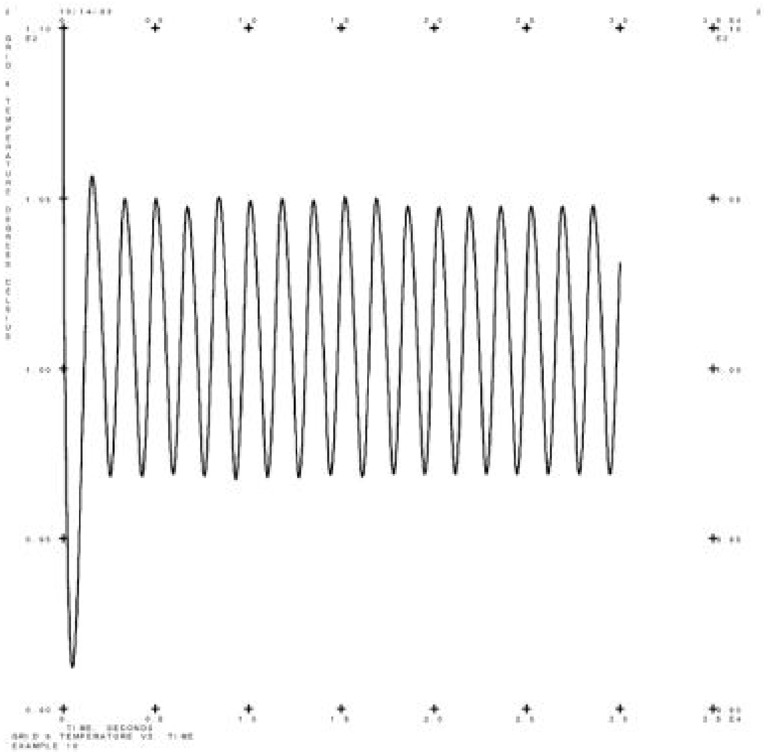


Figure 5-59. Grid 6 Temperature versus Time

11 – Transient Forced Convection

Demonstrated Principle

- Evolving Fluid Transients

Discussion

It may be desirable to consider fluid flow problems from a transient view point. In particular, fluid loops when used in conjunction with the thermostat control described in "Example 10 – Thermostat Control" are most useful in transient analysis. Accurate temporal response requires some user control be exerted over the Courant Number as discussed in "Thermal Capabilities".

In some cases, where steady state convergence is difficult or impossible to achieve, it may prove beneficial to let the transient system evolve toward its long time solution, thereby achieving the steady state equivalent. The transient analysis has inherent damping associated with the heat capacitance and can also utilize numerical damping through the NDAMP parameter. Additionally, loading patterns can be applied gradually with respect to time in an ad hoc load incrementing scheme which may prove more flexible than the load incrementing which is available in the steady state solution sequence.

Fluid Problems – Consistent Units

H20 Example:

$$C_p \sim 4200.\ \mathrm{J/kg\ ^oC}\ (1\mathrm{J} = 1\mathrm{W/sec})$$

$$\rho \sim 1000.\ \mathrm{kg/m^3}$$

$$\mu \sim 10^{-3}\frac{\mathrm{kg}}{\mathrm{m \cdot sec}}$$

$$\dot{m} \sim \mathrm{kg/sec}$$

$$l \sim \mathrm{m}$$

$$\nu \sim \mathrm{m/sec}$$

$$h \sim \mathrm{W/m^2\ ^oC}$$

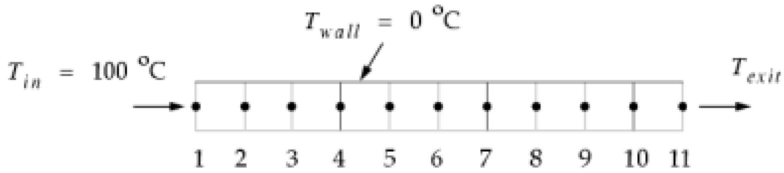
$$k \sim \mathrm{W/m\ ^oC}\ (.65\ \mathrm{W/m\ ^oC})$$

$$\mathrm{Re} = \frac{D\nu\rho}{\mu} \Rightarrow \frac{\mathrm{m \cdot m/sec \cdot kg/m^3}}{\mathrm{kg/m\ sec}} \Rightarrow NONDIMENSIONAL$$

$$\dot{m} = \rho\nu A \Rightarrow \mathrm{kg/m^3 \cdot m/sec \cdot m^2} \Rightarrow \mathrm{kg/s}$$

$$\mathrm{Pr} = \frac{C_p\mu}{k} \Rightarrow \frac{\mathrm{J/kg\ ^oC \cdot kg/m\ sec}}{\mathrm{W/m\ ^oC}} \Rightarrow NONDIMENSIONAL$$

$$Nu = \frac{hx}{k} \Rightarrow \frac{\mathrm{W/m^2\ ^oC \cdot m}}{\mathrm{W/m\ ^oC}} \Rightarrow NONDIMENSIONAL$$



$L = 1.0$ m, $D = 0.01$ m, $\dot{m} = 0.1$ kg / sec

$$H = 0.023 \frac{K}{D} \mathrm{Re}^{0.8} \mathrm{Pr}^{n}$$

$n = 0.4$ (heating of fluid)

$n = 0.3$ (cooling of fluid)

valid for $0.7 \le \mathrm{Pr} \le 160.$

$\mathrm{Re} \le 10{,}000.$

$\frac{L}{D} \ge 10.$

Use water properties at T = 82.22 °C (Heat Transfer, J. P. Holman).

Figure 5-60. Example 11

The NX Nastran input file is shown in Table 1.

Table 5-54. Example 11 Input File

```
ID NX NASTRAN V3
SOL 159
TIME 10
CEND
TITLE = EXAMPLE 11
ANALYSIS = HEAT
THERMAL = ALL
SPC = 10
IC =20
TSTEPNL = 100
OUTPUT(XYPLOT)
XTITLE = TIME, SECONDS
YTITLE = EXIT TEMPERATURE DEGREES CELSIUS
TCURVE = EXIT TEMPERATURE VS. TIME
XYPLOT TEMP/11(T1)
BEGIN BULK
TSTEPNL,100,400,0.005,1,,,,U,+TSTP
+TSTP,0.05

$
GRID,1,,0.0,0.0,0.0
GRID,2,,0.1,0.0,0.0
GRID,3,,0.2,0.0,0.0
GRID,4,,0.3,0.0,0.0
GRID,5,,0.4,0.0,0.0
GRID,6,,0.5,0.0,0.0
GRID,7,,0.6,0.0,0.0
GRID,8,,0.7,0.0,0.0
GRID,9,,0.8,0.0,0.0
GRID,10,,0.9,0.0,0.0
GRID,11,,1.0,0.0,0.0
GRID,50,,50.0,50.0,50.0
GRID,99,,99.0,99.0,99.0
```

```
$
CHBDYP,10,25,FTUBE,,,1,2
CHBDYP,20,25,FTUBE,,,2,3
CHBDYP,30,25,FTUBE,,,3,4
CHBDYP,40,25,FTUBE,,,4,5
CHBDYP,50,25,FTUBE,,,5,6
CHBDYP,60,25,FTUBE,,,6,7
CHBDYP,70,25,FTUBE,,,7,8
CHBDYP,80,25,FTUBE,,,8,9
CHBDYP,90,25,FTUBE,,,9,10
CHBDYP,100,25,FTUBE,,,10,11

PHBDY,25,,0.01,0.01
$
CONVM,10,35,,50,99
CONVM,20,35,,50,99
CONVM,30,35,,50,99
CONVM,40,35,,50,99
CONVM,50,35,,50,99
CONVM,60,35,,50,99
CONVM,70,35,,50,99
CONVM,80,35,,50,99
CONVM,90,35,,50,99

CONVM,100,35,,50,99
PCONVM,35,15,1,1,0.023,0.8,0.4,0.3
MAT4,15,0.673,4195.0,970.2,,8.6E-4
$
SPC,10,1,,100.0
SPC,10,50,,0.1
SPC,10,99,,0.0
TEMP,20,1,100.0
TEMP,20,50,0.1
TEMP,20,99,0.0
TEMPD,20,100.0
$
ENDDATA
```

Results

Temperature versus distance is shown in Figure 2. Exit temperature versus time is shown in Figure 3. Exit temperature versus mass flow rate is shown in Figure 4.

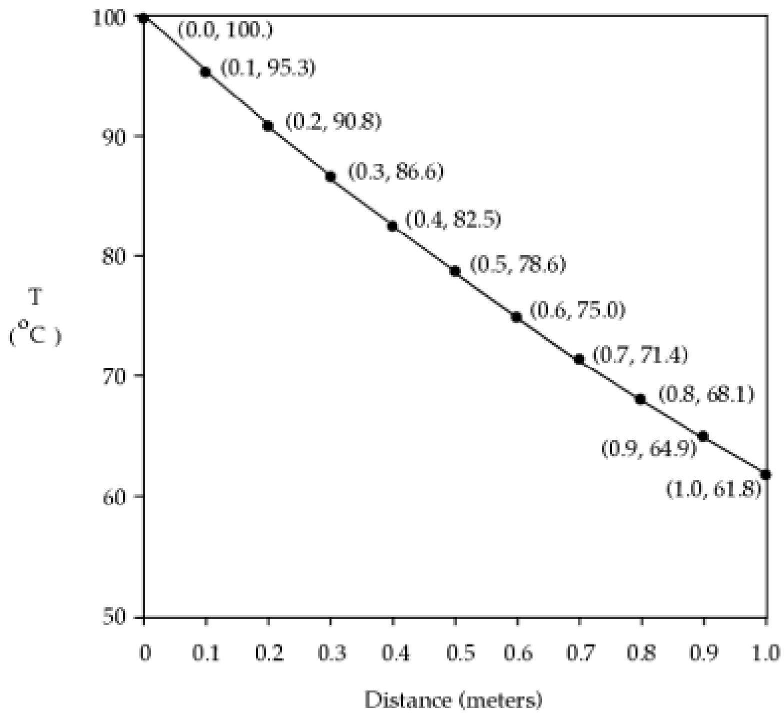


Figure 5-61. Temperature versus Distance

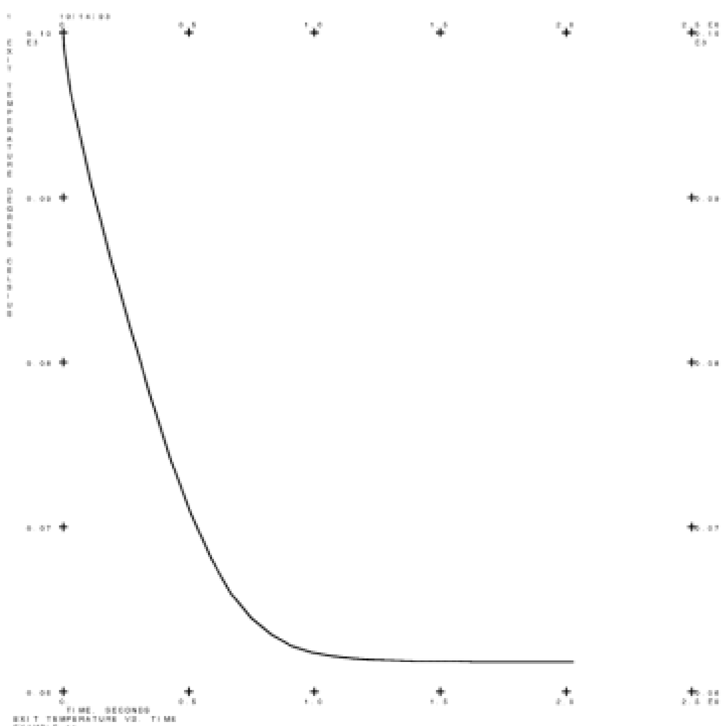


Figure 5-62. Exit Temperature versus Time

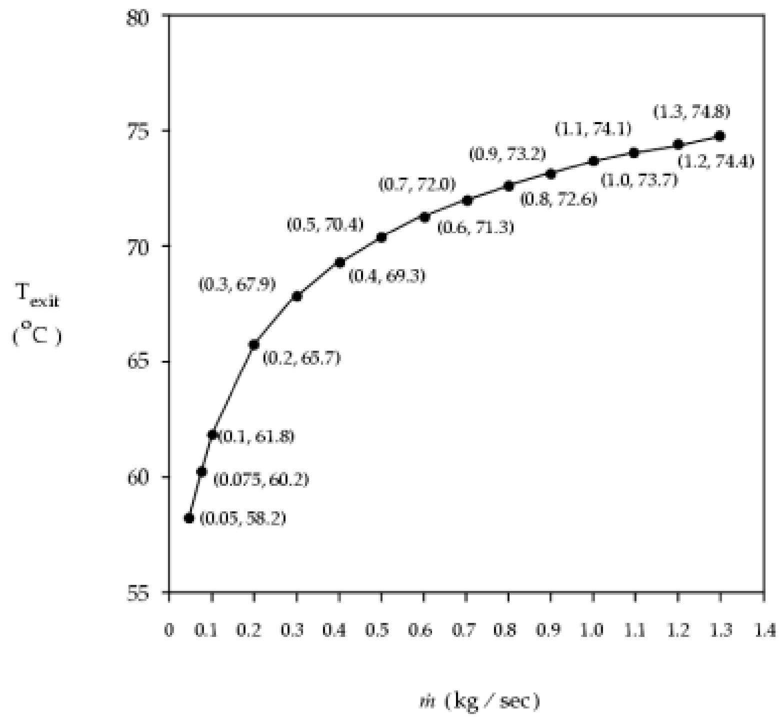


Figure 5-63. Exit Temperature versus Mass Flow Rate at Equilibrium (Constant Properties)

Appendix

A Commonly Used Terms

This appendix provides nomenclature for terms commonly used in thermal analysis.

k	Thermal conductivity
ρ	Density
C_p	Specific heat
h, H	Free convection heat transfer coefficient
H	Enthalpy
V	Velocity
μ	Dynamic viscosity
υ	Kinematic viscosity
Nu	Nusselt's number
Re	Reynolds' number
Pr	Prandtl's number
Gr	Grashof's number
β	Volume coefficient of expansion
q	Heat flux
Q	Heat flow
T, u	Temperature
g	Acceleration due to gravity
T_w	Wall temperature
T_∞	Ambient temperature
σ	Stefan-Boltzmann constant
υ	Planck's Second constant
F_{ij}	View factor
t	Time
ϵ	Emissivity
α	Absorptivity
$\dot{m}$	Mass flow rate

Appendix

B Commonly Used Commands for Thermal Analysis

B.1 Executive Control Statements

This section lists the Executive Control statements that are often used for thermal analysis. See the *NX Nastran Quick Reference Guide* for complete descriptions of these statements.

- CEND
- DIAG
- ECHO
- ID
- SOL
- TIME

B.2 Case Control Commands

This section lists the case control commands that are often used for thermal analysis. See the *NX Nastran Quick Reference Guide* for complete descriptions of these statements.

- Comment
- ANALYSIS
- DLOAD
- ENTHALPY
- FLUX
- HDOT
- IC
- INCLUDE
- LOAD
- MPC

- NLPARM
- NONLINEAR
- OLOAD
- OUTPUT
- PARAM
- SET
- SPC
- SUBCASE
- TEMPERATURE
- TFL
- THERMAL
- TSTEP
- TSTEPNL

B.3 Bulk Data Entries

This section lists the bulk data entries that are often used for thermal analysis. See the *NX Nastran Quick Reference Guide* for complete descriptions of these ENTRIES.

Comment	DLOAD	PARAM	RADMTX	TF
BDYOR	DMI	PCONV	RADSET	TLOAD1
CDAMP1	DMIG	PCONVM	SET1	TLOAD2
CDAMP2	DPHASE	PDAMP	SLOAD	TSTEPNL
CDAMP3	INCLUDE	RDAMP5	SPC	VIEW
CDAMP4	LOAD	PELAS	SPC1	VIEW3D
CDAMP5	MAT4	PHBDY	SPCADD	
CELAS1	MAT5	QBDY1	SPCD	
CELAS2	MATT4	QBDY2	SPOINT	
CELAS3	MATT5	QBDY3	SUPAX	
CELAS4	MPC	QVECT	TABLED1	
CHBDYE	MPCADD	QVOL	TABLED2	
CHBDYG	NLPARM	RADBC	TABLED3	
CHBDYP	NOLIN1	RADBND	TABLED4	
CONV	NOLIN2	RADCAV	TEMP	
CONVM	NOLIN3	RADLST	TEMPAX	
	NOLIN4	RADM	TEMPD	

Figure B-1 illustrates the interaction between the various Case Control commands and Bulk Data entries involved in the specification of thermal loads.

Figure B-2 illustrates the Bulk Data entry interaction for the application of heat transfer boundary conditions involving radiation and convection.

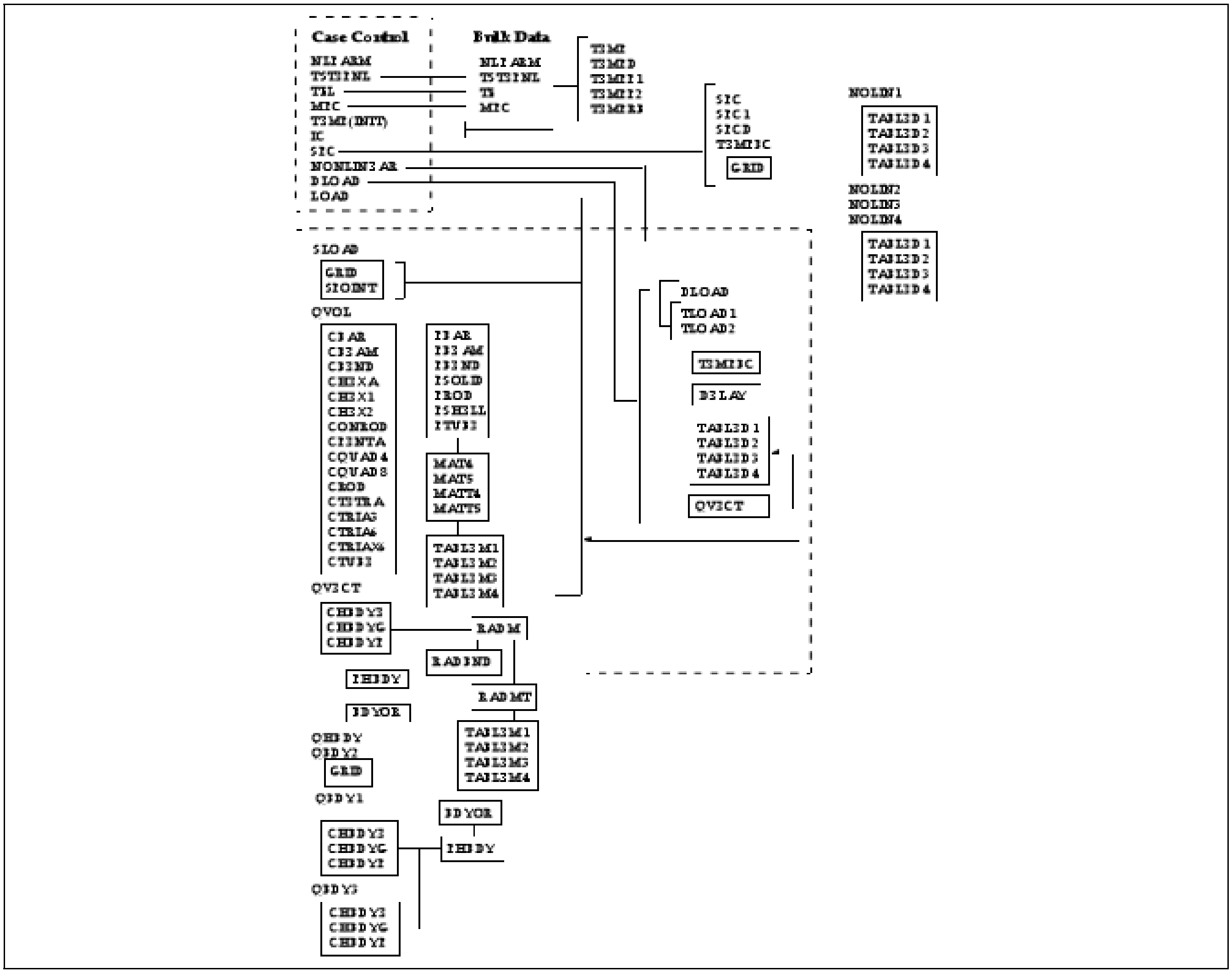


Figure B-1. Thermal Loads – Bulk Data and Case Control Interaction

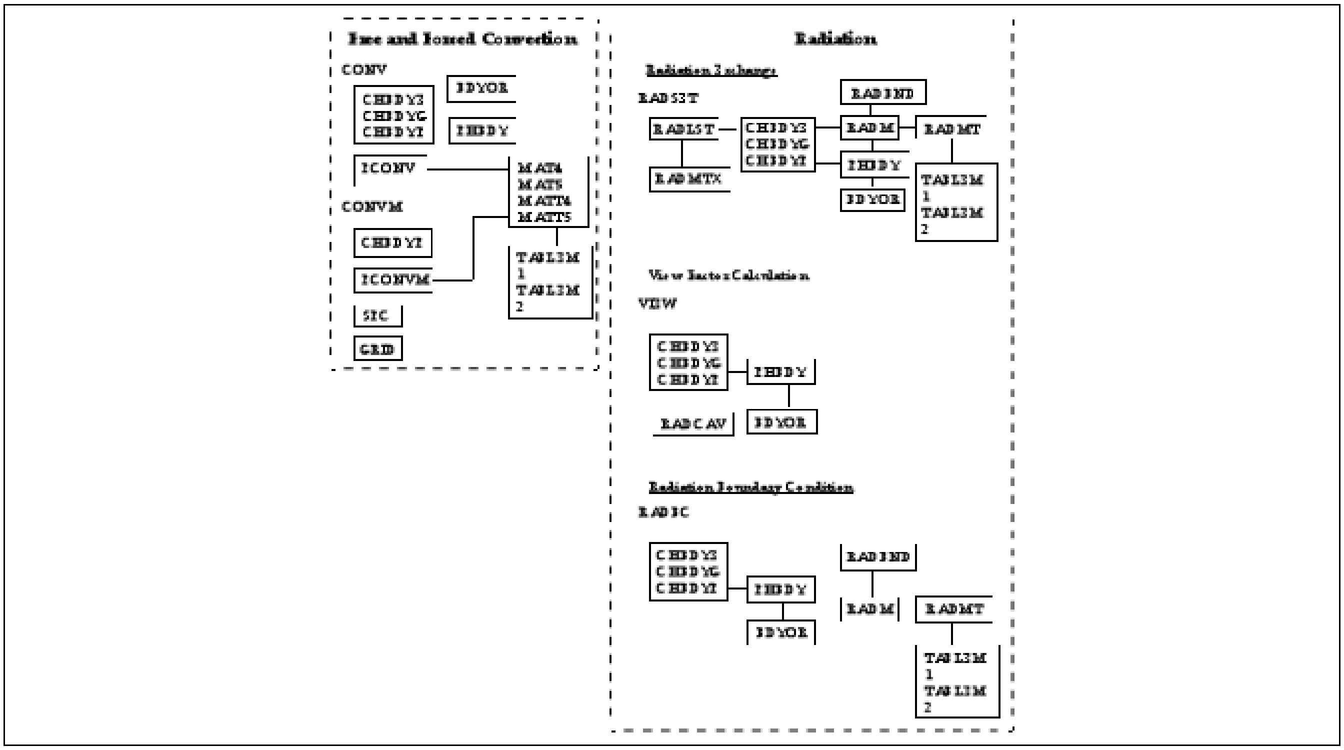


Figure B-2. Thermal Boundary Conditions – Bulk Data Interaction

Appendix

C View Factor Calculation Methods

C.1 Calculation of View Factors

NX Nastran has two independent routines available for the calculation of view factors between gray diffuse surface elements. The default routine, the VIEW module, relies on a user defined combination of area and contour discretization to determine the geometric view factor. The second module, VIEW3D, utilizes Gaussian integration and semi-analytic contour integration to evaluate view factors. In the material that follows, the two methods are compared and contrasted from a user standpoint in an effort to direct their most efficient application.

C.2 Fundamentals of View Factor Calculation

1. View factors can only be determined between surfaces that have been identified with CHBDYi surface elements.

2. Because of the geometric or visual nature of the view factor calculation, it is often necessary to identify both sides of conduction elements with independent surface elements, particularly when third-body shadowing is of concern. Only active surface elements can participate, or be seen, in a view factor calculation.

3. The active side of the surface element is defined relative to the grid point connections. The right hand rule specifies the outward surface normal as one proceeds from G1 to Gn thereby defining the active surface element.

4. The overall quality of the view factor calculated is highly dependent on the surface element mesh model. When the distance between any two elements is reduced below a level on the order of an element length or width, inaccuracies can develop. At the same time, a large number of small elements can create a very computationally intensive problem.

5. There are two types of shadowing which can also reduce the quality of the overall view factor. Self-shadowing reduces the total view factor between two surfaces due simply to their relative orientations in space (Figure C-1). Third-body shadowing (Figure C-2) takes into account the reduced view between two surfaces due to other interelement interference surfaces. In this figure, note the existence of both the K and L surfaces.

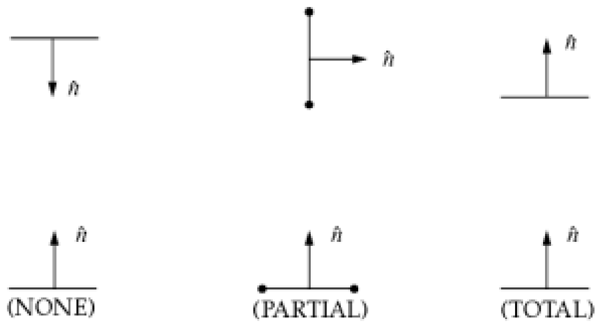


Figure C-1. Self-Shadowing

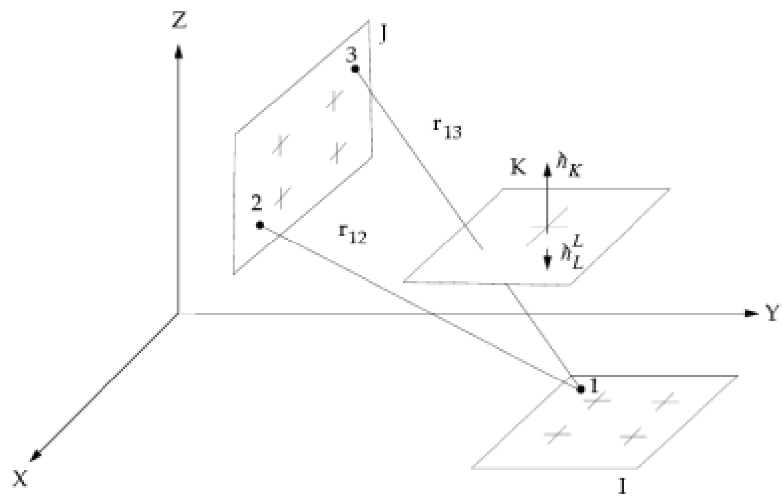


Figure C-2. Third Surface Shadowing

6. The CHBDYi element types available for radiation view factor calculation include:

   POINT

   LINE

   REV

   AREA3

   AREA4

   AREA6 — VIEW3D Module Only

   AREA8 — VIEW3D Module Only

   All surface elements may be used for radiation enclosure analysis with the appropriate user supplied view or exchange factors.

7. NX Nastran allows for isolated surface element groupings when performing view factor calculations – multiple radiation cavities. This procedure can eliminate a great deal of needless calculation among surfaces when one group of elements clearly cannot see another group of elements. The surface element groups therefore are arranged by unique cavity IDs. No surface element may reside in more than on cavity.

8. The VIEW entry invokes the calculation of the view factors for the overall thermal analysis. It also separates the CHBDYi surface elements into the desired cavities. The IVIEW field identifies the CHBDYi elements and the ICAVITY field assigns the elements to a cavity.

Using the VIEW Module

1. The geometric integral equation to be solved for the view factor is given below. Figure C-4 depicts the pertinent terms.

$$F_{ij} = \frac{1}{A_i} \iint_{A_i A_j} \left(\frac{\cos\beta_i \cos\beta_j}{\pi r_{ij}^2} \right) dA_i dA_j \,\textbf{(dimensionless)}$$

Figure C-3.

where F_{ij} is defined as the fraction of the radiant emission leaving surface i which arrives at surface j.

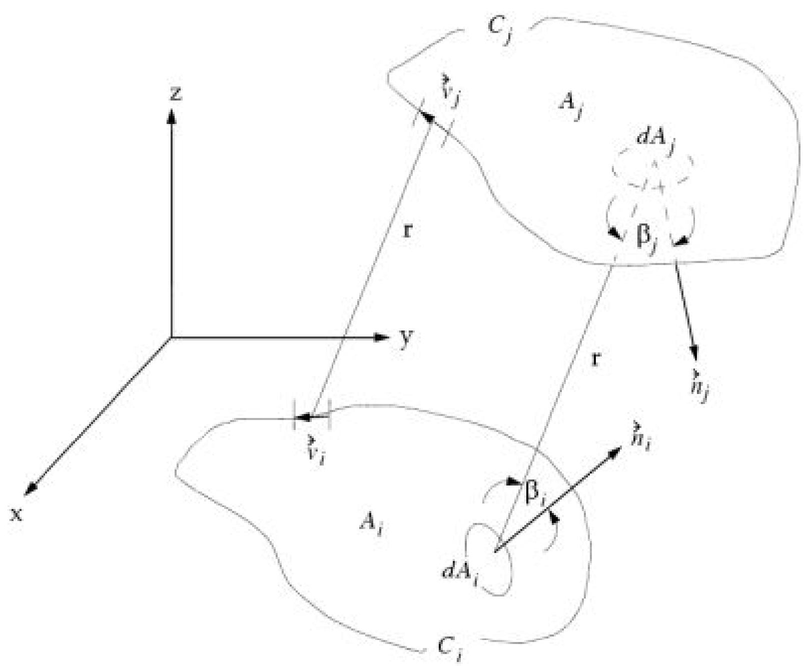


Figure C-4. Arbitrary Enclosure Radiation Surfaces

A_i and A_j are diffuse emitters and reflectors
A_i and A_j are black.
A_i and A_j are isothermal.

2. The VIEW Module solves Figure C-3 by two methods. The first method discretizes the surface elements into a number of finite subelements and treats the integrals as dual summations over all the subelements on surfaces I and J. This method is often referred to as the finite difference method, but is just an extension of view factor algebra. Consider the surfaces I and II below with subdivision $1 \rightarrow 8$.

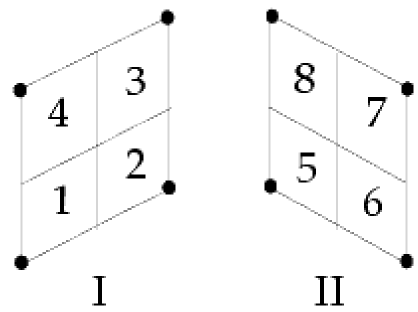


Figure C-5.

From view factor algebra,

a. $$f_{1-II} = f_{1-5} + f_{1-6} + f_{1-7} + f_{1-8}$$

and similarly for f_{2-II} , f_{3-II} , and f_{4-II}

Reciprocity provides;

b. $$A_1 f_{1-II} = A_{II} f_{II-1} \; ; \quad f_{II-1} = \frac{A_1}{A_{II}} f_{1-II}$$

c. Now, $f_{II-I} = f_{II-1} + f_{II-2} + f_{II-3} + f_{II-4}$

d. and, $A_{II} f_{II-I} = A_1 f_{1-II} + A_2 f_{2-II} + A_3 f_{3-II} + A_4 f_{f-II}$

$$\begin{aligned} A_{II} F_{II-I} = {} & A_1(f_{1-5} + f_{1-6} + f_{1-7} + f_{1-8}) \\ & + A_2(f_{2-5} + f_{2-6} + f_{2-7} + f_{2-8}) \\ & + A_2(f_{3-5} + f_{3-6} + f_{3-7} + f_{3-8}) \\ & + A_4(f_{4-5} + f_{4-6} + f_{4-7} + f_{4-8}) \end{aligned}$$

e. using, a. then

$$f_{I-II} = \frac{1}{A_I} \sum_{i=1}^{4} \sum_{j=5}^{8} \frac{\cos\beta_i \cos\beta_j A_i A_j}{\Pi R_{ij}^2}$$

f. so

The second method transforms the area integrals into contour integrals and subdivides the perimeter into finite line segments. A similar dual contour summation is then performed around surfaces I and J. This method is commonly referred to as the contour integration method.

3. In general, area integration is faster than contour integration, but does not provide as accurate an answer. Several choices can be made by the user as a result. The RADCAV entry has information fields on it for the control and manipulation of the view factor calculation:

   NFECI = FD Finite Difference methods are used to calculate the view factors (applies to the VIEW Module only).

   NFECI = CONT Contour integration methods are used to calculate the view factors (applies to the VIEW Module only).

   NFECI = blank or 0. This is the default value signifying that the code will make an estimate based on geometry and the field value of RMAX as to whether it will use finite differences or contour integration. Figure C-6 below illustrates the criteria enforced.

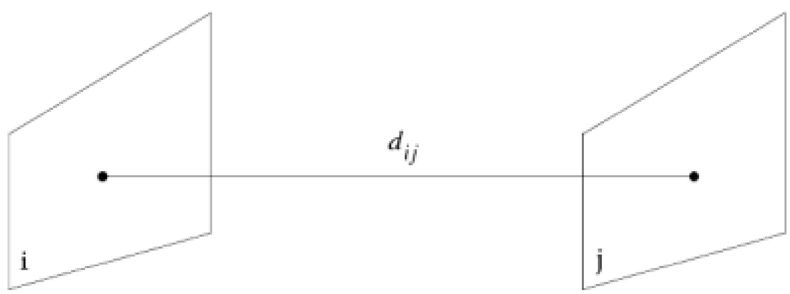


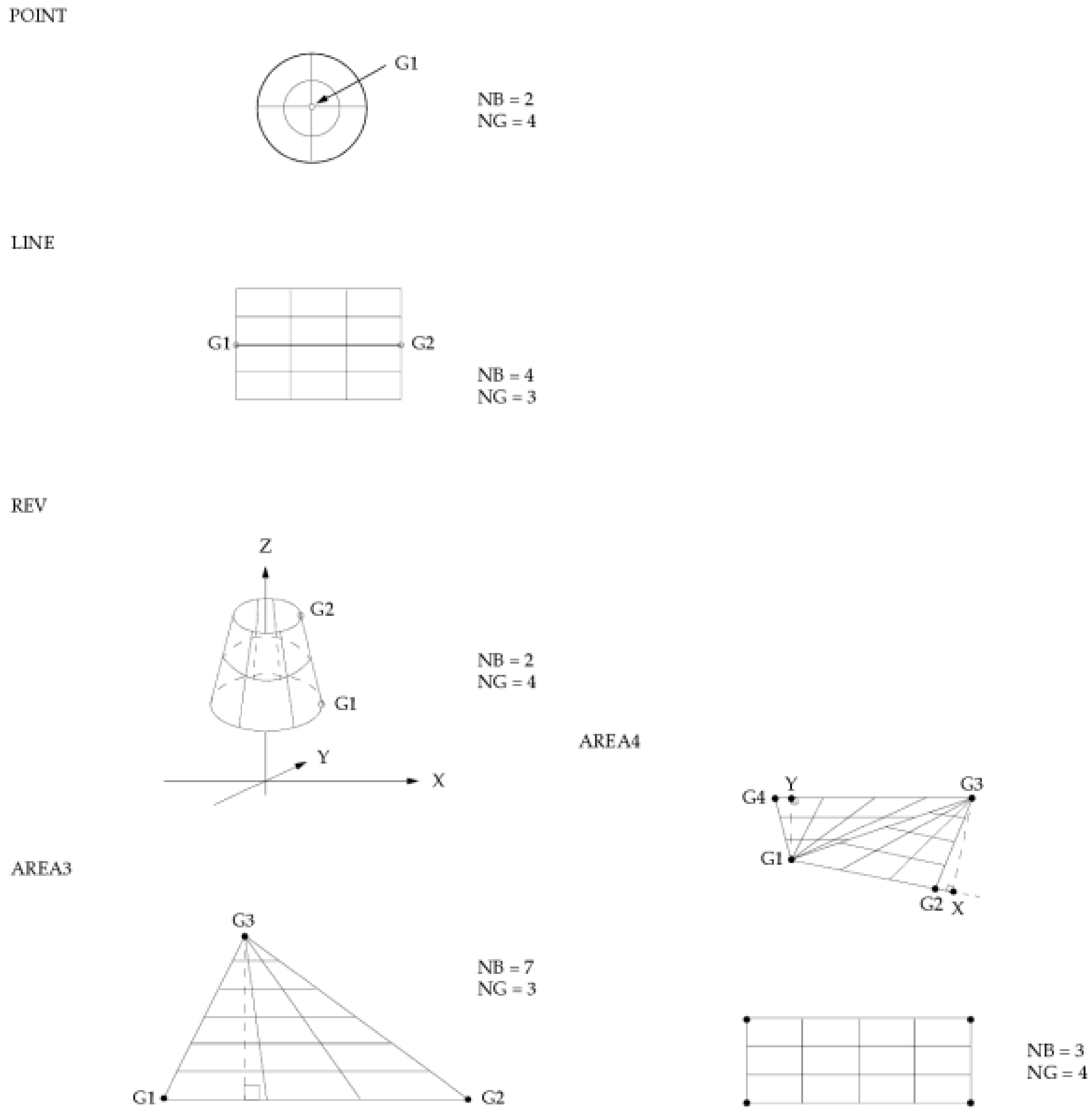
Figure C-6.

Contour integration is used on any element pair for which;

$$\frac{A_j}{(d_{ij})^2} > \mathrm{RMAX}$$

For example, if $A_j = 1$, $d_{ij} < \sqrt{10}$ enforces contour integration.

4. Since the VIEW Module relies on element subdivision in its calculation method, a means of requesting the level of subdivision is made available. The number of element subdivisions are specified on the NB and NG field of the VIEW entry. The subdivision process is illustrated below for the pertinent surface element types.



Using the VIEW3D Module

1. The VIEW3D Module relies on Gaussian integration techniques for the solution of Figure C-3. This view module is accessed by introducing the VIEW3D Bulk Data entry. This view factor calculator is semi-adaptive in that detection of excessive error or shadowing, will automatically invoke semi-analytic contour integration techniques or higher Gaussian integration order to reduce the error. For a general 3D geometry, this procedure is superior in both accuracy and speed to that available with the VIEW module.

2. The VIEW3D Module is designed only for the calculation of view factors for general 3D geometries. Planar view factors must be calculated with the VIEW routine.

3. There is no surface subdivision available with VIEW3D, therefore a responsible initial mesh is required for good results. Accuracy levels can be substantially controlled by requesting the use of various integration orders.

4. This module is requested by including the Bulk Data entry VIEW3D. The VIEW3D entry contains specific fields for defining the various integration orders desired for unobstructed view factors, self and third-body shadowing view factors, and improved view factors when excessive error is detected.

5. The view factor error is defined as:

$$\mathrm{ERROR} = F_{ij} \cdot (\mathrm{RMAX} / \mathrm{RMIN})$$

   In this equation, F_{ij} is the initially calculated view factor (always an integration order of 2 by 2) and RMAX and RMIN represent the largest and smallest integration point (surface I) to integration point (surface J) vector lengths. Surface proximity and angular orientation are reflected in this value.

6. When a large number of surfaces are involved in an enclosure (1000+), it may be advisable to reduce the values of the field data for GITB, GIPS, and CIER to the value of (2).

7. Because view factors solely involve geometry, it is important to work in dimensions/units that do not lead to machine accuracy problems. In particular, in transformed space, the view factor equation has an integration point to integration point distance raised to the fourth power in the denominator.

Miscellaneous View Factor Capabilities (VIEW or VIEW3D)

1. Shadowing calculations absorb considerable resources while calculating view factors. If the geometry is such that no shadowing can occur, it is recommended to turn off the calculation process by utilizing the SHADOW field on the RADCAV entry. A NO declaration will eliminate any shadowing calculations. The default value is YES. If a limited subset of surfaces in a problem are involved in shadowing, the most efficient calculation will result if the SHADE field of the VIEW Bulk Data entry is appropriately identified.

2. If a complete radiation enclosure is being analyzed, small inaccuracies in the individual view factors may lead to view factor sums that exceed 1.0 by a small (1 or 2 percent) amount. In this case, the view factors can be scaled to provide a sum of exactly 1.0 by utilizing the SCALE field on the RADCAV entry.

3. If an incomplete enclosure is being analyzed and it is desirable to complete the enclosure with a dummy or space element, this can be facilitated by using the ELEAMB field of the RADCAV entry. The ambient element must be an existing surface element of the problem, however, it is not used explicitly in the determination of the view factors. Subsequent to the view factor calculations, the view factor 1.0 – SUMMATION is assigned to the space element for each individual enclosure surface element.

4. View factor output can be controlled through the PRTPCH field of the RADCAV entry.

5. We define a global view factor as the view factor that exists between one group of surface elements and another group of surface elements. If global view factors are of interest, perhaps for some system level analysis, these can be determined while executing the VIEW module. The SET_{ij} fields on the RADCAV entry reference the desired surface element sets.

Appendix

D Radiation Enclosures

D.1 Method of Poljak

$$A_k q_{i,k} = \sum_{j=1}^{N} A_j q_{o,j} f_{j-k}$$

Figure D-1.

$$A_j f_{j-k} = A_k f_{k-j}$$

Figure D-2.

$$q_{i,k} = \sum_{j=1}^{N} f_{k-j} q_{o,j}$$

Figure D-3.

$$q_{o,k} = \varepsilon_k \sigma T_k^4 + (1 - \varepsilon_k) q_{i,k}$$

Figure D-4.

$$q_{i,k} = \sum_{j=1}^{N} f_{k-j}(\varepsilon_k \sigma T_k^4 + (1 - \varepsilon_k) q_{i,k})$$

Figure D-5.

$$q_{i,k} = \sum_{j=1}^{N} f_{k-j}\varepsilon_k\sigma T_k^4 + \sum_{j=1}^{N} f_{k-j}(1-\varepsilon_k)q_{i,k}$$

Figure D-6.

$$q_{i,k}\left(1 - \sum_{j=1}^{N} f_{k-j}(1-\varepsilon_k)\right) = \sum_{j=1}^{N} f_{k-j}\varepsilon_k\sigma T_k^4$$

Figure D-7.

$$q_{i,k} = \sum_{j=1}^{N}\left(1 - \sum_{j=1}^{N} f_{k-j}(1-\varepsilon_k)\right)^{-1} f_{k-j}\varepsilon_k\sigma T_k^4$$

Figure D-8.

where:

A	=	elemental areas
f	=	basic view factors
N	=	number of element in enclosure
$q_{i,k}$	=	heat flux into surface element k
$q_{o,j}$	=	heat flux leaving surface element j

Similarly for $q_{o,j}$, then

$$q_k^{N\varepsilon T} = q_{i,k} - q_{o,k}$$

Figure D-9.

or

$$Q_k^{N\varepsilon T} = A_k(q_{i,k} - q_{o,k})$$

Figure D-10.

D.2 Method of Poljak - Radiation Exchange in Matrix Format

$$[A]\{q\}_e^{\mathrm{IN}} = [F]\{q\}_e^{\mathrm{OUT}}$$

(compare to Figure D-1)

Figure D-11.

$$\{q\}_e^{\mathrm{OUT}} = \sigma[\varepsilon]\{u_e\}^4 + [I - \varepsilon]\{q\}_e^{\mathrm{IN}}$$

Figure D-12.

(compare to Figure D-4) where:

$$\begin{bmatrix} \diagdown & & \\ & A & \\ & & \diagdown \end{bmatrix}$$ = diagonal matrix of element areas

$\{q\}_e^{\mathrm{IN}}$ = irradiation

$[F]$ = matrix of exchange coefficients $(A_i f_{ij})$

$\{q\}_e^{\mathrm{OUT}}$ = radiosity

σ = Stephan-Boltzmann constant

$$\begin{bmatrix} \diagdown & & \\ & \varepsilon & \\ & & \diagdown \end{bmatrix}$$ = diagonal matrix of surface emissivities

$$\begin{bmatrix} \diagdown & & \\ & \alpha & \\ & & \diagdown \end{bmatrix}$$ = diagonal matrix of surface absorptivities

Substituting Figure D-12 into Figure D-11 yields:

$$\{q\}_e^{\mathrm{IN}} = \sigma[(A - F(I - \alpha))^{-1}F\varepsilon]\{u\}_e^4$$

Figure D-13.

$$\{q\}_e^{\mathrm{OUT}} = \sigma[\varepsilon + (I - \alpha)(A - F(I - \alpha))^{-1}F\varepsilon]\{u\}_e^4$$

Figure D-14.

$$\{Q\}_e = [A](\{q\}_e^{\mathrm{IN}} - \{q\}_e^{\mathrm{OUT}}) \equiv -[R_e]\{u\}_e^4$$

Figure D-15.

Substituting Figure D-14 into Figure D-15 yields:

$$[R_e] = \sigma[A\varepsilon - A\alpha(A - F(I - \alpha))^{-1}F\varepsilon]$$

Figure D-16.

$[R_e]$ = radiation exchange matrix.

If $\varepsilon = \alpha$ and F_{SYM} then $[R_e]_{SYM}$.

D.3 Transformation from Element Heat Flows to Grid Point Heat Flows

NX Nastran solves the system equations for the grid point temperatures. The view factors, however, are calculated between geometric surface elements. Therefore, the introduction of radiation exchange into the system equations requires the transformation of the radiation exchange matrix from an element based representation to a grid point based representation.

$$\{Q\}_g = [G]^T\{Q\}_e$$

Figure D-17.

where:

$[G]^T$	=	matrix of constant coefficients constructed from the fraction of the element area associated with the connecting grid points.

then:

$$\{u\}_e^4 = [G]\{u_g + T_a\}^4$$

Figure D-18.

and

$$[R]_g = [G]^T[R]_e[G]$$

Figure D-19.

$$[R]_{g_{SYM}} \text{ if } [R]_{e_{SYM}}$$

Figure D-20.

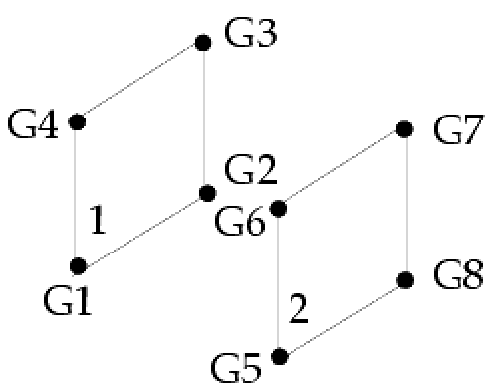
$$\{Q\}_e = -\sigma[R]_e[G]\{u_g + T_a\}^4$$

Figure D-21.

$$\{Q\}_g = -\sigma[R]_g\{u_g + T_a\}^4$$

Figure D-22.

D.4 Example of Element/Grid Transformation



$$[R]_e = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix}$$

Figure D-23.

$$\begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix}_e = -\sigma \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix}_e \begin{Bmatrix} u_1^4 \\ u_2^4 \end{Bmatrix}_e$$

Figure D-24.

$$\begin{Bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \\ Q_7 \\ Q_8 \end{Bmatrix}_g = \begin{bmatrix} \mathrm{AF1} & 0 \\ \mathrm{AF2} & 0 \\ \mathrm{AF3} & 0 \\ \mathrm{AF4} & 0 \\ 0 & \mathrm{AF5} \\ 0 & \mathrm{AF6} \\ 0 & \mathrm{AF7} \\ 0 & \mathrm{AF8} \end{bmatrix} \begin{Bmatrix} Q_1 \\ Q_2 \end{Bmatrix}_e$$

Figure D-25.

Comparing Figure D-25 to Figure D-17 then,

$$[G] = \begin{bmatrix} \mathrm{AF1} & \mathrm{AF2} & \mathrm{AF3} & \mathrm{AF4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathrm{AF5} & \mathrm{AF6} & \mathrm{AF7} & \mathrm{AF8} \end{bmatrix}$$

Figure D-26.

Where AFi (i = 1, 8) is the fractional area of the element associated with grid point Gi.

$$[R]_g \;=\; [G]^T [R]_e [G]$$

Figure D-27.

$$[R]_g = \begin{bmatrix} \mathbf{AF1} & \mathbf{0} \\ \mathbf{AF2} & \mathbf{0} \\ \mathbf{AF3} & \mathbf{0} \\ \mathbf{AF4} & \mathbf{0} \\ \mathbf{0} & \mathbf{AF5} \\ \mathbf{0} & \mathbf{AF6} \\ \mathbf{0} & \mathbf{AF7} \\ \mathbf{0} & \mathbf{AF8} \end{bmatrix} \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix}_e \begin{bmatrix} \mathbf{AF1} & \mathbf{AF2} & \mathbf{AF3} & \mathbf{AF4} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{AF5} & \mathbf{AF6} & \mathbf{AF7} & \mathbf{AF8} \end{bmatrix}$$

Figure D-28.

$$[R]_g = \begin{bmatrix} \mathbf{AF1R_{11}AF1} & \mathbf{AF1R_{11}AF2} & \mathbf{AF1R_{12}AF8} \\ \mathbf{AF2R_{11}AF1} & \mathbf{AF2R_{11}AF2} & \\ \mathbf{AF3R_{11}AF1} & \mathbf{AF3R_{11}AF2} & \\ \mathbf{AF4R_{11}AF1} & & \\ \mathbf{0} & & \\ \mathbf{0} & & \\ \mathbf{0} & & \\ \mathbf{AF8R_{21}AF1} & & \mathbf{AF8R_{22}AF8} \end{bmatrix}$$

Figure D-29.

D.5 Two Element Example for Radiant Exchange

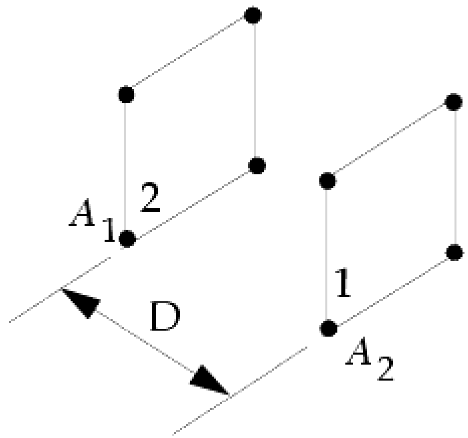


Figure D-30.

$$[R]_e = \sigma[A\varepsilon - A\alpha(A - F(I - \alpha))^{-1}F\varepsilon]$$

Figure D-31.

$$[F] = \begin{bmatrix} \diagdown & & \\ & A & \\ & & \diagdown \end{bmatrix}[f]$$

Figure D-32.

$$(A - F(I - \alpha))^{-1} = \left[\begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix} - \begin{bmatrix} 0 & A_1 f_{12} \\ A_2 f_{21} & 0 \end{bmatrix}\begin{bmatrix} 1 - \varepsilon_1 & 0 \\ 0 & 1 - \varepsilon_2 \end{bmatrix}\right]^{-1}$$

$$= \begin{bmatrix} A_1 & -A_1 f_{12}(1 - \varepsilon_2) \\ -A_2 f_{21}(1 - \varepsilon_1) & A_2 \end{bmatrix}^{-1}$$

Figure D-33.

For ease of illustration (and manipulation) let surfaces 1 and 2 be black bodies, then $\epsilon_1 = \epsilon_2 = 1.0$ then

$$(A - F(I - \alpha))^{-1} = \begin{bmatrix} \frac{1}{A_1} & 0 \\ 0 & \frac{1}{A_2} \end{bmatrix}$$

Figure D-34.

$$[R]_e = \sigma\left[\begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix} - \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}\begin{bmatrix} \frac{1}{A_1} & 0 \\ 0 & \frac{1}{A_2} \end{bmatrix}\begin{bmatrix} 0 & A_1 f_{12} \\ A_2 f_{21} & 0 \end{bmatrix}\right]$$

Figure D-35.

$$[R]_e = \sigma\begin{bmatrix} A_1 & -A_1 f_{12} \\ -A_2 f_{21} & A_2 \end{bmatrix}$$

Figure D-36.

$$\{Q\}_e = -\sigma\begin{bmatrix} A_1 & -A_1 F_{12} \\ -A_2 F_{21} & A_2 \end{bmatrix}_e \begin{Bmatrix} u_1^4 \\ u_2^4 \end{Bmatrix}_e$$

Figure D-37.

To further define a specific problem, let $A_1 = A_2 = D = 1.0, T_1 = 1000$ and $T_2 = 0.0$. For this geometry then, $f_{12} = f_{21} \equiv .20$. The resulting heat flows are:

$$Q_1 = -\sigma(1000^4 - .2(0)) = -\sigma(1000)^4$$

$$Q_2 = -\sigma(-.2(0) - .2(1000)^4) = .2\sigma(1000)^4$$

Figure D-38.

Note

Since the exchange matrix $[R]_e$ is not conservative, we recognize that the NX Nastran default condition assumes a third exchange surface representing a loss to space. Therefore,

$$Q_1 + Q_2 + Q_3 = 0.0$$

the loss to space is:

$$Q_3 = .8\sigma(1000)^4$$

D.6 Resistive Network Approach to the Two Surface Problem

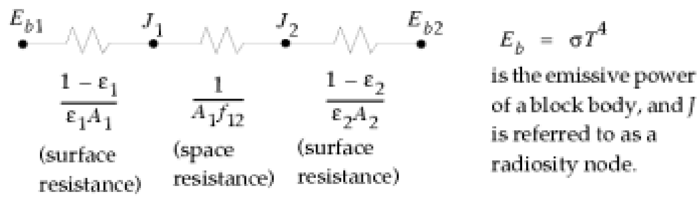


Figure D-39.

The heat flow then is;

$$Q_{1-2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 f_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$

Figure D-40.

Using the same example problem considered in the exchange matrix development,

$$\varepsilon_1 = \varepsilon_2 = 1.0$$

$$A_1 = A_2 = 1.0$$

$$f_{12} = .20$$

$$Q_{1-2} = \sigma A_1 f_{12}(T_1^4 - T_2^4) = -Q_{2-1}$$
$$= .2\sigma(1000)^4$$

Figure D-41.

in a matrix format,

$$\{Q\}_e = -\sigma \begin{bmatrix} A_1 f_{12} & -A_1 f_{12} \\ -A_1 f_{12} & A_1 f_{12} \end{bmatrix} \begin{Bmatrix} u_1^4 \\ u_2^4 \end{Bmatrix}$$

Figure D-42.

Note

There is no exchange with the environment in these equations.

D.7 Radiation Enclosure Analysis

Radiation Matrix Formation - General

The basic exchange relationship for a radiation enclosure is given in Figure D-43

$$\{Q\}_n = [R]_n\{u + T_a\}^4$$

Figure D-43.

where:

$[R]_n$	=	$\sigma[A\varepsilon - A\alpha[A - F(I-\alpha)]^{-1}F\varepsilon]_n$ (α = ϵ for radiation enclosure)
$\{Q\}_n$	=	Vector of net elemental heat flows from radiant exchange for cavity n
$[R]_n$	=	Radiation exchange matrix for cavity n
$\{u\}$	=	Vector of grid point temperatures
σ	=	Stefan-Boltzmann constant

$\begin{bmatrix} \diagdown & & \\ & A & \\ & & \diagdown \end{bmatrix}$	=	Diagonal matrix of surface element areas
$\begin{bmatrix} \diagdown & & \\ & I & \\ & & \diagdown \end{bmatrix}$	=	Identity matrix
$\begin{bmatrix} \diagdown & & \\ & \varepsilon & \\ & & \diagdown \end{bmatrix}$	=	Diagonal matrix of surface emissivities
$\begin{bmatrix} \diagdown & & \\ & \alpha & \\ & & \diagdown \end{bmatrix}$	=	Diagonal matrix of surface absorptivities
$[F]_n$	=	Lower triangular matrix of exchange coefficients ($A_j f_{ji}$) for cavity n
T_a	=	Scale factor to correct for absolute temperature

User supplied data:

σ	=	Supplied on the PARAM,SIGMA Bulk Data entry
T_a	=	Supplied on the PARAM,TABS Bulk Data entry
$\begin{bmatrix} \diagdown & & \\ & A & \\ & & \diagdown \end{bmatrix}$	=	Calculated from the input data for CHBDYi surface elements
$[F]$	=	Supplied from the RADLST/RADMTX Bulk Data entries or calculated internally using the VIEW or VIEW3D modules

$$\begin{bmatrix} \diagdown & & \\ & \varepsilon & \\ & & \diagdown \end{bmatrix}, \begin{bmatrix} \diagdown & & \\ & \alpha & \\ & & \diagdown \end{bmatrix} \quad = \quad \text{Supplied from the RADM Bulk Data entries}$$

Radiation Matrix Formation Using NX Nastran View Factors

As described in "View Factor Calculation Methods", NX Nastran can calculate diffuse grey geometric view factors (stored as $A_j \bullet f_{ji}$) to be used in radiation enclosure analysis. Those view factors are used in Figure D-43 to generate a total radiation exchange matrix. This matrix is symmetric and generally non-conservative in the sense that the column summations will not be equal to zero. This would imply that in an isothermal enclosure, there would exist net heat flow. This could be the result of an incomplete enclosure with resultant energy loss to space. If a complete enclosure is desired, an ambient element can be requested. The total view factor summations can also be scaled to exactly equal 1.0 for any summations exceeding 1.0. These options are discussed beginning on "View Factor Calculation Methods".

Control over the form of the radiation matrix can be effected by specifying the matrix type (MTXTYP) on the RADLST Bulk Data entry. Once these entries are generated by the VIEW or VIEW3D module, the matrix type can either remain as MTXTYP = 1, or it can be changed to a MTXTYP = 4. In this case, the radiation matrix will have its diagonal terms adjusted to provide a column sum of exactly zero. This is referred to as a conservative radiation matrix.

Radiation Matrix Formation Using User-Supplied Exchange Factors

It may be desirable to input the radiation exchange matrix directly. In this case the user provides exchange factors with the RADLST/RADMTX Bulk Data entries. Exchange factors can be used to account for specular effects, transmissive surface character, and enclosure gas absorption. When used in this fashion, the input represents the following system:

$$\text{RADMTX} \qquad \text{“SCRIPT-F”}$$

$$[R] = -\sigma * \text{“SCRIPT-F”} \qquad (\text{Off Diagonal Terms})$$

$$\text{RADLST} \quad \begin{cases} \text{MTXTYP} = 2 & \text{– Symmetric} \\ & \text{– Conservative} \\ \text{MTXTYP} = 3 & \text{– Unsymmetric} \\ & \text{– Conservative} \end{cases}$$

In this instance CONSERVATIVE means that the diagonal terms of $[R]$ are adjusted to make the column summations equal to 0.0. Since all the radiation matrix values are user supplied, no control over the system can be effected by the view factor module. A user warning message is issued if Figure D-44 is satisfied.

$$\sum_i A_i f_{ij} > A_i.(1.001)$$

Figure D-44.

calculated for each j where:

i	=	Column in view factor matrix
j	=	Row in view factor matrix
A	=	Surface element area
f	=	View Factor

Appendix

E Real Surface Approximation and Radiation Exchange

In the most general sense, radiative surface properties can vary with absorption and emission angle, surface temperature, and spectral distribution of incident and emitted radiation. For an enclosure analysis, the many reflections and re-reflections tend to smooth out directional behavior. Additionally, it may be difficult if not impossible to acquire good directional, temperature, or wavelength dependent surface properties. Based on this, many radiation problems are approximated at the first level of analysis with surfaces which exhibit diffuse gray absorption and emission radiative character.

NX Nastran allows for a second level of analysis which presumes that radiation surface interaction is diffuse, but admits emissivity and absorptivity to be functions of temperature and/or wavelength. The concept of a diffuse view factor is still applicable for this type of analysis since it is a simple geometric construct. The basic notion involved here is to consider the energy transport associated with separate wavelength intervals (wavebands). Numerically, this can be implemented with a method known as the band-energy approximation.

Figure E-1 illustrates the hemispherical spectral emissivity for tungsten. Figure E-2 depicts a potential waveband approximation for the hemispherical spectral emissivity for input to NX Nastran.

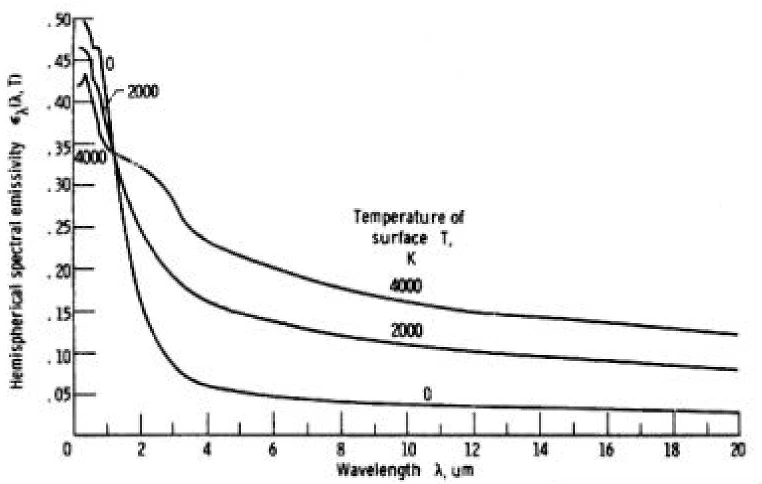


Figure E-1. Hemispherical Spectral Emissivity of Tungsten*

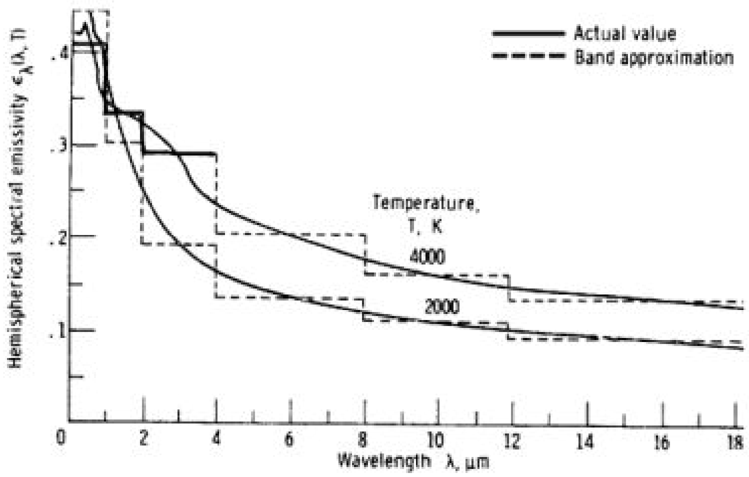


Figure E-2. Band Approximations to Hemispherical Spectral Emissivity of Tungsten*

*From Siegel and Howell, *Thermal Radiation Heat Transfer*, Second Edition.

E.1 Radiation Exchange Relationship for Diffuse Spectral Surface Behavior

$$\{Q_e\} = \sum_{\lambda} \{Q_e^{\lambda}\}$$

$$\{Q_e^{\lambda}\} = [A]\left(\left\{q_e^{\lambda}\right\}^{in} - \left\{q_e^{\lambda}\right\}^{out}\right)$$

$$\{q_e^{\lambda}\}^{in} = \sigma[(A - F(I - \alpha(\lambda)))^{-1}F\varepsilon(\lambda)]\begin{bmatrix} \ddots & & \\ & f_e & \\ & & \ddots \end{bmatrix}\{U_e\}^4$$

$$\{q_e^{\lambda}\}^{out} = \sigma[\varepsilon(\lambda) + (I - \alpha(\lambda))(A - F(I - \alpha(\lambda)))^{-1}F\varepsilon(\lambda)]\begin{bmatrix} \ddots & & \\ & f_e & \\ & & \ddots \end{bmatrix}\{U_e\}^4$$

$$\{f_e\} = \left\{ FRAC_{0-\lambda_2 U_e} - FRAC_{0-\lambda_1 U_e} \right\}$$

f_e = Fraction of the total radiant output of a black body that is contained in the n-th wavelength band where $\Delta\lambda = \lambda_2 - \lambda_1$.

U_e = Elemental temperatures

$$FRAC_{0-\lambda U_e} = \frac{15}{\pi^4} \sum_{m=1,2,\ldots} \frac{e^{-m\nu}}{m^4} \left\{ \left[(m\nu + 3)m\nu + 6 \right] m\nu + 6 \right\}, \nu \geq 2$$

$$FRAC_{0-\lambda U_e} = 1 - \frac{15}{\pi^4} \nu^3 \left\{ \frac{1}{3} - \frac{\nu}{8} + \frac{\nu^2}{60} - \frac{\nu^4}{5040} + \frac{\nu^6}{272160} - \frac{\nu^8}{13305600} \right\}, \nu < 2$$

$$\nu = \frac{PLANCK2}{\lambda U_e}, \text{where } PLANCK2 = \left. \begin{matrix} 25898\,\mu m^\circ R \\ 14388\,\mu m^\circ K \end{matrix} \right\} (TYP)$$

$$[R_e^\lambda]_n = [A\varepsilon(\lambda) - A\alpha(\lambda)(A - F(I - \alpha(\lambda)))^{-1} F\varepsilon(\lambda)]_n$$

$$\{Q_e^\lambda\}_n = -[R_e^\lambda]_n \begin{bmatrix} \diagdown & & \\ & f_e & \\ & & \diagdown \end{bmatrix} \{U_e\}^4$$

$$\{Q_e^\lambda\}^{net} = -[R_e^\lambda]^{net} \{U_e\}^4$$

where,

$$[R_e^\lambda]^{\mathrm{NET}} = \sum_{n=1}^{n_{max}} [R_e^\lambda]_n \begin{bmatrix} \diagdown & & \\ & f_e & \\ & & \diagdown \end{bmatrix}_n$$

E.2 Key Points regarding Spectral Radiation Band Analysis within NX Nastran

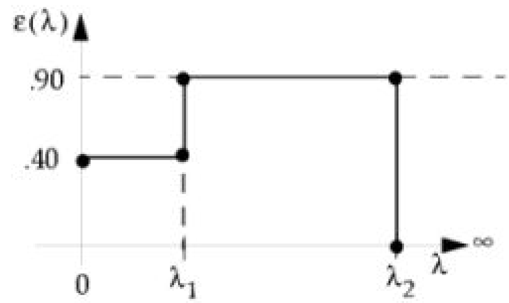
1. Only one RADBND (wavelength break point) entry can be specified with any input file. This does not mean that all surfaces of all cavities must display spectral surface behavior. For any surfaces which are to remain as grey or blackbody, each waveband emissivity value associated with its RADM entry can be given the same emissivity value resulting in a constant emissivity over all wavelengths. Recall that radiation material surface properties are associated with the CHBDYi surface element description, so every element in every cavity can potentially exhibit its own radiative character.

2. Temperature and/or wavelength dependent radiative surface properties can be applied to radiation enclosure analyses as well as the radiation boundary condition.

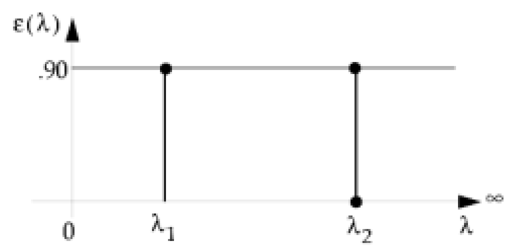
3. Within each waveband the emissivity must be a constant value. Each discontinuity (vertical jump) in the emissivity vs. wavelength piecewise linear curve must be input as a waveband of zero width.

4. The necessary inputs for spectral exchange in NX Nastran are given in "Thermal Capabilities".

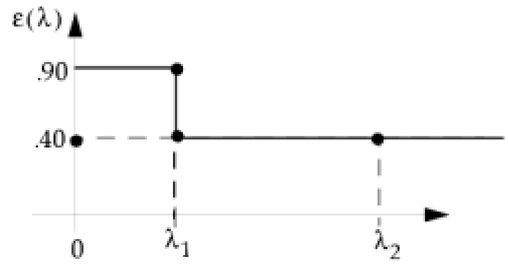
E.3 Input Example - Real Surface Behavior



RADBND	5	25898.	2.0	2.0	9.0
RADM	1	1.0	.40	.90	0.0



RADBND	3	25898.	2.0	9.0
RADM	1	1.0	.90	



RADBND	4	25898.	2.0	2.0	9.0
RADM	1	1.0	.90	.40	

Appendix

F Consistent Units for Thermal Analysis

NX Nastran is unitless. Accordingly, the units for physical quantities defining the geometry, material properties, and boundary conditions of an NX Nastran model must be consistent. Because NX Nastran cannot detect inconsistent units, a warning message is not issued when inconsistent units are used. The software simply calculates erroneous results.

For thermal analysis, it is usually advantageous to specify energy, length, time, and temperature as the base units. Table F-1 lists five sets of consistent units for use in thermal analysis with energy, length, time, and temperature used as base units.

Table F-1. Consistent Sets of Units for Thermal Analysis – Base Units of Energy, Length, Time, and Temperature

Physical Quantity	Dimen -sions	English lbf-in-s-F	English lbf-ft-s-F	SI μJ-mm-s-C	SI mJ-mm-s-C	SI J-m-s-C
Base units						
Energy	E	lbf·in	lbf·ft	μJ	mJ	J
Length	L	in	ft	mm	mm	m
Time	T	s	s	s	s	s
Temperature	θ	°F	°F	°C	°C	°C
Consistent units for typical inputs						
Coordinate	L	in	ft	mm	mm	m
Density	$E \cdot T^2/L^5$	$lbf \cdot s^2/in^4$	$slug/ft^3$	kg/mm^3	$tonne/mm^3$	kg/m^3
Heat flux	$E/T \cdot L^2$	lbf/in·s	lbf/ft·s	$\mu W/mm^2$	mW/mm^2	W/m^2
Heat transfer coef.	$E/T \cdot L^2 \cdot \theta$	lbf/in·s·°F	lbf/ft·s·°F	$\mu W/mm^2 \cdot °C$	$mW/mm^2 \cdot °C$	$W/m^2 \cdot °C$
Latent heat	L^2/T^2	in^2/s^2	ft^2/s^2	μJ/kg	mJ/tonne	J/kg
Mass	$E \cdot T^2/L^2$	$lbf \cdot s^2/in$	slug	kg	tonne	kg
Specific heat	$L^2/T^2 \cdot \theta$	$in^2/s^2 \cdot °F$	$ft^2/s^2 \cdot °F$	μJ/kg·°C	mJ/tonne·°C	J/kg·°C
Temperature	θ	°F	°F	°C	°C	°C
Thermal conductivity	E/T·L·θ	lbf/s·°F	lbf/s·°F	μW/mm·°C	mW/mm·°C	W/m·°C
Volumetric heat gen.	$E/T \cdot L^3$	$lbf/in^2 \cdot s$	$lbf/ft^2 \cdot s$	$\mu W/mm^3$	mW/mm^3	W/m^3
Consistent units for typical results						
Heat flux	$E/T \cdot L^2$	lbf/in·s	lbf/ft·s	$\mu W/mm^2$	mW/mm^2	W/m^2
Temperature	θ	°F	°F	°C	°C	°C
1 J = 1 N·m; 1 slug = 1 $lbf \cdot s^2/ft$; 1 tonne = 1000 kg; 1 W = 1 J/s						
E, L, T, and θ refer to energy, length, time, and temperature, respectively.						

In thermal analysis, specific heat and latent heat are always multiplied by the density. Because the underlying unit for mass identically cancels, only the units of the product of specific heat and density, or latent heat and density need be consistent with other units used in the analysis. For example, consider the units resulting from the product of specific heat and density when the underlying unit of mass is lbm:

(Btu/lbm·°F) x (lbm/ft^3) = Btu/ft^3·°F

Now consider the same product when slug is the underlying unit of mass:

(Btu/slug·°F) x (slug/ft^3) = Btu/ft^3·°F

The units associated with both products are identical.

Table F-2 makes use of this property to present two additional sets of consistent units that use Btu as the unit for energy and lbm as the unit for mass.

Table F-2. Consistent Sets of Units for Thermal Analysis using Customary Units

Physical Quantity	Dimen -sions	English Btu-in-min-F	English Btu-ft-hr-F
Base units			
Energy	E	Btu	Btu
Length	L	in	ft
Time	T	min	hr
Temperature	θ	°F	°F
Consistent units for typical inputs			
Coordinate	L	in	ft
Density	—	lbm/in^3	lbm/ft^3
Heat flux	E/T·L^2	Btu/min·in^2	Btu/hr·ft^2
Heat transfer coef.	E/T·L^2·θ	Btu/min·in^2·°F	Btu/hr·ft^2·°F
Latent heat	—	Btu/lbm	Btu/lbm
Mass	—	lbm	lbm
Specific heat	—	Btu/lbm·°F	Btu/lbm·°F
Temperature	θ	°F	°F
Thermal conductivity	E/T·L·θ	Btu/min·in·°F	Btu/hr·ft·°F
Volumetric heat gen.	E/T·L^3	Btu/min·in^3	Btu/hr·ft^3
Consistent units for typical results			
Heat flux	E/T·L^2	Btu/min·in^2	Btu/hr·ft^2
Temperature	θ	°F	°F
1 Btu = 778 ft-lbf			
E, L, T, and θ refer to energy, length, time, and temperature, respectively.			