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THERMAL STRESS ANALYSIS OF THE SLAC MOVEABLE MASK

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ABSTRACT

X-ray beams emerging from the new SLAC electron-positron storage ring (PEP) can impinge on the walls of tangential divertor channels. A moveable mask made of 6061-T6 aluminum is installed in the channel to limit wall heating. The mask is cooled with water flowing axially at 30 °C. Beam strikes on the mask cause highly localized heating in the channel structure. Analyses were completed to determine the temperatures and thermally-induced stresses due to this heating. The current design and operating conditions should result in the entrance to the moveable mask operating at a peak temperature of 88 °C with a peak thermal stress at 19% of the yield of 6061-T6 aluminum.

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SUMMARY

X-ray beams emerging from the undulator of the new SLAC electron-positron storage ring (PEP) can impinge on the uncooled portions of the walls of tangential divertor channels. This causes highly localized heating and thus highly localized thermal stresses in the channel structure. A water cooled mask is installed in the channel to intercept the portions of the x-ray beams which could strike the channel walls. Shifting the beam orientation can cause a corresponding shift in this locally heated and stressed region.

The resultant temperatures and thermally-induced stresses in the moveable mask were determined using the LLNL finite element heat transfer computer code TACO3D and the LLNL finite element structural computer code GEMINI. The geometry of the 6061-T6 aluminum structure is described in Figure 1. Room temperature thermal/mechanical properties are used for the 6061-T6 aluminum. The x-ray beam, originating from the undulator falls, at the midpoint of the 10^{o} ramp surface. The absorbed x-rays are modeled as a "local heat generation". All surfaces are assumed to be adiabatic except the outside surfaces of the walls parallel to the plane of symmetry. Water flows axially over these outside surfaces at 30 ^{o}C. All surfaces are assumed to be structurally free (unloaded and able to move in any direction) except the centerplane and the rear plane which have zero displacement limits.

The peak temperature for the mid-ramp beam strike is 88 ^{o}C. The peak thermal stress is 48.8 MPa, or about 19% of the yield stress for 6061-T6 aluminum.

INTRODUCTION

X-ray beams originating in the undulator of the new SLAC electron-positron storage ring (PEP) will fall on uncooled portions of the walls in the ring's tangential side channels. These regions are protected from overheating by water-cooled masks installed inside the channels (Figure 1). The moveable mask being reviewed in this analysis is made of 6061-T6 aluminum.

The beams strike the mask causing highly localized heating. This heating can vary in location because of shifts in the magnetic fields of the undulator. Highly localized heating in a constrained structure will induce large local thermal stresses. Thermal stresses occurring in other components of these channels have been analyzed previously (References 1 and 2).

Analyses were completed to determine the resultant temperatures and thermally-induced stresses in the moveable mask for one beam strike location; i.e. mid-way up the mask's 10^{o} ramp on the symmetry line. The temperature distributions are calculated based on a three dimensional, steady state, linear heat transfer analysis using the LLNL finite element computer code, TACO3D. The calculated temperatures were used as input for the three dimensional, steady state, linear stress analyses using the LLNL finite element computer code GEMINI to determine the thermally-induced stresses.

DISCUSSION

Mask Geometry

The moveable mask is a ramped, rectangular structure made from 6061-T6 aluminum (Figure 1). The figure has been rotated 90° from its installed orientation. Since the heating is symmetric, the mask is modeled as a half-symmetry problem to keep the number of nodes and elements to a minimum. All dimensions in the figures and the text are given in millimeters. The ramped inner face inclines at an angle of 10° to the horizontal (yz) plane and the outside surface of the top and bottom walls is finned.

Model Boundary Conditions

The thermal boundary conditions are summarized in Figure 2. All surfaces are assumed to be adiabatic (no energy flow across the surface) with the exception of the outside surface. The effects of thermal radiation heat transfer are neglected. The outside surface of the half section is water-cooled and has 24 channels running parallel to the z-axis. Each channel is 6.35 mm high and 1.35 mm wide. Each fin is 6.35 mm high and 1.52 mm wide. The 24 channels are arranged in two groups of twelve with a "spacer fin" 2.65 mm wide between the two groups.

To simplify the analysis further, the fins were not modeled as discrete elements, but their influence is included by using a higher effective heat transfer coefficient on this surface. The heat transfer coefficient is scaled using a ratio of the actual finned surface area to the corresponding surface area used in the model (i.e. a flat surface in place of the fins). The heat transfer coefficient "amplification factor" resulting from the finned surfaces is 5.55.

The heat transfer coefficient for the flow in the channels was calculated as follows. The 30 ^{o}C water flows at a velocity of 6.1 m/sec. The channel geometry equates to a hydraulic diameter, d, of 2.[illegible]21x10^{-3} m. For 30 ^{o}C water, the Prandtl number, Pr, is 5.49, the kinematic viscosity, ν, is 8.09 x 10^{-7} m^2/sec, and the thermal conductivity, k, is 0.619 W/m ^{o}C. At a velocity, V, of 6.1 m/s, the Reynold's Number, Re_d, equals 1.675x10^{4}. Using the most popular relation for turbulent flow in a channel,

$$Nu_d = (.023)(Re_d^{0.8})(Pr^{0.4})$$

the Nusselt number, Nu_d, is 108.0. The heat transfer coefficient is defined from the Nusselt number by,

$$h_d = \frac{(Nu_d)k}{d}$$

Thus, h_d is 3.04x10^{4} W/m^2 ^{o}C. Applying the heat transfer coefficient "amplification factor" for the finned surfaces, the modified heat transfer coefficient is 1.67x10^{5} W/m^2 ^{o}C.

The structural boundary conditions are also described in Figure 1. All surfaces are assumed to be free (unloaded and able to move in any direction) with the exception of the symmetry planes and the rear plane. The allowable displacement perpendicular to these planes is fixed to zero. The node on the corner of the x=0 plane, the rear plane, and the outside surface of the wall has its allowable "x" displacement set to zero.

There are no pressure loads applied to the convectively cooled walls due to coolant pressure because the hydrostatic pressure (about 200 psi) is significantly lower than the expected thermal stresses (about 10 kpsi).

Heat Loads

The depth of penetration of a given energy level of x-ray is inversely proportional to the electron density (which is nearly proportional to the mass density). Since the x-rays are absorbed over a significant depth in this aluminum, the absorbed energy heat load is modeled as a "local heat generation". For this case (modeling the thermal loading from the x-ray beam originating in the undulator) the beam, 6.5 mm tall, 1.5 mm thick, and centered at 44.45 mm from the yz plane, falls on the ramped portion of the crotch. Each beam is assumed to be uniform over its cross section. The total beam power is 475 watts. The x-ray energy deposition rate and its corresponding local heat generation rate is given in Table III of Reference 1.

Material Properties of 6061-T6 Aluminum

The moveable mask is made of 6061-T6 aluminum. The analyses used the following room temperature thermal and mechanical properties for this material (References 3 and 4).

density	= 2710 kg/m^3
specific heat	= 963 (W s)/kg K
conductivity	= 166.15 W/m K
thermal expansion coefficient	= 2.369 x 10-5 m/m K
elastic modulus	= 68,900 MPa (10100 kpsi)
Poisson's ratio	= 0.3
yield strength	= 283 MPa (41.6 kpsi)

The thermal properties of 6061-T6 aluminum do not change significantly over the expected temperature range 0 ^{o}C to 150 ^{o}C. The temperature variations are described in Reference 1. Comparisons with the yield stress will be made based on the local temperature of the element.

Finite Element Zoning

The SLIC computer code, a 2-D and 3-D finite element mesh generator developed at LLNL, was used to zone the parts for the finite element analyses. Table I gives the number of nodes and elements for each case. Variable spacing between nodes was used to concentrate nodes in areas of high thermal gradients (and, thus high thermal-stress levels). The high gradients were expected near the interfaces between the hot volumes absorbing the x-rays and the unheated adjacent volumes (Figure 3). The same zoning was used for the TACO3D heat transfer calculations and the GEMINI stress calculations.

RESULTS

Thermal Analyses

A summary of the results of the analyses is documented as maximum temperature and stress in Table I and as isotherm plots and isobar plots in Figures 3 through 8. The peak temperature for the mid-ramp strike is 88 °C It is located on the surface of the ramp at the center of the beam. The temperature gradients are especially high within 6 to 9 beam hal widths (about 2 mm to 5 mm) of the location of the peak temperature. The high thermal conductivity of the aluminum contributes to much lower temperatures outside this region.

Stress Analyses

For the mid-ramp beam strike case, the peak thermal stress is 48.8 MPa (7.2 kpsi). The effective stresses are used for comparison with the material's yield stress. The peak is about 19% of the yield stress for 6061-T6 aluminum (defined at the local element temperature). The high stresses are concentrated in a small volume near the beam strike.

Additional isobar contour plots of the thermally-induced stresses cases are given in the Appendix. The principal stresses (Appendix) are used for defining the direction and type of stress (i.e. tensile or compressive).

CONCLUSIONS

The current design and operating conditions should result in the moveable mask running at a peak temperature of 88 ^{o}C with a peak thermal stress of 19% of yield.

REFERENCES

1. Johnson, Gary L., Werner Stein, Stephen C. Lu, and Robert A. Riddle, "SLAC Divertor Channel Entrance Thermal Stress Analysis," LLNL Report UCID - 20498, July 1985.

2. Johnson, Gary L., Raymond E. Pierce, "Thermal Stress Analysis of the SLAC Fixed Mask," LLNL Report UCID - 20498 (Addendum), July 1985.

3. Metals' Handbook, 8th edition and the Structural Alloy Handbook, 1973.

4. Kreith, F.,"Principles of Heat Transfer",Intext Educational Publishers, N.Y., N.Y., 1976.

Table I

Analyses Cases Synopsis

Location of Heating	Beam Height/Width (mm)	Number of Nodes	Number of Elements
mid-ramp	1.5/6.5	2550	1856

Analysis Results Synopsis

Maximum Temperature (°C)	Location of Max. T (Node No.)	Maximum Stress (MPa)	Location of Max. Stress (Elem No.)	Maximum Stress* (%of Yield)
88.	1282	48.8	102	18.7

* Versus tensile yield at the temperature of the maximum stress element.

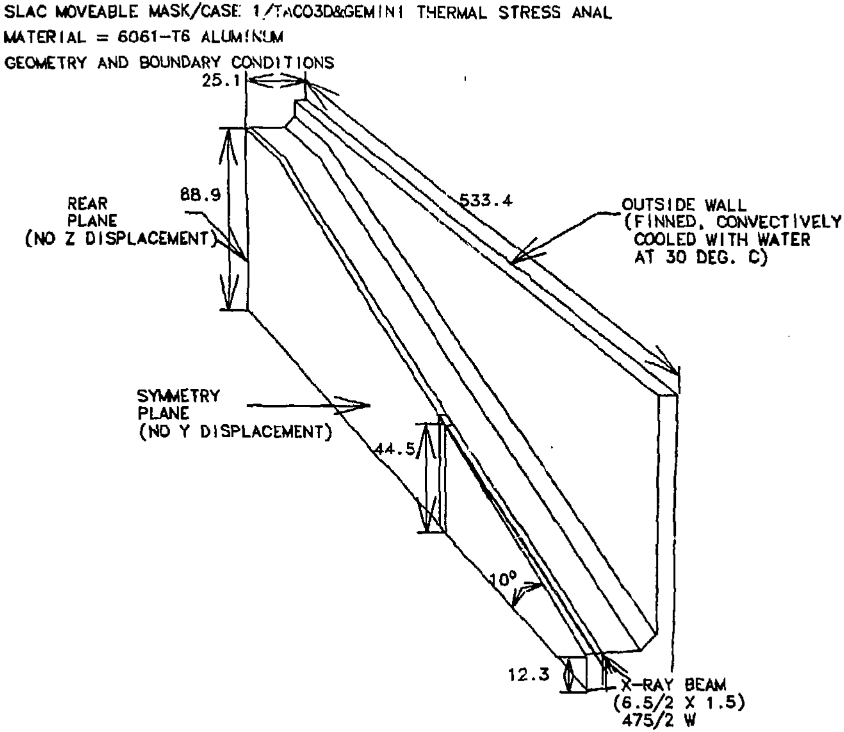


Figure 1. Schematic of the moveable mask (including boundary conditions) with the characteristic dimensions in mm.

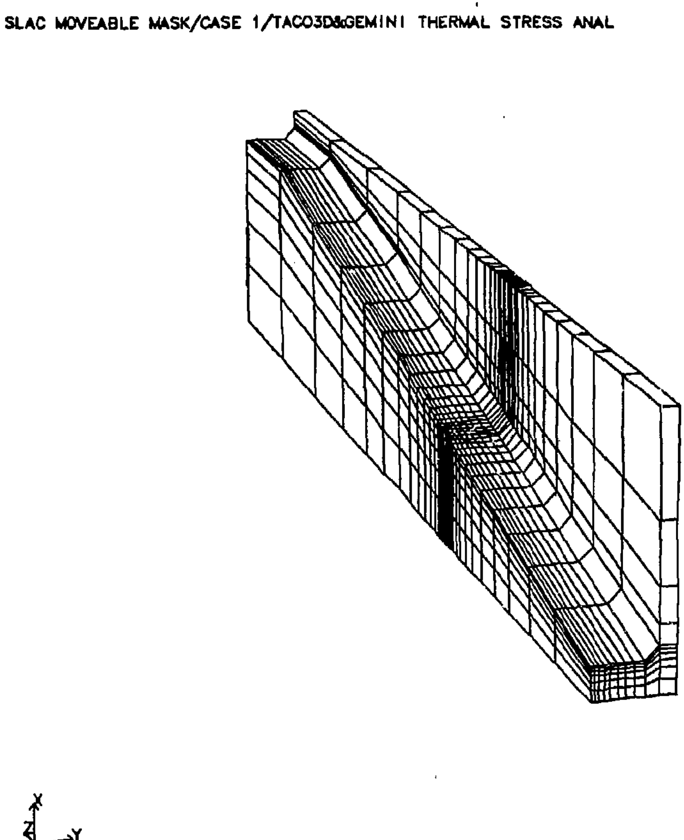


Figure 2. Schematic of the zoning of the modeled part for the mid-ramp beam strike location.

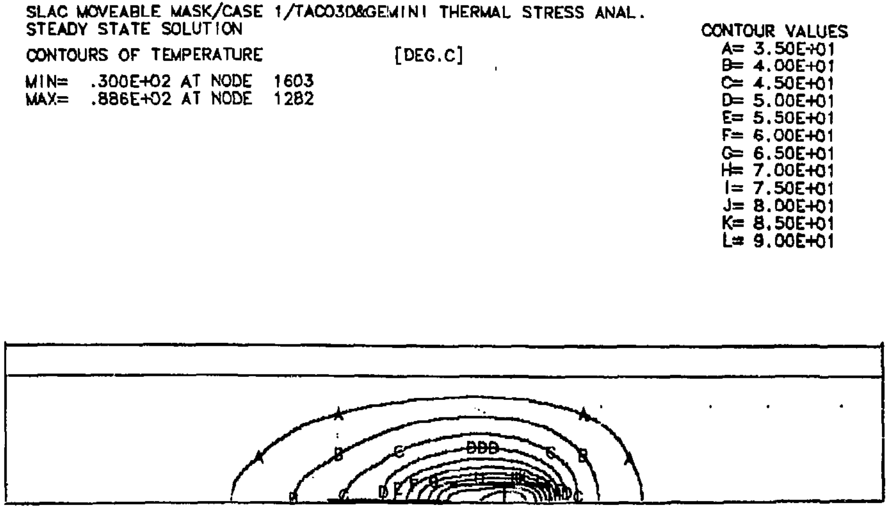


Figure 3. Isotherm contour plot of surface temperatures for the mid-ramp beam strike - from a view perpendicular to horizontal plane of symmetry.

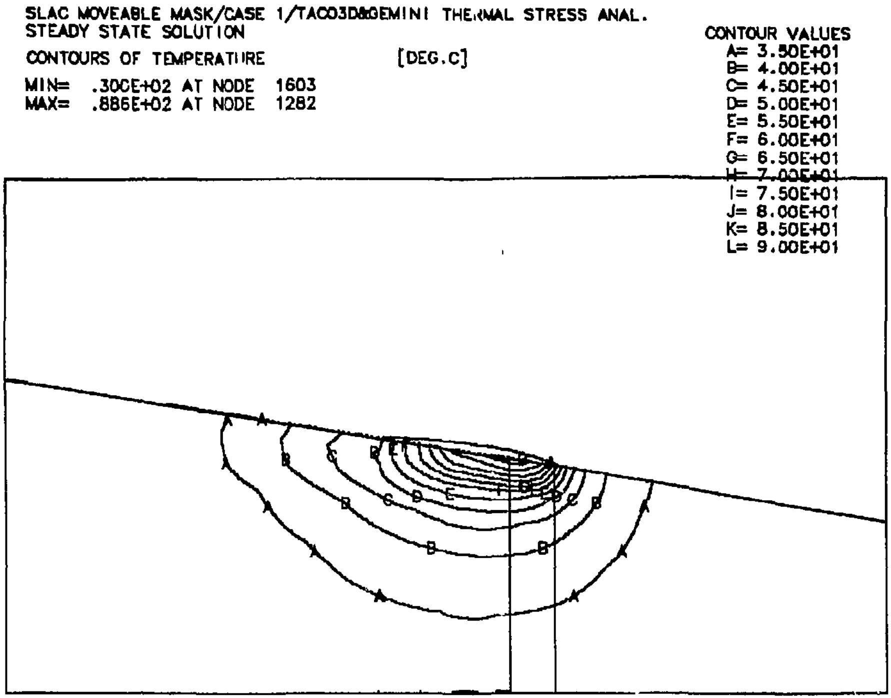


Figure 4. Isotherm contour plot of surface temperatures for the mid-ramp beam strike - from a view perpendicular to vertical plane of symmetry.

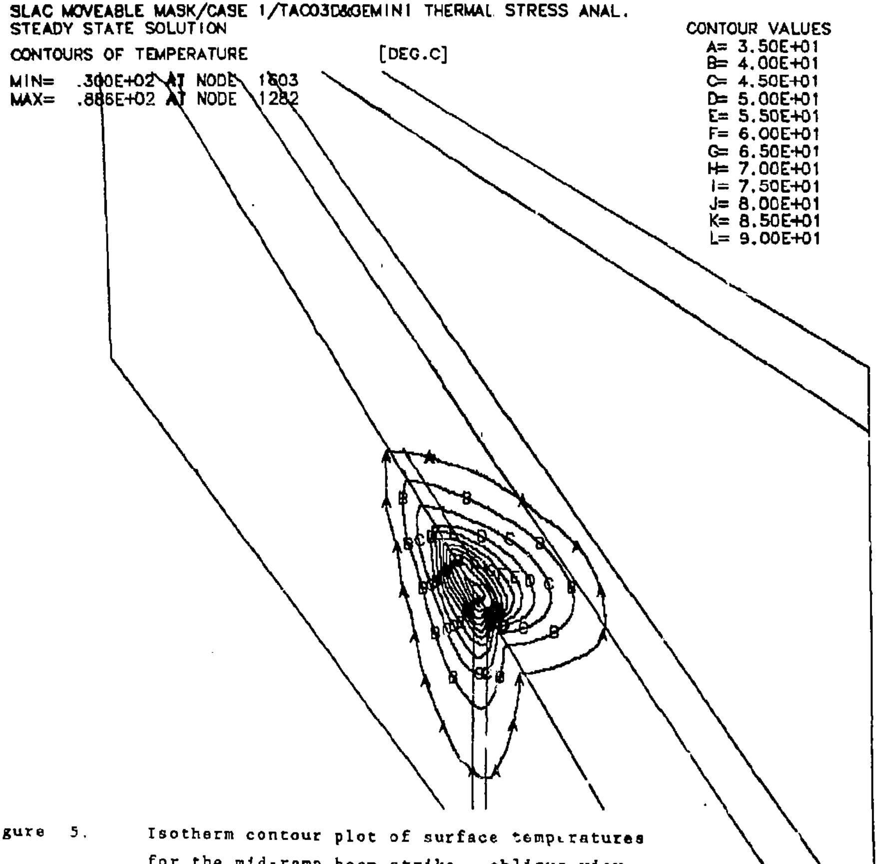


Figure 5. Isotherm contour plot of surface temperatures for the mid-ramp beam strike - oblique view.

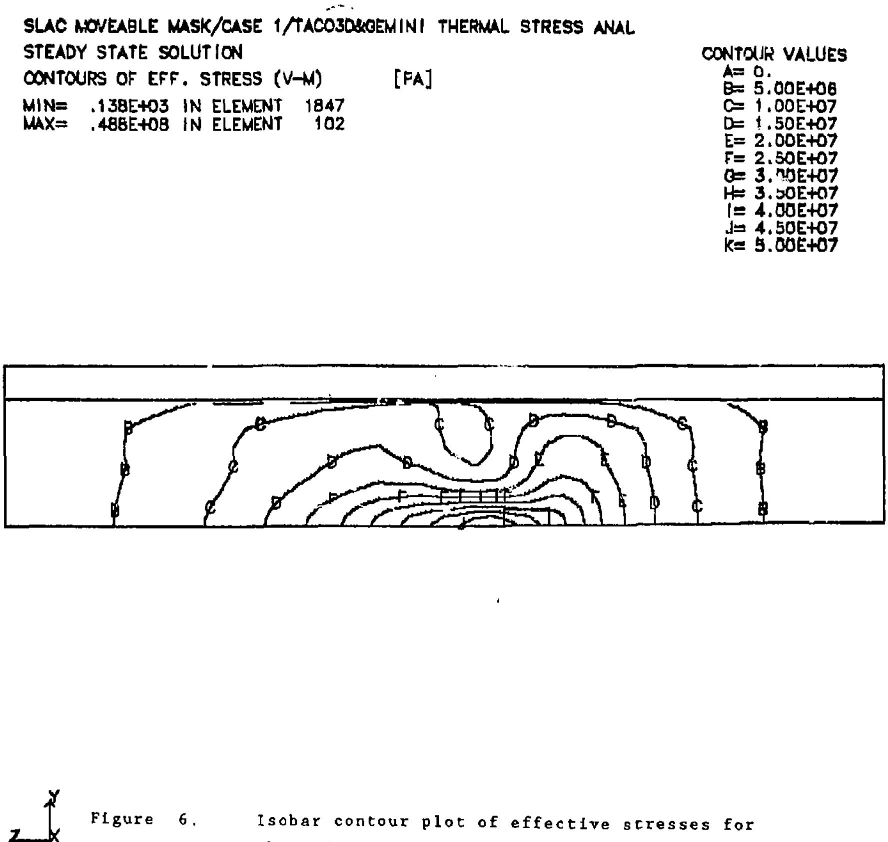


Figure 6. Isobar contour plot of effective stresses for the mid-ramp beam strike - from a view perpendicular to horizontal plane of symmetry.

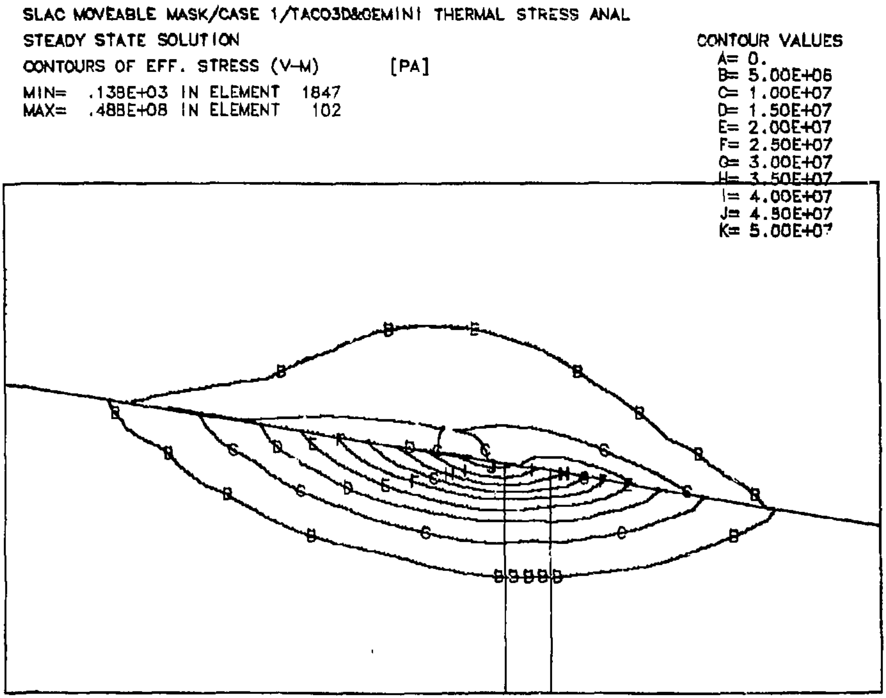


Figure 7. Isobar contour plot of effective stresses for the mid-ramp beam strike - from a view perpendicular to vertical plane of symmetry.

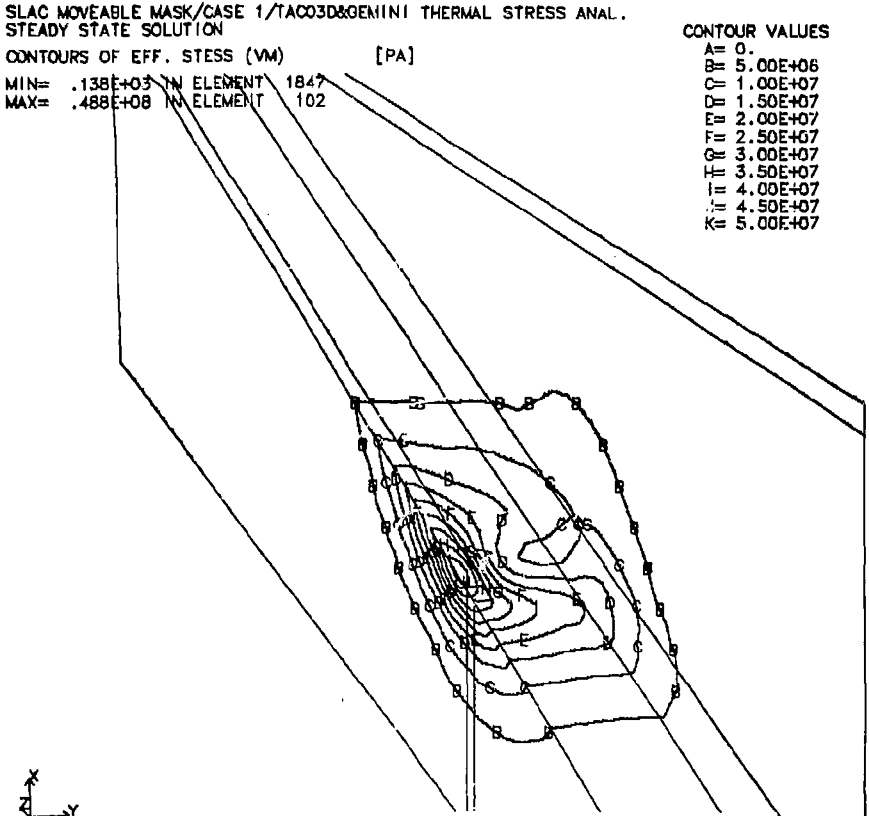


Figure 8. Isobar contour plot of effective stresses for the mid-ramp beam strike - oblique view.

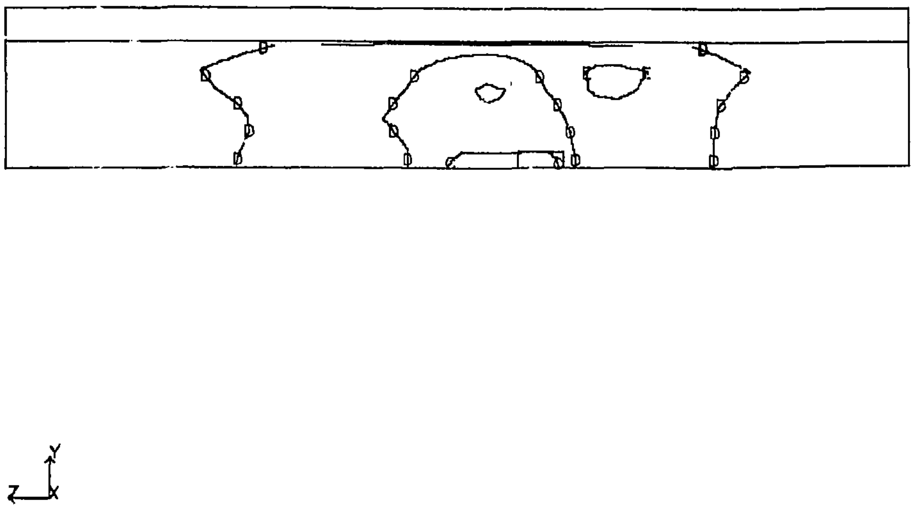
SLAC MOVEABLE MASK/CASE 1/TACO3D&GEMINI THERMAL STRESS ANAL

STEADY STATE SOLUTION

CONTOURS OF MAXIMUM PRINC STRESS [PA]

MIN= -.466E+07 IN ELEMENT 113
MAX= .117E+08 IN ELEMENT 852

CONTOUR VALUES
A=-1.00E+07
B=-5.00E+06
C= 0.
D= 5.00E+06
E= 1.00E+07
F= 1.50E+07
G= 2.00E+07



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STEADY STATE SOLUTION

CONTOURS OF INT PRINC STRESS [PA]

MIN= -.177E+08 IN ELEMENT 89
MAX= .773E+06 IN ELEMENT 701

CONTOUR VALUES
A=-2.00E+07
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F= 5.00E+06
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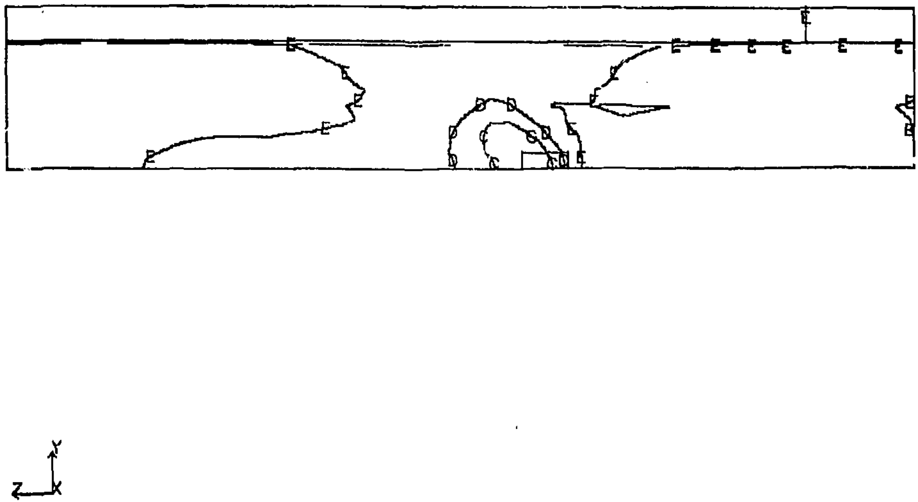

SLAC MOVEABLE MASK/CASE 1/TACO3D&GEMINI THERMAL STRESS ANAL

STEADY STATE SOLUTION

CONTOURS OF MINIMUM PRINC STRESS [PA]

MIN= -.539E+08 IN ELEMENT 96
MAX= .351E+05 IN ELEMENT 667

CONTOUR VALUES
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B=-5.00E+07
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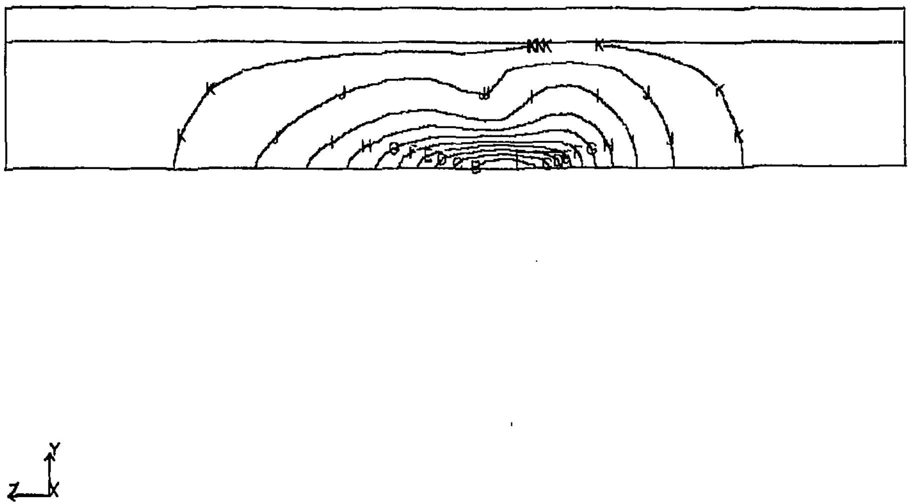

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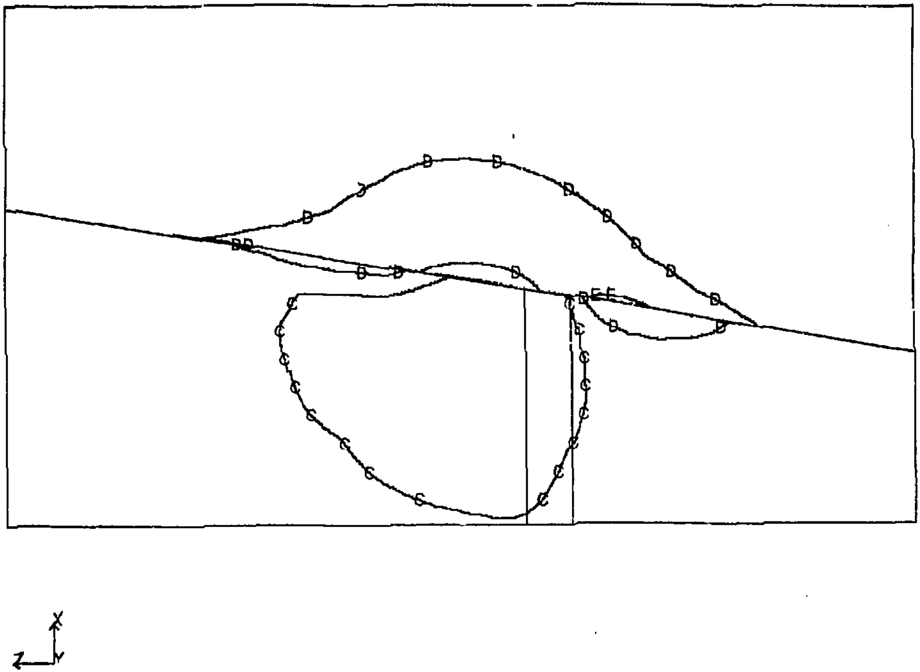

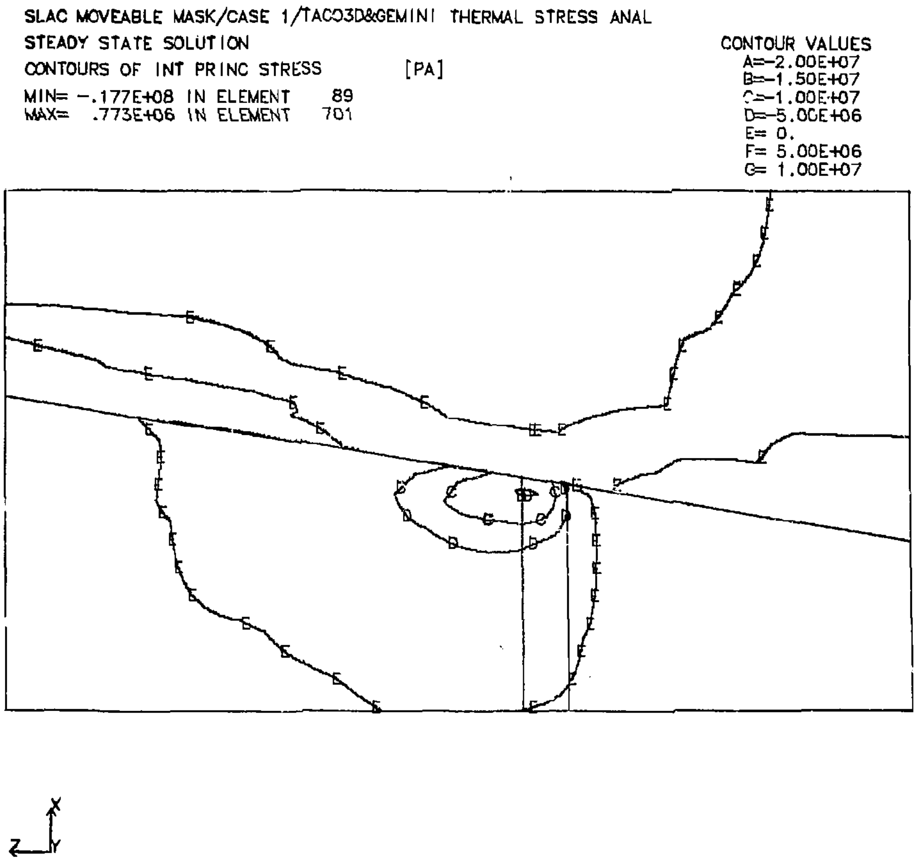
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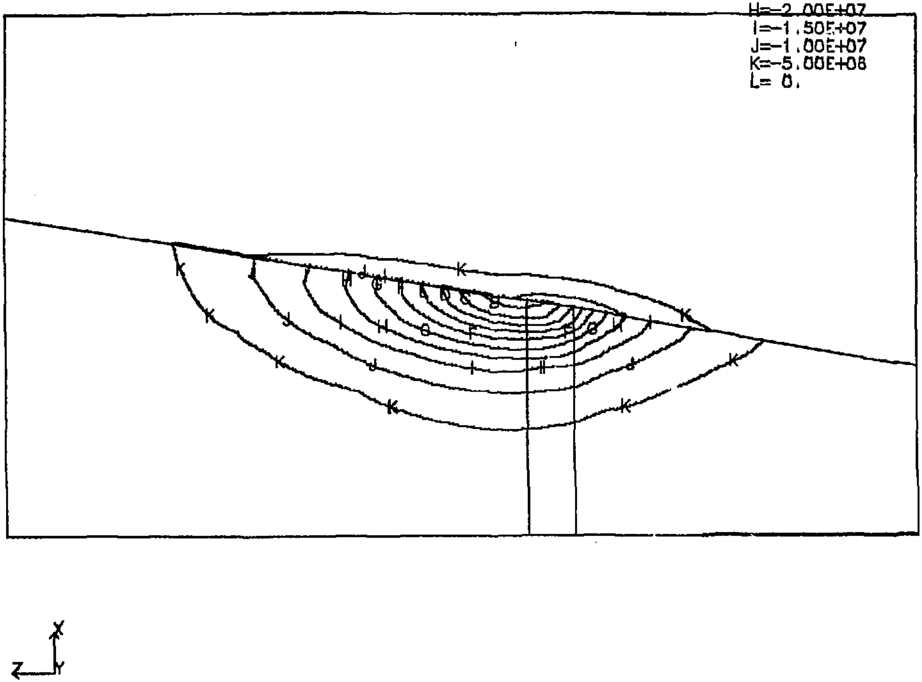

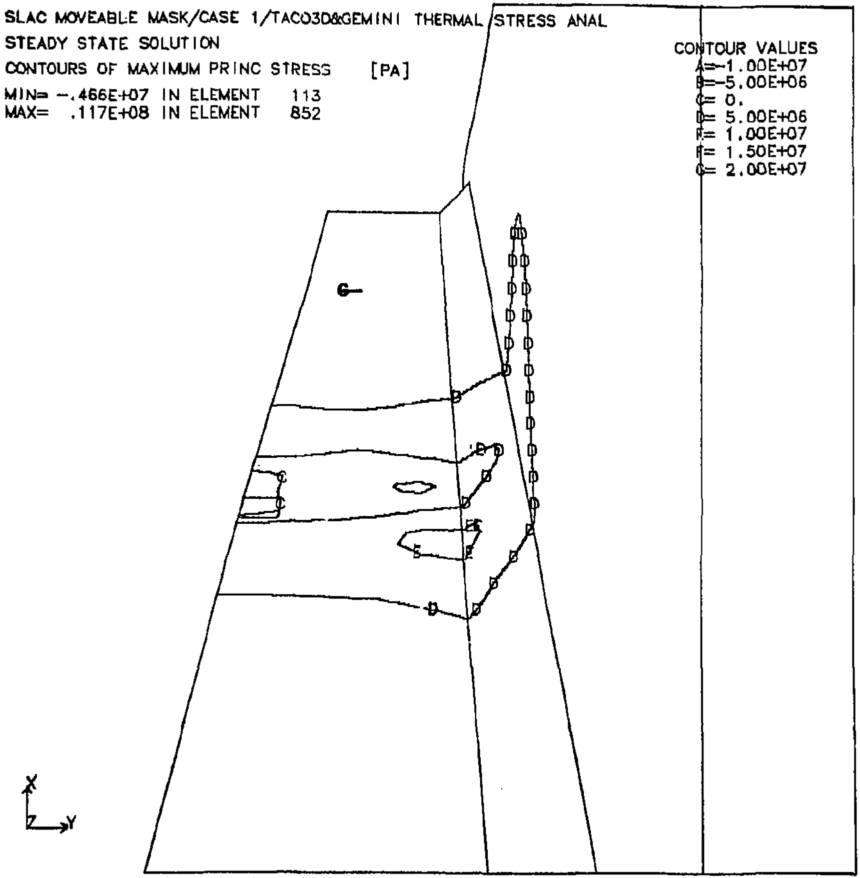
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X
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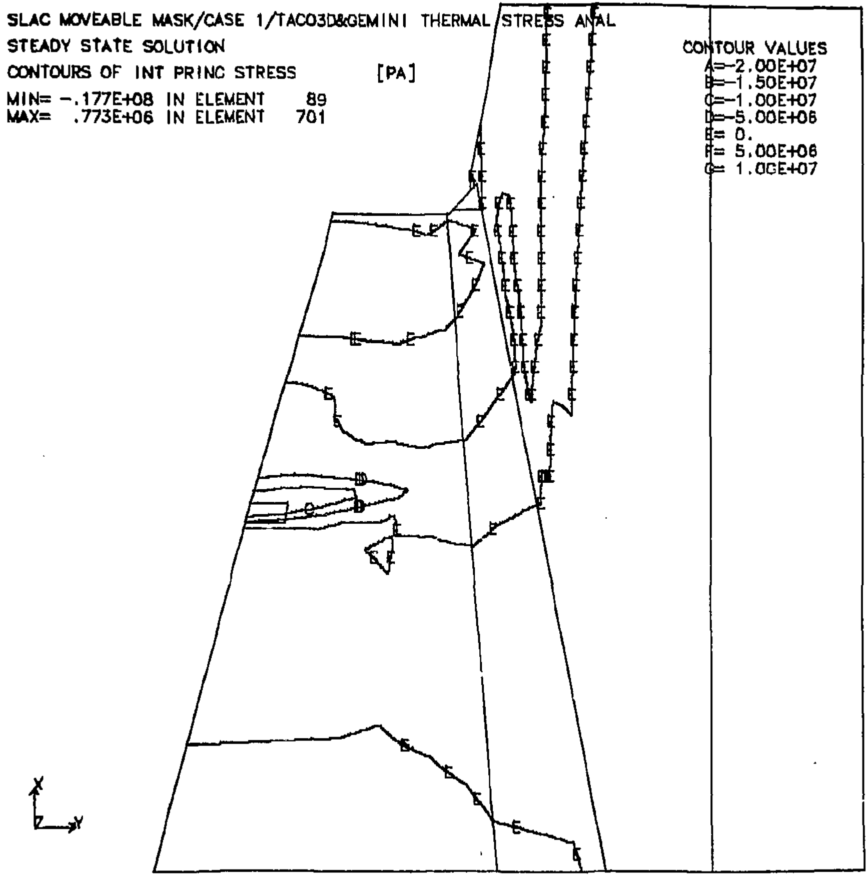
922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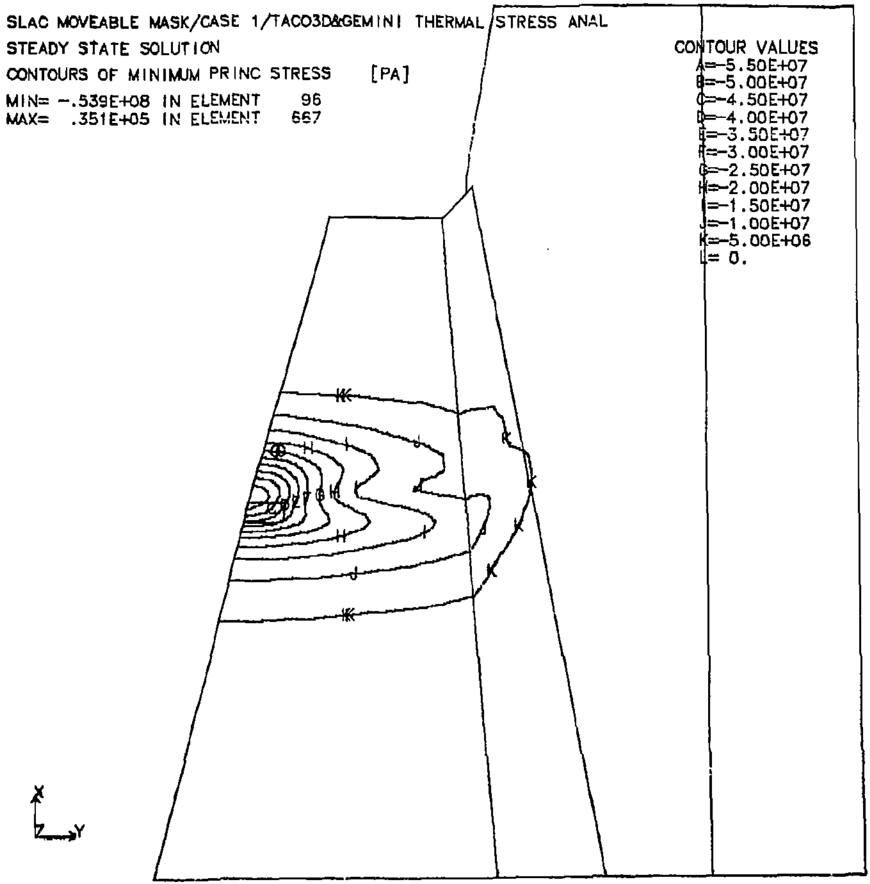
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926

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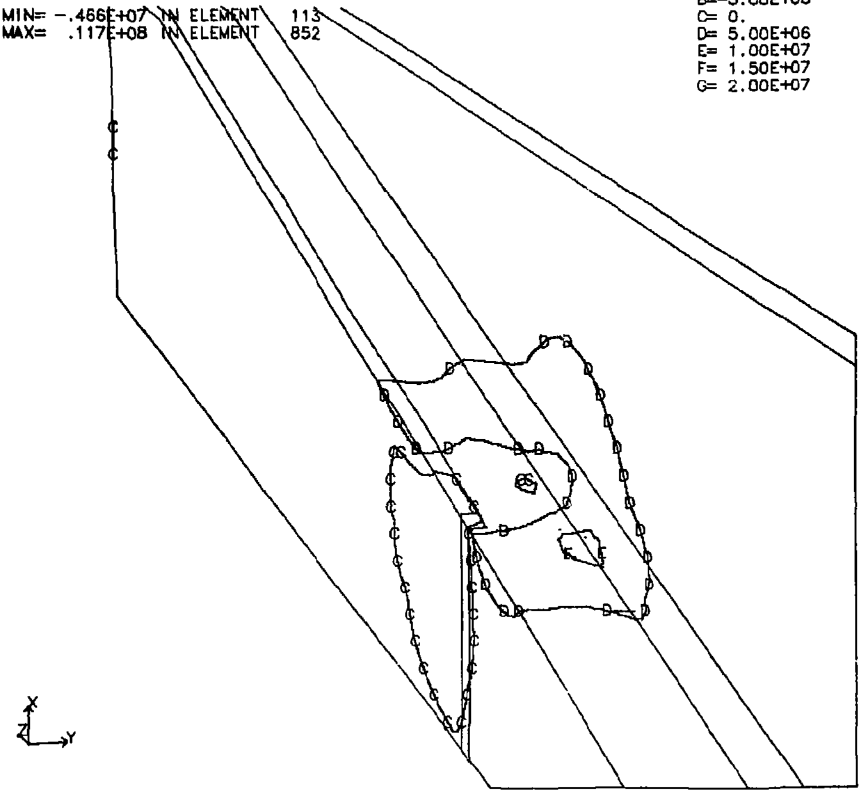

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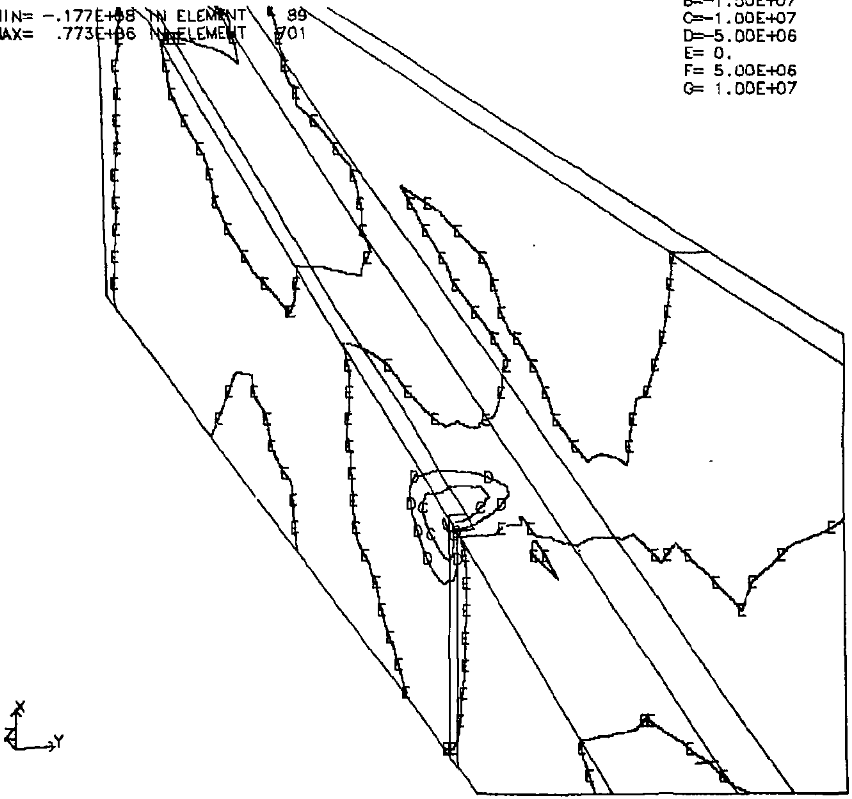

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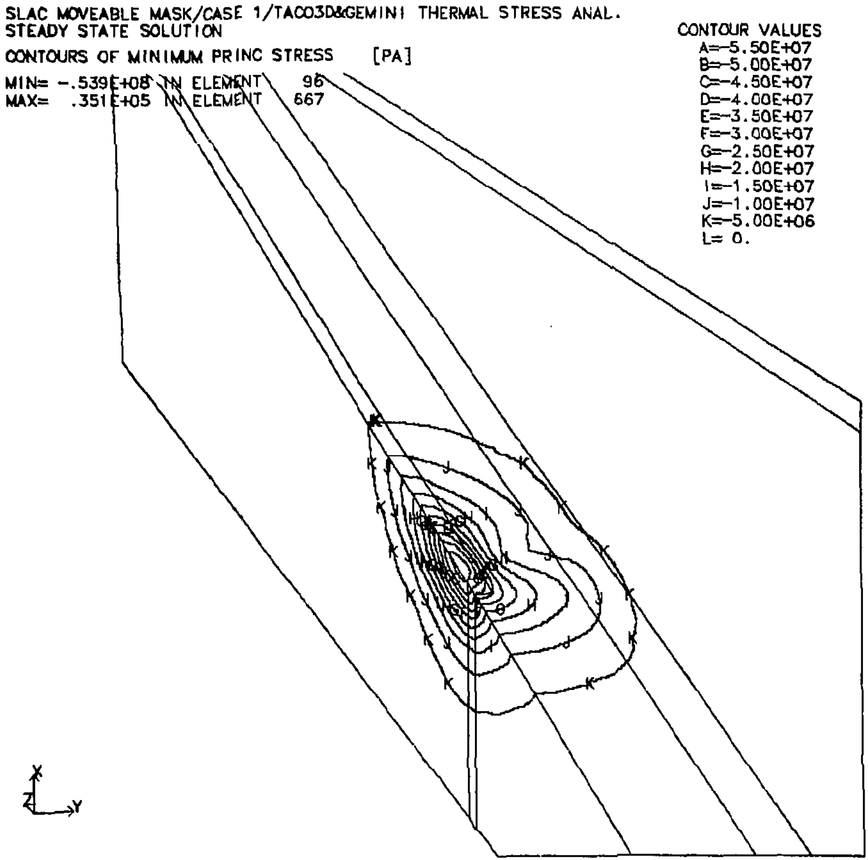
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