Induction Furnaces:
Integrated MSC/EMAS, MSC/XL, and MSC/NASTRAN Analysis

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Abstract

A generic induction−heated high temperature furnace is modeled using MSC/EMAS to determine power loss density distribution in a 3−D segment with a cylindrical coil surrounding the furnace. MSC/XL is used to display color plots of furnace induced power loss density as well as magnetic flux density within furnace and coil components. MSC/XL is next used to generate internal heat generation records for an MSC/NASTRAN nonlinear steady state thermal analysis using a full radiation matrix (assuming radiation shields closely spaced). An alternative to full radiation analysis is presented using a theory developed for radiation−equivalent convection. The two methods are compared, and furnace temperature contours are presented using MSC/XL. Results of a C−language program are presented to calculate heat flux and display the results graphically. Finally, the authors present several recommendations for forthcoming releases of MSC/NASTRAN to improve user friendliness.

Introduction

A simplified generic high temperature induction furnace is sketched in Figure 1. It is assumed that a cylindrical crucible and charge being inductively heated are located within a circular coil. The furnace bottom is assumed adiabatic with heat transfer by radiation to a top shield, which is convectively cooled by the surrounding ambient. Table 1 contains electric, magnetic, and thermal properties of furnace components.

Figure 2a shows a solid element model of the furnace, which is 3 elements deep over a 30 degree segment. These solid elements are used in both electromagnetic and thermal analysis.

Figure 2b shows thermal surface elements on the crucible−charge surface and both surfaces on the radiation shields. These elements were created in MSC/XL as QUAD4 and TRIA3 elements by hand−connecting grid points such that active radiation surfaces face each other (using the right−hand rule). The MSC/XL command to find free faces does not ensure user−desired normals required for radiation analysis. Unique property identification numbers are assigned to the five radiation surface−element groups.

Figure 3 shows a 30 degree segment of a hexagonal crucible (and shields) with a cylindrical charge and coil. A one−twelfth furnace model could show power loss density and thermal gradients in the angular coordinate. An octagonal crystal−growing furnace [Reference 1] operates at high temperature with closely−spaced radiation shields. A 22.5 degree segment would be required to model such a furnace.

MSC/EMAS Induction Analysis

Figure 4 shows an MSC/EMAS model of the 30 degree segment in a completely cylindrical furnace. The figure shows all air within the furnace is modeled as well as outside air to a spherical surface. Open Boundary elements (QUADOB and TRIAOB) on the spherical surface simulate infinite air space around the furnace.

The two cut–planes (at zero and 30 degrees) require cylindrical displacement coordinates such that tangential magnetic vector potential DOF may be constrained. Furnace axis grid points are constrained in DOF 2.

The fourth DOF, psi, must be included in MSC/EMAS models that have truly 3–D eddy currents [2]. Inclusion of psi allows eddy current J to be discontinuous at interfaces of conductors and nonconductors, even though magnetic vector potential A is continuous. The boundary conditions on psi for the furnace model are the natural boundary conditions on all boundaries that have no current J. However, it is known that substantial current J will pass through the zero –degree and 30–degree cut–plane boundaries, and thus psi must be constrained to zero on these two surfaces.

An excitation current density is applied to the three coil elements using the CUR-DEN record (with the cylindrical coordinate system).

MSC/EMAS AC Analysis (SOL 302) is used to impose high frequency current on the model. MSC/XL is used to generate constraints, dynamic and static load records, as well as Case Control for induction analysis. Output requests include magnetic vector potential and solid element fields, which includes the scalar power loss density. The printout file includes a total power loss summary. This result, in addition to total power loss by element property identification, is available using MSC/XL and the results database.

MSC/EMAS Results

Figure 5 shows line contours of furnace power loss density for the Figure 4 model. The figure shows highest power loss density occurs at the upper crucible circumference with a maximum of 3.1 W/cm^3.

Figure 6 shows an arrow plot of magnetic flux density (teslas) for the Figure 4 model.

Table 2 summarizes induced power loss in the four conductive furnace components (Table 1). Total power loss in the table agrees with the MSC/EMAS printout summary.

MSC/NASTRAN QVOL Records

MSC/XL will automatically create internal heat generation records (QVOL) from the power loss results of an MSC/EMAS solution for use in a subsequent MSC/NASTRAN thermal analysis. MSC/XL Version 3A required the user to supply a continuation field for double field records output (or edit the records to single field). However, that is no longer required in Version 3B.

MSC/NASTRAN Radiation—Equivalent Convection Analysis

Theory

Two closely—spaced surfaces may exchange heat by thermal radiation. Each surface is one meter square and spaced on the order of 1 mm such that the geometric view factor between opposing subsurfaces is unity.

Radiation heat flux between the two surfaces may be hand calculated as follows:

$$q = \varepsilon_{eff}\, \sigma\, (T_h^4 - T_c^4) \quad W/m^2 \qquad\qquad 1)$$

where temperatures are absolute (K) by adding 273 C to temperatures in C. The effective emissivity [3] and Stefan—Boltzmann constant are defined as follows:

$$\varepsilon_{eff} = 1\, /\, [1/\varepsilon_h + 1/\varepsilon_c - 1], \qquad\qquad 2a)$$

$$\sigma = 5.67E{-}8\ W/m^2\,K^4 \qquad\qquad 2b).$$

If $\varepsilon_h = \varepsilon_c = 0.8$, $T_h = 773$ K, and $T_c = 373$ K, then $\varepsilon_{eff} = 0.666$ and Eq. 1 yields $q = 12{,}752$ W/m^2 in good agreement with 12,841 W/m^2 from MSC/NASTRAN.

Equation 1 may be written in the form of convection between the hot surface and cold surface as follows:

$$q = h_r\, (T_h - T_c). \qquad\qquad 3)$$

Equating Eqs. 1 and 3 yields a radiation−equivalent convection heat transfer coefficient:

$$h_r = \varepsilon_{eff}\, \sigma\, (T_h^4 - T_c^4) / (T_h - T_c)$$
$$= \varepsilon_{eff}\, \sigma\, (T_h^2 + T_c^2)\, (T_h + T_c) \qquad 4)$$

Using this radiation−equivalent convection coefficient, the heat flux may be calculated (Eq. 3) as follows:

$$q = \varepsilon_{eff}(\sigma * 10^6) * [(T_h/100)^2 + (T_c/100)^2] * [(T_h/100) + (T_c/100)] * (T_h - T_c) \qquad 5)$$

$$= 0.666\, (5.67E-2) * [59.753 + 13.913] * [7.73 + 3.73] * (773 - 373)$$

$$= 12,751 \text{ W/m}^2.$$

This compares favorably with MSC/NASTRAN radiation heat flux (see above) and convection analysis heat flux of 12,829 W/m^2 using T_c as reference temperature on HBDY records.

Floating Constant Reference Temperature Between Surfaces

An alternative to using cold surface temperatures as reference temperatures to the hot surface is desirable. An MSC/NASTRAN SPOINT (scalar point) temperature is allowed to "float" for radiation−equivalent convection from the hot surface to the reference temperature and from the reference temperature to the cold surface. This series convection heat flow requires a convection coefficient on the hot surface (h_1) and a convection coefficient on the cold surface (h_2). Series heat transfer requires:

$$h_1(T_h - T_r) = h_2(T_r - T_c) = h_r\, (T_h - T_c) \qquad 6)$$

These two equations result in the following relationships between h_r, h_1, h_2, and T_r:

$$1/h_r = 1/h_1 + 1/h_2 \; ; \; h_r = h_1 * h_2 \, / \, (h_1 + h_2) \qquad \text{7a)}$$

$$T_r = (h_1 * T_h + h_2 * T_c) \, / \, (h_1 + h_2) \qquad \text{7b)}$$

If $h_1 = h_2$, then $h_1 = h_2 = 2h_r$ and $T_r = (T_h + T_c)/2$.

Floating Temperature with Temperature – Dependent h

MSC/NASTRAN evaluates temperature – dependent convection coefficients at an average of surface temperature and reference temperature. Rewriting Eq. 4 (using a floating reference temperature, T_r) and $T_h = T_c = T$ results in the following equation for the hot and cold surfaces:

$$h = 2 \, \varepsilon_{eff} * \sigma * 4 \, T^3 \qquad \text{8)}$$

where $T = (T_h + T_r)/2$ for the hot surface, and $T = (T_r + T_c)/2$ for the cold surface.

Table 3 shows hand calculations for low–temperature and high–temperature radiation–equivalent convection analysis of closely–spaced surfaces using Eq. 8. The two surface flux equations yield reference temperature and flux. Full radiation matrix heat flux is also tabulated.

The Eq. 8 relationship for a temperature–dependent convection coefficient may be input to MSC/NASTRAN using MAT4, MATT4, and TABLEM1 records. The user adjusts for the $2*(\varepsilon_{eff})*\sigma$ product on a MAT4 record, which is multiplied by the temperature function for total heat transfer coefficient.

MSC/NASTRAN Nonlinear Steady–State Thermal Analysis

The Fig. 2a furnace model (without air or coil) is evaluated for three levels of power loss density calculated in MSC/EMAS using the MSC/XL–generated

QVOL records. Radiation zone surface elements shown in Fig. 2b are closely spaced (1.0 mm) to obtain a full radiation matrix (RADMTX and RADLST) using the VIEW module. This matrix is used for radiation heat transfer using Table 1 thermal emissivity. The upper surface of Radiation Shield 2 is convectively cooled with a coefficient of 0.05 W/cm^2 C and a 100^0 C ambient.

Next, the Figure 2a model (without air or coil) is evaluated with the same ambient heat sink at three input powers using the Figure 2b surface elements for radiation − equivalent convection analysis as detailed above. Table 4 summarizes calculation of the constant term in Eq. 8 for the two radiation zones. A single TABLEM1 record inputs the $4*(T/100)^3$ temperature relationship for both radiation zones.

MSC/NASTRAN SOL 74 is used in both thermal analyses using a convergence factor (EPSHT) of 0.001 and a maximum of 200 iterations. The parameters TABS = 273. and SIGMA = 5.67E−12 are used in full radiation analysis. Since only the ambient is constrained at 100^0 C, a default temperature (TEMPD) of 1500^0 C is used for the required initial temperature estimate in Nonlinear Steady−State Analysis.

The cut−plane cylindrical displacement coordinate system must be removed in MSC/NASTRAN V67 analysis so that the VECPLOT module outputs OLOAD resultant in agreement with MSC/EMAS. Iteration convergence is improved using a Basic displacement coordinate system. The Apollo editor "block delete" command may be used, or MSC/XL may modify all grid points.

MSC/NASTRAN Temperature Results

Figure 7 shows an MSC/XL flat−shade temperature contour display of furnace temperature distribution at 100 percent power loss density input using the full radiation matrix. The figure shows temperature variation from 296 C (Shield 2) to 1601 C on the crucible.

Figure 8 shows a similar temperature distribution plot using the radiation—equivalent convection analysis. Comparing this figure to Fig. 7 shows maximum temperature agreement within 3 percent.

Table 5 compares temperature extremes in the furnace at 100 percent, 50 percent, and 35 percent of the MSC/EMAS power loss density. The table also shows the convergence factor value at normal convergence. Floating reference temperatures in the two radiation zones using radiation—equivalent convection analysis are also tabulated.

A Nonlinear Steady—State Thermal analysis at 25 percent input power was unstable for both analysis techniques.

Thermal Heat Flux

MSC/NASTRAN HBDY elements output total heat flow (Watts) rather than the useful heat flux (W/cm^2). The sign convention is that negative heat flows from a surface element, while positive heat flows to the element. SOL 74 reanalysis was required in V65 (with temperature—dependent conduction and convection properties) using initial—run temperatures as the initial temperature profile. Heat flow into sinks (SPCF) also required a second analysis. This is not necessary in V67, and heat flow into sinks closely agrees with the OLOAD resultant.

A C—language program was written to read the printout file (using parameter EST,1 to output HBDY element area), divide HBDY heat flow by area for heat flux, and output an MSC/XL Results Import file with absolute and signed heat flux for surface elements. The program also echoes solid element heat flux as well as absolute value of the heat flux resultant for each conduction element.

Figure 9 shows absolute heat flux for the Figure 7 model using the MSC/XL Results Import file. Figure 2b plate elements are required for this display, since MSC/XL does not recognize HBDY elements. The figure shows similar heat flux entering and leaving Radiation Shield 2.

Concluding Remarks

This integrated analysis of a generic high–temperature induction furnace shows that MSC/XL serves as a link between MSC/EMAS and MSC/NASTRAN analyses. Several useful features are described above as well as a few minor short–comings in MSC/XL V3a and MSC/NASTRAN V67. The following suggestions are expected to be largely satisfied with a new thermal analyzer in MSC/NAS-TRAN V68 (and upgraded MSC/XL):

- Multiple radiation zones RADMTX – RADLST records will allow automatic assembly of the global radiation matrix with the VIEW module processing surface elements serially in user–selected zones isolated from each other. This will allow use of "Can–shade" and "Can–be–shaded" flags in a judicious manner within selected zones. Also, much improvement is required in directing active HBDY element surface normals so they "see" each other.

- MSC/EMAS and MSC/NASTRAN Nonlinear solvers (SOL 66, SOL 99, SOL 304, SOL 305, Etc.) must be applied to thermal analysis to expand user options for convergence.

- MSC/XL Version 3B accepts all electromagnetic, structural, and thermal records in both large–field and small–field format, making coupled Power loss and Thermal analysis even easier. A visually appealing color plot of electromagnetic, structural, and thermal results should have edges of solid elements outlined by PID as is available for 2–D models. This is accomplished currently using CBAR and CLINE elements.

Acknowledgement

References

1. Rajendran, S., et al, "Magnetic and thermal field model of EFG system", Journal of Crystal Growth, 1991, pp 82–87.

2. Brauer, J., et al, "3–D Eddy Current Computations Using Magnetic Vector Potential and Time–Integrated Electric Scalar Potential," Proceedings of the IGTE Conference, University of Graz, Graz, Austria, June 1992.

3. Kreith, F., **Principles of Heat Transfer**, International Text-book Co., Scranton, PA, 1958, Chapter 5.

Table 1

Generic Furnace Material Properties

(Thermal Conductivity in W/Cm ^{0}C)

Component Name	Electrical Conductivity (S/M)	Magnetic Relative Permeability	Thermal Conductivity			Thermal Emissivity (Dimensionless)
			500 ^{0}C	1000 ^{0}C	2000 ^{0}C	
Crucible	120,000	1.0	0.6	0.4	0.25	0.8
Charge	1,200,000	1.0	0.4	0.4	0.4	0.8
Shield 1	80,000	1.0	0.5	0.4	0.3	0.5
Shield 2	80,000	1.0	0.5	0.4	0.3	0.65
Coil	0	1.0				

Table 2

MSC/EMAS Induced Power Loss Summary (30 Degree Segment)

Furnace Component*	Power Loss (KW)
Crucible	0.621
Charge	0.002
Shield 1	0.132
Shield 2	0.026
Total	0.781

* See Figure 1

Table 3

Hand Calculation of Radiation-Equivalent Heat Flux

Using Eq. 8 with Surface Emissivity = 0.8

Condition	Hot Surface		Cold Surface		Surface Flux (W/m²) *	T_r^{**}(C)	Heat Flux Resultant KW/m²		
	C	K	C	K			Hot	Cold	Rad. Mtx.
Low–Temp	500	773	100	373	$h_{10}*4*((773+T_r)/200)^3*(773-T_r)$ $h_{20}*4*((T_r+373)/200)^3*(T_r-373)$	390.8	12.23	12.23	12.84
High–Temp	2000	2273	1500	1773	$h_{10}*4*((2273+T_r)/200)^3*(2273-T_r)$ $h_{20}*4*((T_r+1773)/200)^3*(T_r-1773)$	1795.4	632.2	632.2	634.8

* $h_{10} = h_{20} = 2 * \varepsilon_{eff} * \sigma * 1.E6 = 0.07552$

** Trial and Error Solution

Table 4

Constant Factor in Equation 8 Radiation—Equivalent Convection Coefficient

Radiation Zone*	Surface Emissivity*		ε_{eff}**	$2 * \varepsilon_{eff} * \sigma * 1.E6$
1	0.8	0.5	0.444	5.04E−6
2	0.5	0.65	0.394	4.47E−6

*   See Table 1 and Figure 2b

** $\varepsilon_{eff} = 1/[(1/\varepsilon_1) + (1/\varepsilon_2) - 1]$

     $\sigma = 5.67E-12 \ \text{W/Cm}^2 \text{ K}^4$

Table 5

Thermal Analysis Summary (Temperatures in Degrees C)

Input Power	Full Radiation Matrix Analysis			Radiation Equivalent Convection Analysis				
(Percent)	Max. T	Min. T	EPSHT*	Max. T	Min. T	EPSHT*	Z1 T_r	Z2 T_r
100	1601	296	5.46E−5	1646	330	6.68E−4	1422	1042
50	1234	201	6.82E−4	1269	215	6.82E−4	1134	831
35	1088	172	4.74E−4	1118	180	7.67E−4	1008	737
25	UNSTABLE							

* EPSHT at Normal Convergence
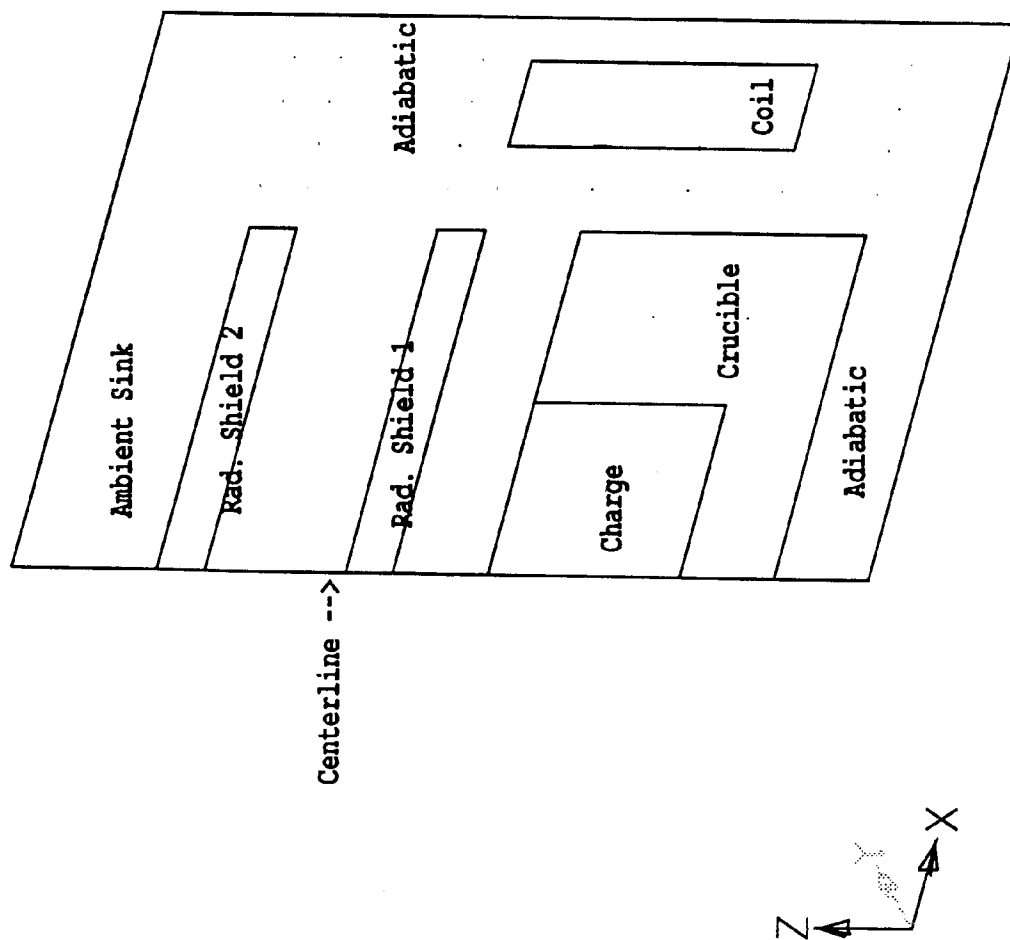
Figure 1 Generic Induction Furnace Components

Ambient Sink

Rad. Shield 2

Rad. Shield 1

Centerline -->

Adiabatic

Coil

Charge

Crucible

Adiabatic

X

Z
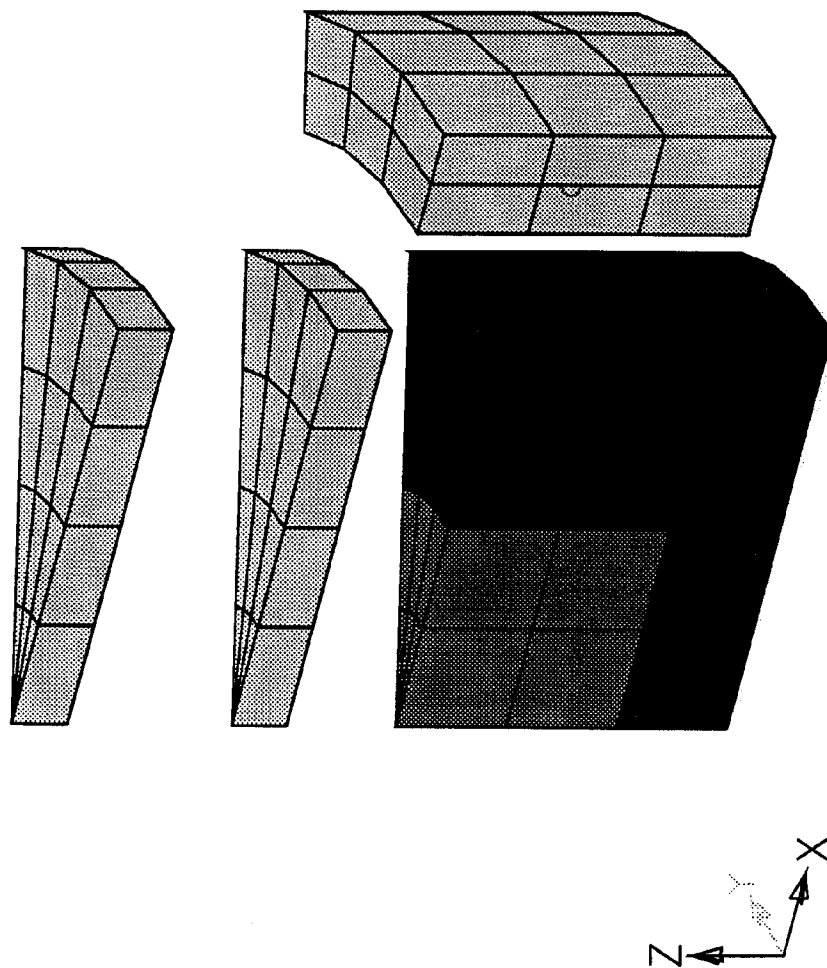
Figure 2a   Generic Furnace, 3-D Model, 30 Degree Segment

Convection Zone 3
Shield 2 to Ambient
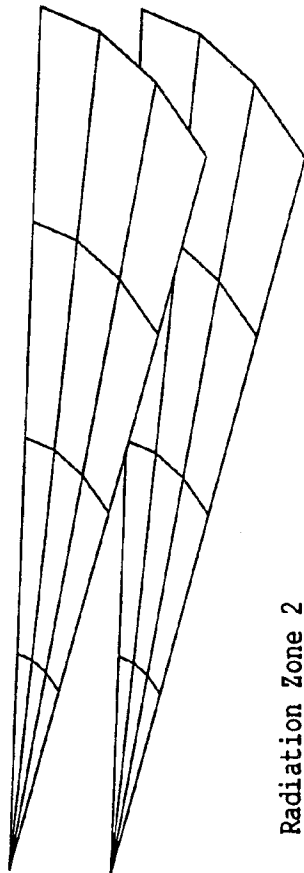
Radiation Zone 2
Shield 1 to Shield 2
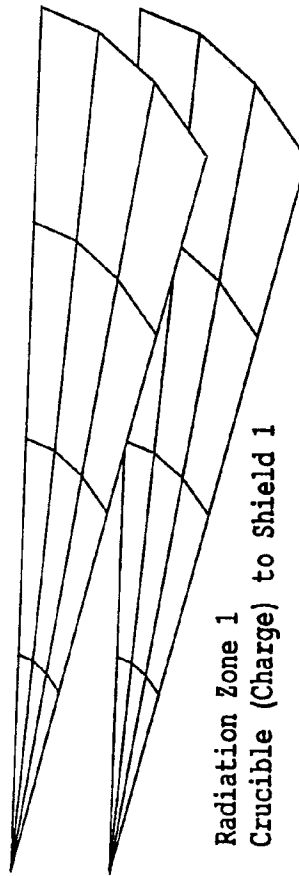
Radiation Zone 1
Crucible (Charge) to Shield 1
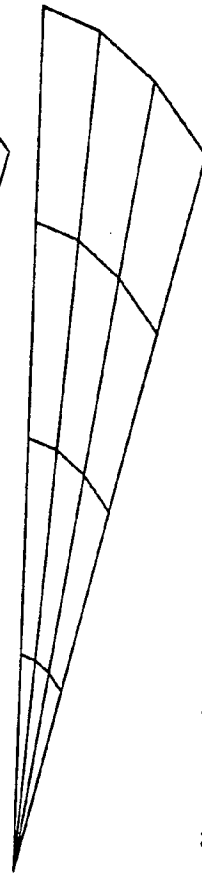
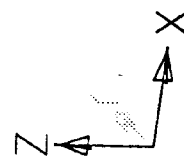Figure 2b Generic Furnace Radiation Zones
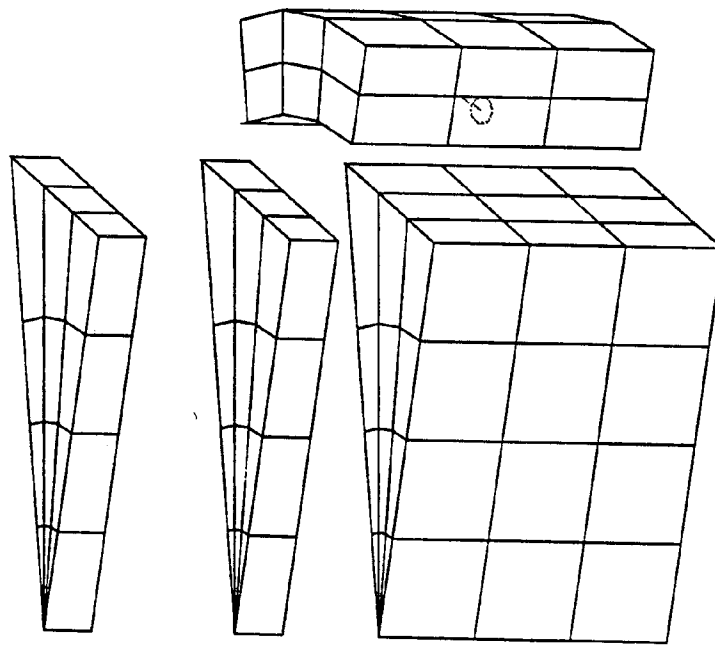
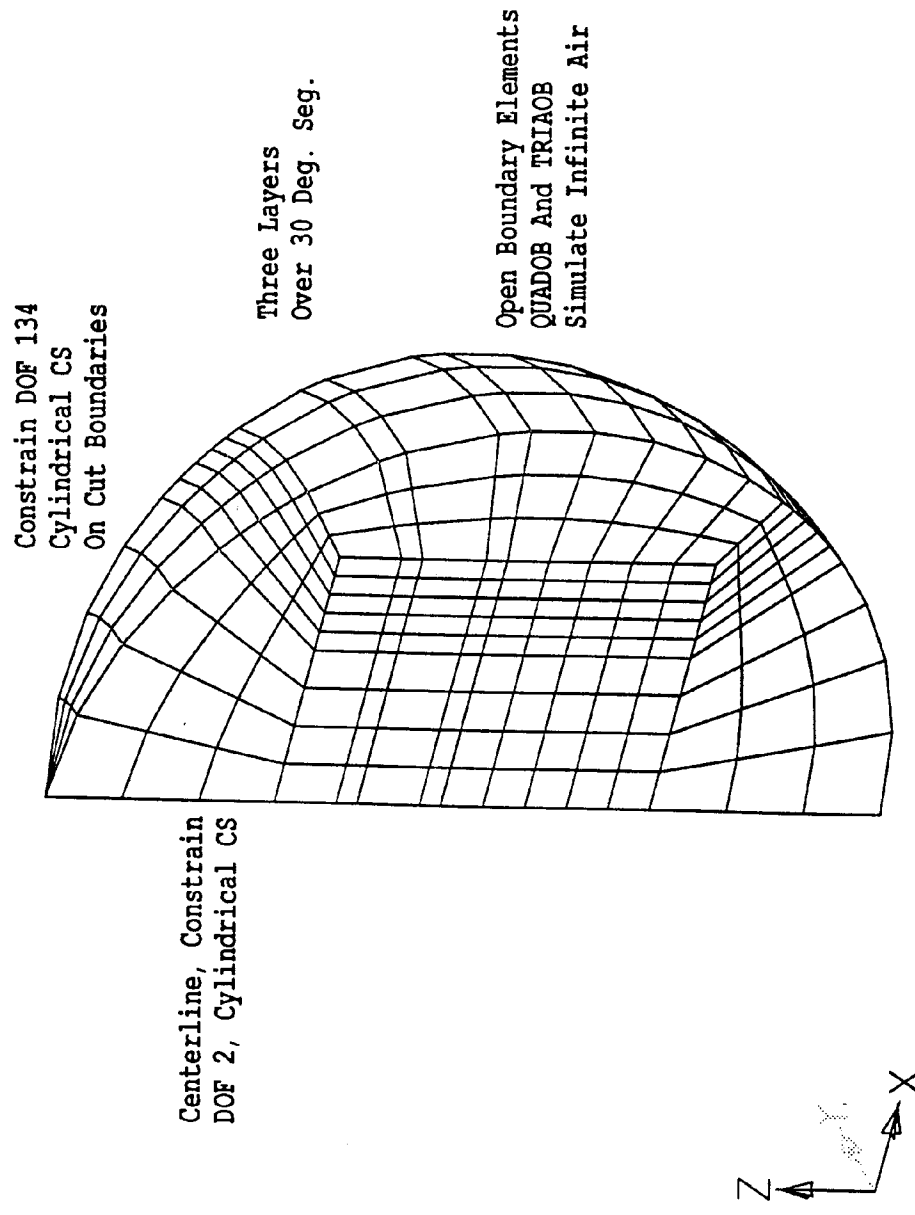Figure 3 Generic Furnace, 3-D Model, Hexagonal Crucible
Charge and Coil are Cylindrical
Model One Twelth of Furnace

Constrain DOF 134
Cylindrical CS
On Cut Boundaries

Three Layers
Over 30 Deg. Seg.

Open Boundary Elements
QUADOB And TRIAOB
Simulate Infinite Air

Centerline, Constrain
DOF 2, Cylindrical CS

Z

X

Figure 4   MSC/EMAS Induced Power Loss Finite Element Model

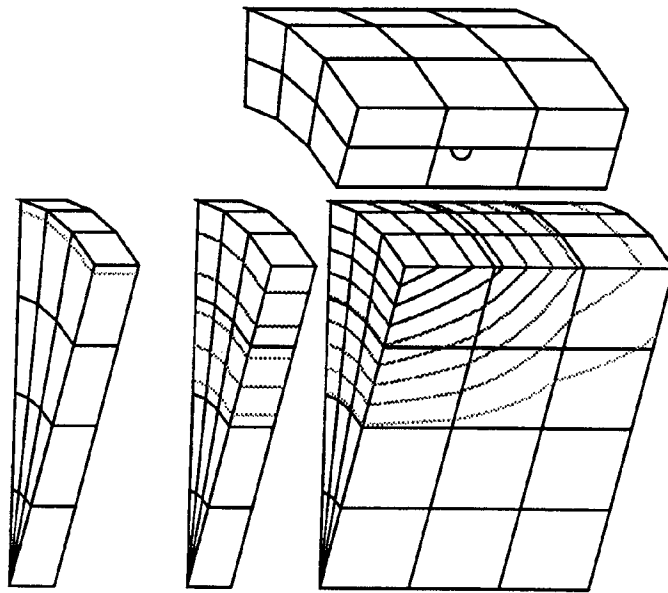-1.0e-15 3.4e+05 6.9e+05 1.0e+06 1.4e+06 1.7e+06 2.1e+06 2.4e+06 2.7e+06 3.1e+06
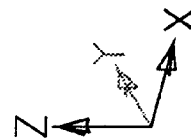
Figure 5 Generic Furnace, Power Loss Density Contours
Coil Current Density: Input as Amps/Sq. Meter
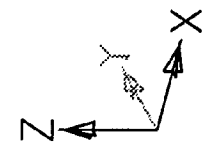Power Loss Density: Watts/Cubic Meter
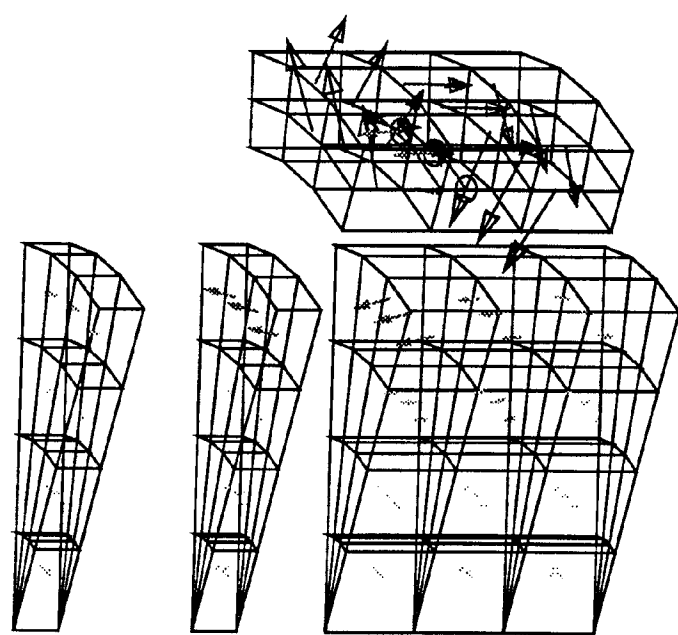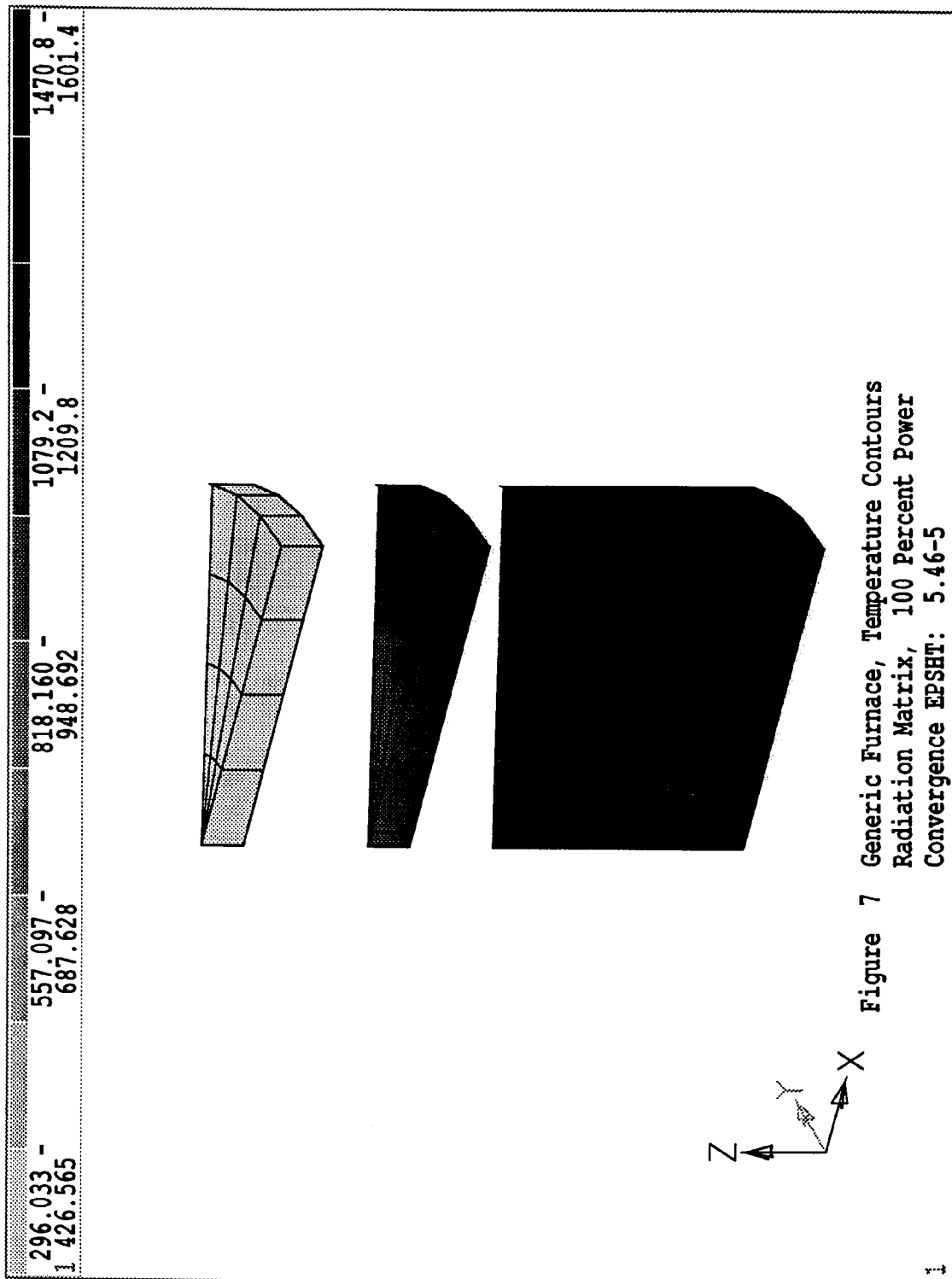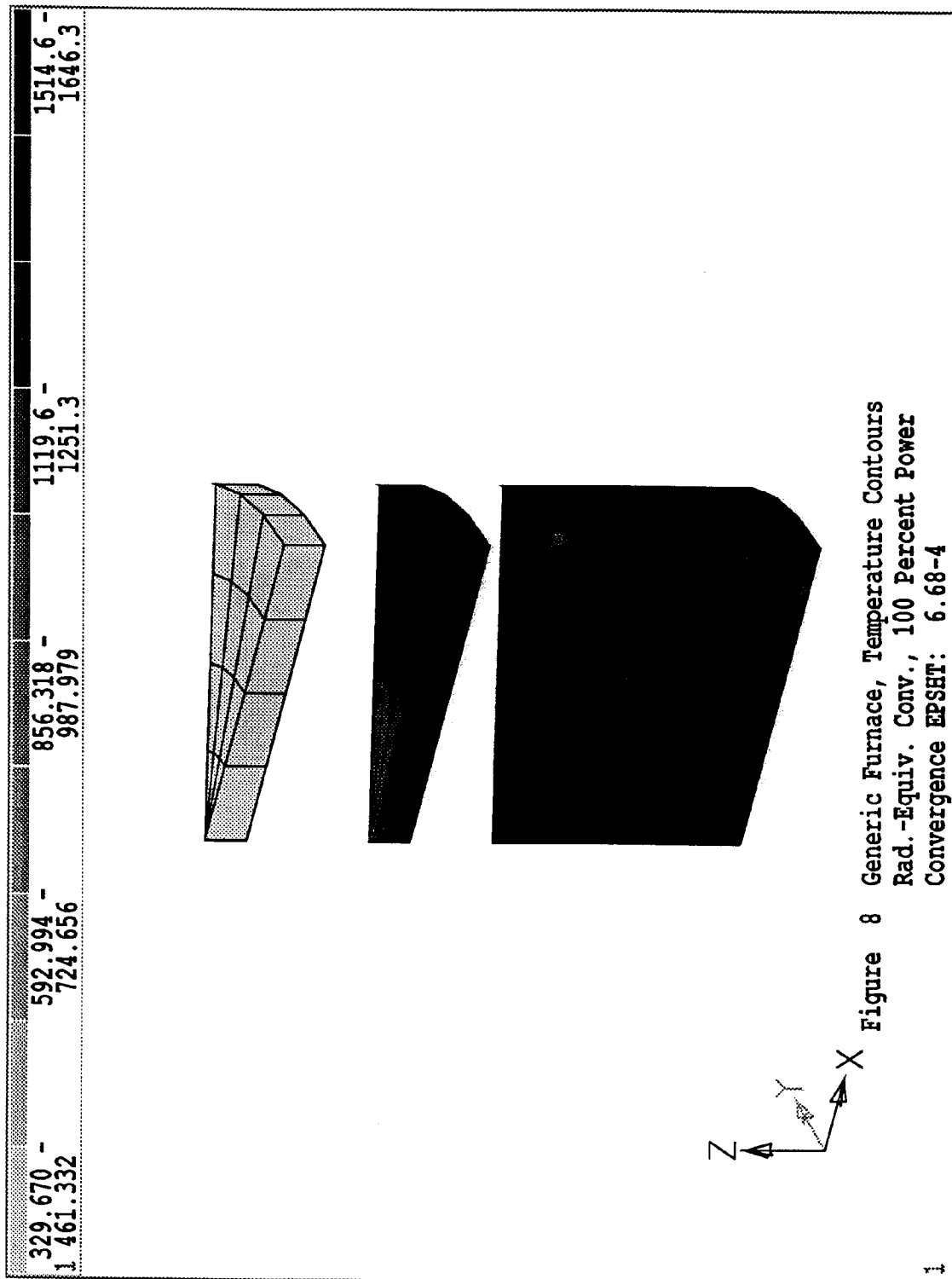
Figure 6 Generic Furnace, Magnetic Flux Density Arrow Plot
Coil Current Density: Input as Amps/Sq. Meter
Magnetic Flux Density in Teslas

Figure 7 Generic Furnace, Temperature Contours
Radiation Matrix, 100 Percent Power
Convergence EPSHT: 5.46-5

296.033 -   557.097 -   818.160 -   1079.2 -   1470.8 -
1 426.565   687.628   948.692   1209.8   1601.4

329.670 — 592.994 — 856.318 — 1119.6 — 1514.6 —
1 461.332 724.656 987.979 1251.3 1646.3

Figure 8 Generic Furnace, Temperature Contours
Rad.-Equiv. Conv., 100 Percent Power
Convergence EPSHT: 6.68-4

5.07816 - 5.83142 - 6.58468 - 7.33794 - 8.09120 - 8.84445 - 9.59771 - 10.351 - 11.104 - 11.857 -
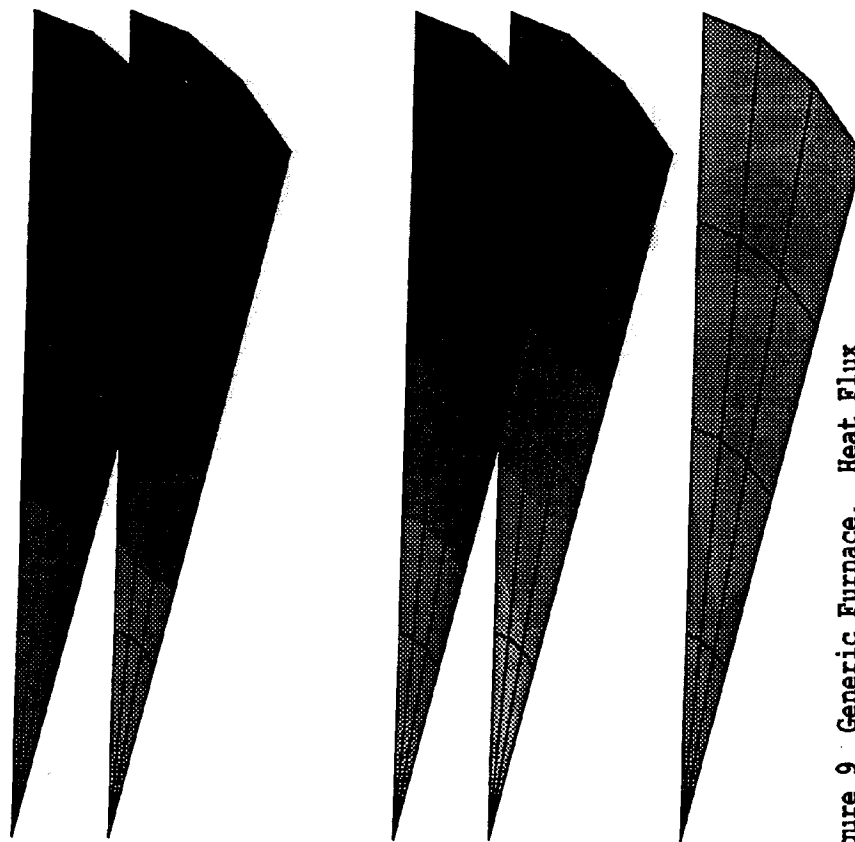5.83142   6.58468   7.33794   8.09120   8.84445   9.59771   10.351   11.104   11.857   12.611

Figure 9 Generic Furnace, Heat Flux
Radiation Matrix, 100 Percent Power
Watts/Sq. Cm., Absolute Flux