# Shuttle Tile Thermal Analysis via NASTRAN

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## ABSTRACT

The Space Shuttle Columbia carried a Tile Gap heating Experiment designed to measure the temperatures within the gaps of the Thermal Protection System (TPS) on the underside of the spacecraft. The thermal analysis entailed the derivation of appropriate boundary conditions from thermocouple data and the calculation of heating rates using NASTRAN. The resulting temperature distributions and heating rates provide information concerning the dependence of convective flow on tile-gap geometry. Results of the work will provide a data base for improved TPS design for future entry vehicles.

## INTRODUCTION

As any spacecraft re-enters the Earth's atmosphere, its kinetic energy is converted to heat. In order to survive this severe environment, the vehicle must have a thermal protection system (TPS) that minimizes heat transfer into the vehicle itself. The shuttle has High Temperature Reusable Surface Insulation (HRSI) covering the underside. HRSI is nominally composed of six inch by six inch silica tiles which are bonded to the structure of the orbiter through a strain isolation pad, or SIP. Central to the concept are gaps between the tiles which allow for thermal expansion and structural flexing. This adds a certain complexity in that the hot, dissociated gas caused by the re-entering vehicle may flow into the gaps augmenting the heat transfer into the sides and bottom of the gap. Describing what conditions precipitate this flow are highly dependent on such geometric factors as gap width, edge radii (a rounded corner designed to open up the radiation view factor to space) and step height (a condition whereby the tops of the tiles aren't lined up).

A good deal of investigative effort has been directed towards understanding this tile gap heat transfer (see refs. 1-3). Much of the earlier work was done using arc jets which simulate re-entry conditions. The results of this type of work lead to empirical equations used to describe surface and in-depth temperatures and heat fluxes. Due to the uncertainty of applying these equations to flight conditions, it was necessary to add a margin of safety based on the pool of experimental data. The result was a successful, though heavier thermal protection system than what may indeed be necessary.

## THE TILE GAP HEATING EXPERIMENT

In order to optimize the TPS for future vehicles, a Tile Gap Heating (TGH) experiment was designed as part of a larger Orbiter Experiment Program (OEX). The TGH experiment consists of HRSI tiles mounted on a removable panel located on the body as shown in figure 1. Both the tiles and tile gaps are instrumented with thermocouples such that the temperature-time history of the re-entry phase would be available. The thermocouples are mounted in three stacks at various depths (see fig. 2). The gas flow near stacks 1,2 and 3 is approximately 1,2 and 3-dimensional, respectively. The intent is to vary the gap width, edge radii and step height over succesive flights and to analyze the impact of these parameters on tile-gap heat transfer (see ref. 4 for a more complete description). Since this is an ongoing project and the data base is not fully complete, data collection will continue with renewed flights of Columbia.

## ANALYSIS

The transient analysis of the flight data was accomplished using the thermal capabilities of NASTRAN. It was selected over other thermal codes for the ease with which complex, two and three dimensional problems can be handled. Also, NASTRAN is capable of solving the transient 'inverse' problem (i.e. producing fluxes from input temperatures). This concept is shown in figure 5. The structural analogue of this would be applying displacements and obtaining the equivalent forces acting on a boundary. With heat transfer, the result is more easily interpreted in that temperature is a scalar quantity and each thermal node has only one degree of freedom.

Three different finite element models were constructed to analyze the three different thermocouple stack locations. A 1-d model comprised of rod elements was used to describe the 1-d thermocouple stack. Similarly, a 2-d model describing the 2-d stack was produced primarily from quadrilateral elements (see figure 6). This represented a mid-tile cross section and was used to describe tile gap heat transfer using temperature contours. The model included heat boundary elements which allowed for the radiation exchange within the gap to be calculated using the NASTRAN view factor module. Finally, a 3-d model was constructed which described the three tile intersection represented by the 3-d stack.

The flow diagram describing the manner in which the data was translated and the analysis performed is given in table 2. The boundary conditions for the various models were derived from flight thermocouple data. This temperature data was converted into NASTRAN TABLED1 format using a FORTRAN routine. For the 1-d model, the surface temperature data obtained from the top thermocouple in the 1-d stack (top curve in figure 4a) were used. The process was somewhat different for the 2-d model in that data from the four gap thermocouples (figure 4b) had to first be interpolated through another FORTRAN routine. This was required in order to produce a separate temperature-time curve for each node down the gap wall. For the current 2-d model, temperature was assumed uniform over the top surface and symmetric accross the gap. Non-symmetric gap temperatures could also be included. More difficult is the interpolation over a surface (for each time step) required for the 3-d model boundary conditions. Sparse flight data has thus far prevented 3-d analysis though the situation will be eventually remedied.

The 2 and 3-d models were constructed using the PATRAN graphics package. The input file was created in such a way as to easily vary such parameters as edge radii, gap width and step height. This would allow the different tile geometries from different flights to be analyzed. The heat boundary surface for the models are defined by CHBDY elements and driven by the a combination of TLOAD1, TABLED1, DAREA, and CELAS2 cards. Since the top surface for the 1-d model is defined by one node, only one such combination is required. For the 2-d model, the upper surface and gap area are defined by 70 nodes and thus are driven by 70 such combinations (some overlap of TABLED1 would reduce the number). Similarly, full transient analysis of the 3-d intersection model would require hundreds of such combinations. A portion of the 2-d model data deck is given in table 1.

## RESULTS

Results for the 1-d analysis are given in figures 7 and 8. The solid lines in figure 7 correspond to actual flight thermocouple data and the dotted curves correspond to NASTRAN predicted values at thermocouple locations. Figure 8 gives the net flux into the surface obtained from the top element. The error reaches 8% of the thermocouple value corresponding to the initial heating pulse. The difference in the predicted thermal response was thought to be due to the temperature and pressure dependency of the thermal conductivity for HRSI.

The resulting contour plots for the 2-d model are given in figure 9. The isotherms are predominantly parallel to the top surface during the heating phase, indicating that the primary mode of heat transfer is heat conduction from the top surface for this relatively narrow gap. If there were significant convective heat flux down the gap, these isotherms would tend to dip down toward the gap region. Good agreement was seen with the equivalent 1-d stack location which helped validate the 2-d model. Also, the effects of the transition heating pulse and cooling phase are well described.

## SUMMARY

In general, this analysis was thought to be a good demonstration of the NASTRAN transient thermal capabilities as applied to a complex problem. Thermocouple data, which is usually readily obtainable, were analyzed to obtain net heating rates (demonstrating the 'inverse' solution capability). NASTRAN generated isotherms were used to assess the type of heat transfer mechanism in the tile-gap system. These techniques were successfuly applied to the analysis of the Tile Gap Heating Experiments. Thus, NASTRAN has provided a unique tool with which to gauge the success of the overall design concept.

## AKNOWLEDGEMENTS

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## REFERENCES

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2. Scott, C. D., and Maraia, R. J., "Gap Heating with Pressure Gradients," AIAA 79-1043, 14th Thermophysics Conference, Orlando, Fla., June 4-6, 1979.

3. Rochelle, W., Hale, M., and Kimbrough, E., "Prediction of Orbiter RSI Tile Gap Heating Ratios From NASA Ames Double Wedge Model Test Data," NASA CR-160147, April 1978.

4. Pitts, W. C., and Murbach, M. S., "Flight Measurements on Tile Gap Heating on the Space Shuttle," AIAA 82-0840, St. Louis, Mo., June 7-11, 1982.

through another FORTRAN routine. This was required in order to produce a separate temperature-time curve for each node down the gap wall. For the current 2-d model, temperature was assumed uniform over the top surface and symmetric accross the gap. Non-symmetric gap temperatures could also be included. More difficult is the interpolation over a surface (for each time step) required for the 3-d model boundary conditions. Sparse flight data has thus far prevented 3-d analysis though the situation will be eventually remedied.

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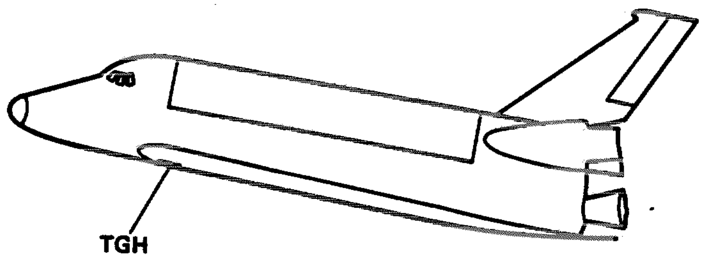



Fig. 1 Location of Tile Gap Heating Experiment on Orbiter.

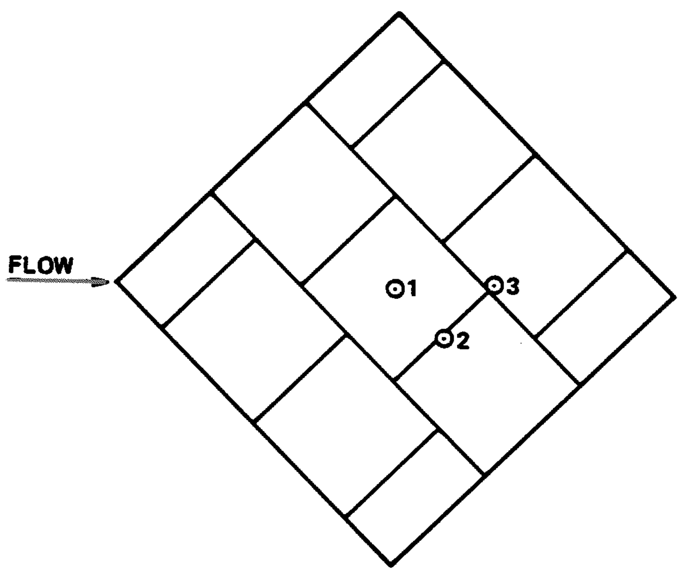
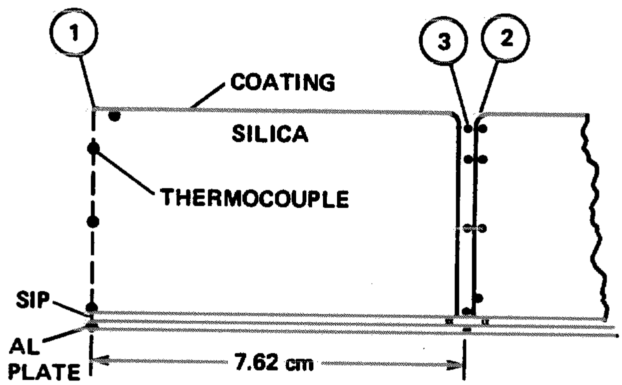



Fig. 2 Thermocouple locations and stack designations for flight-test panel.




THERMOCOUPLE DEPTH, cm

| 1 | 3 | 2 |
|---|---|---|
| 0.02 | – | – |
| – | 0.23 | 0.23 |
| 0.64 | 0.64 | 0.64 |
| 1.90 | 1.90 | 1.90 |
| – | – | 3.81 |
| 4.16 | 4.16 | – |
| Aℓ | Aℓ | – |

Fig. 3 Tile cross section through one-dimensional and two-dimensional stacks; three-dimensional stack seen through gap; gap width exaggerated.

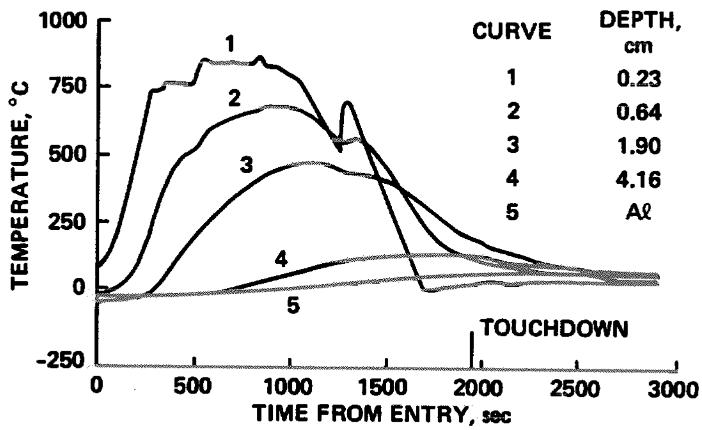
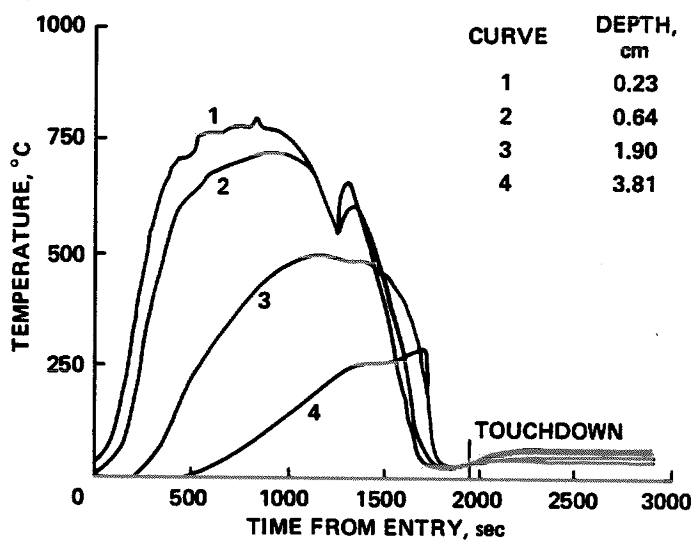



Fig. 4a STS-2 flight-data temperature profiles; one-dimensional stack.




Fib. 4b STS-2 flight-data temperature profiles; two-dimensional stack.

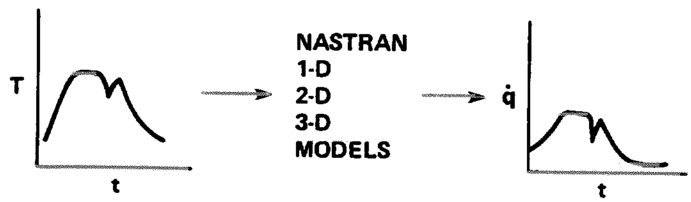



Fig. 5 The inverse solution. Applying thermocouple temperature data and obtaining the heat flux.

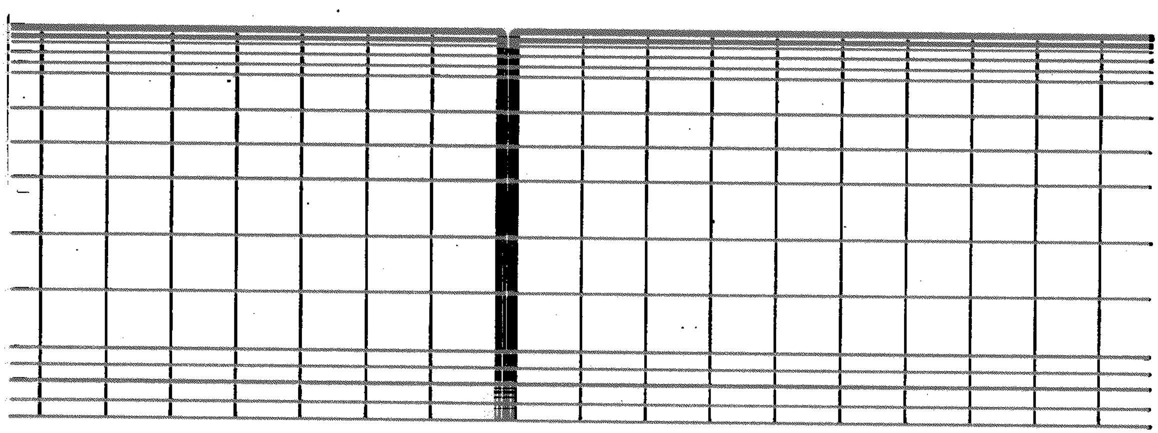


Fig. 6 NASTRAN two-dimensional model.

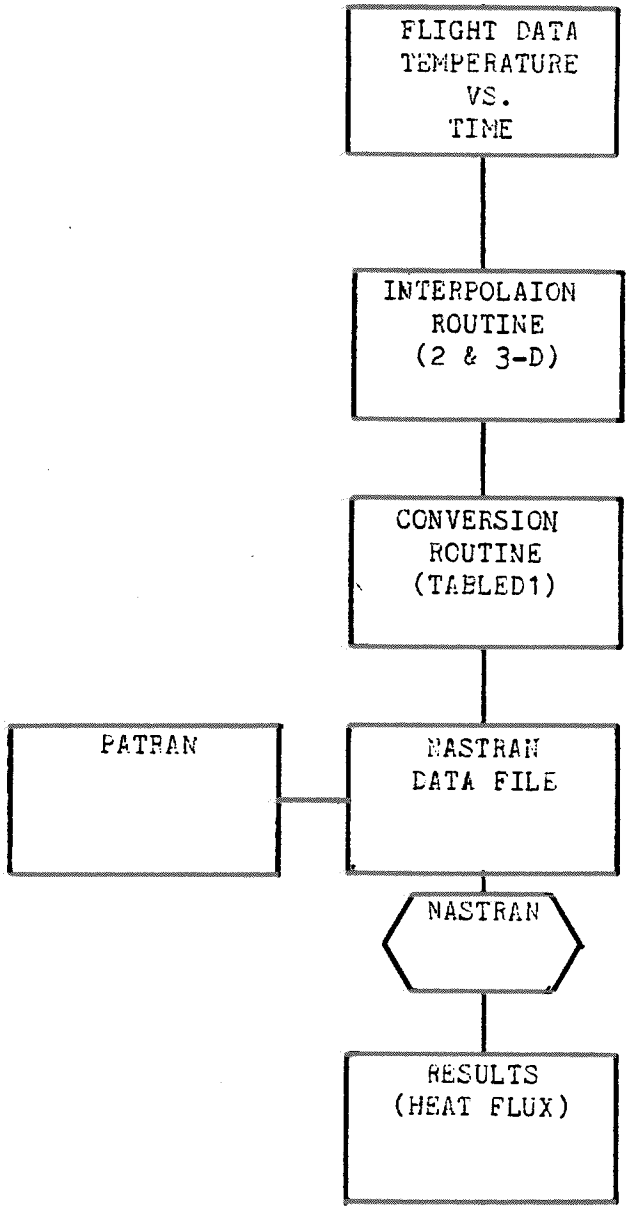



**Fig. 7 Flow diagram for Tile-Gap Heating Thermal Analysis.**

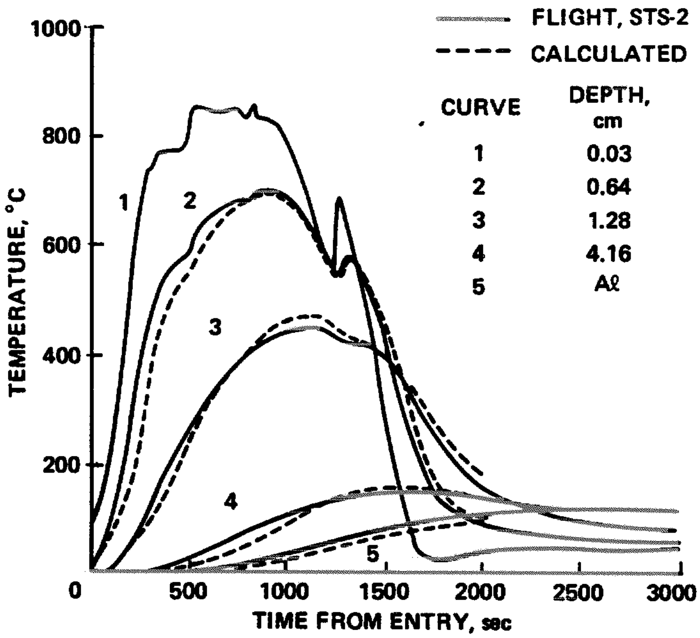



Fig. 8 Comparison of calculated temperature profiles with flight data for one-dimensional stack.

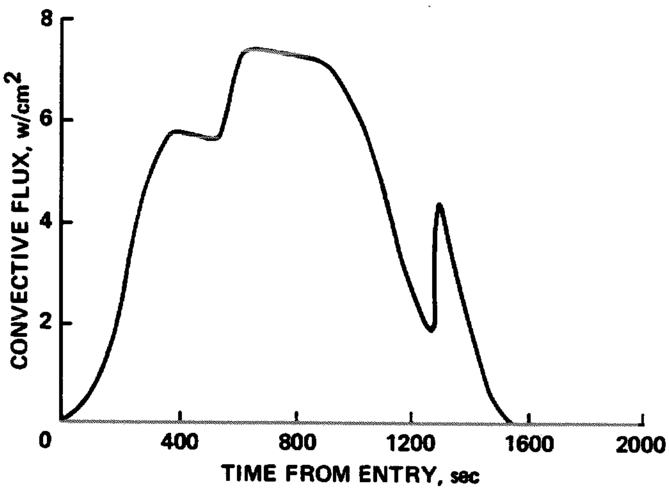
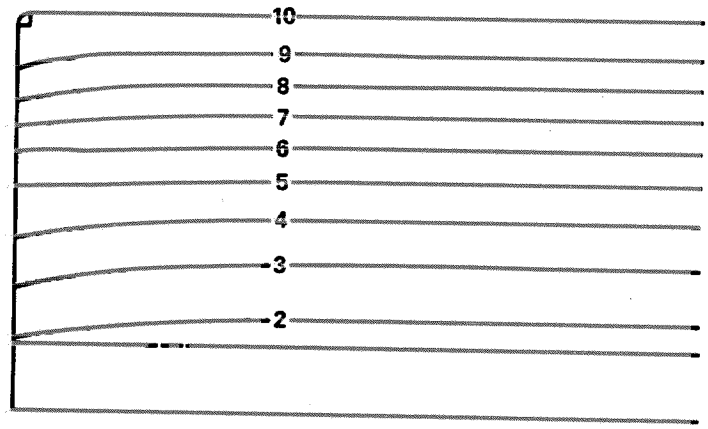
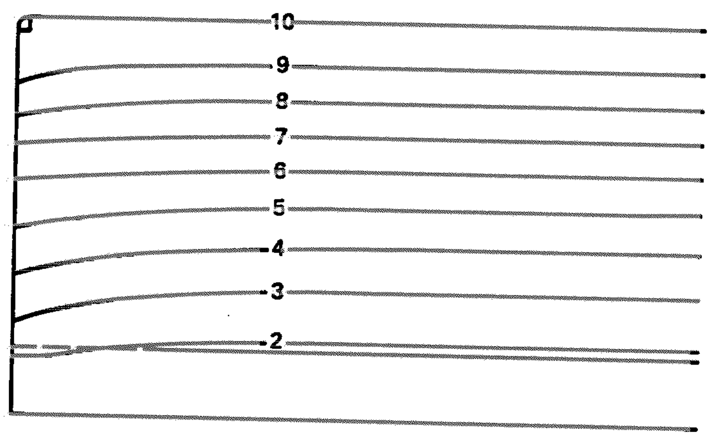



Fig. 9 Derived heat flux from one-dimensional surface temperature.

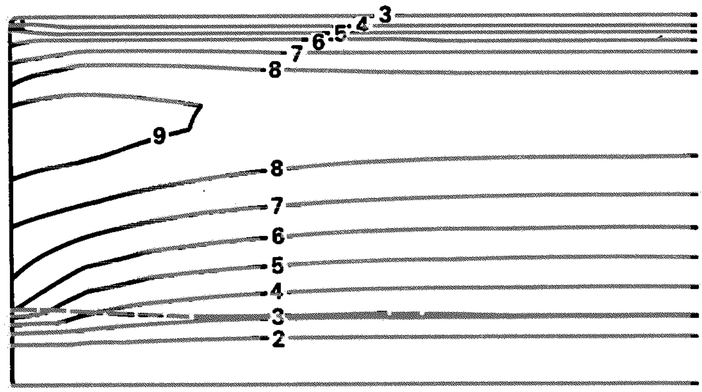



(a) Time = 800 sec, max temperature = 823°C. (isotherm #10)

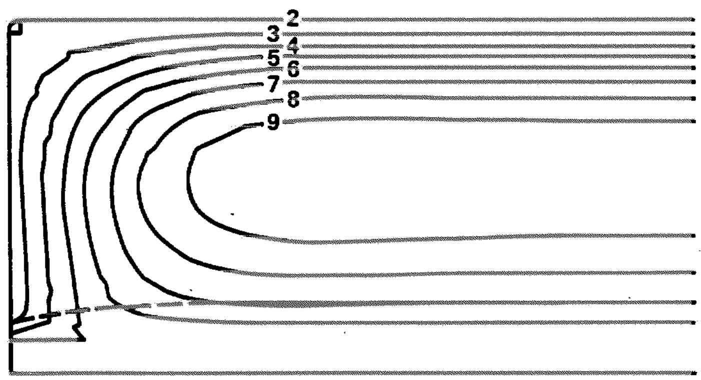



(b) Time = 1000 sec, max temperature = 793°C. (isotherm #10)

Fig. 10 Isotherms within tiles from NASTRAN calculation based on flight data from one-dimensional and two-dimensional thermocouple stacks.




(c) Time = 1600 sec, max temperature = 414°C. (isotherm #10)




(d) Time = 1900 sec, max temperature = 200°C. (isotherm #10)

Fig. 10 Concluded.

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+DL1,1.,4,1.,5,1.,6,1.,7,+DL2
+DL2,1.,8,1.,9,1.,10,1.,11,+DL3
   .
   .
   .
$    ...LOADS
TLOAD1,1,1,,,10
=,*(1),*(1),=,=,=
=(68)
DAREA,1,1,1,1.+5
=,*(1),*(1),=,=
=(68)
CELAS2,1100,1.+5,1,1
=,*(1),=,*(1),=
=(68)
$    ...TIME STEP
TSTEP,400,200,10.,5
$    ...MATERIAL PROPERTIES:
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  .
PSHELL,1000,1000,1.0
  .
PHBDY,1,2,.4902,0.9,.8
$    ...PARAMETERS
PARAM,TABS,460.
PARAM,SIGMA,4.761-13
$    ...INITIAL CONDITIONS; RAD. GUESS
TEMPD,1300,1300.
TEMPD,300,0.
$    ...STS3 FLIGHT DATA
TABLED1 10
      +TQ     1
+TQ     1     0.0     66.0     10.0     66.0     20.0     80.0 ...
+TQ     2    40.0    107.8     50.0    121.6     60.0    135.3 ...
+TQ     3    80.0    176.1     90.0    203.0    100.0    229.7 ...
                .
                .
                .
$    ...GRIDS AND ELEMENTS
                .
                .
```

Table 1. Sample data deck for NASTRAN two dimensional model.