MODELING OF HEAT TRANSFER AND ABLATION OF REFRACTORY MATERIAL DUE TO ROCKET PLUME IMPINGEMENT

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ABSTRACT

CR Tech's Thermal Desktop-SINDA/FLUINT software was used in the thermal analysis of a flame deflector design for Launch Complex 39B at Kennedy Space Center, Florida. The analysis of the flame deflector takes into account heat transfer due to plume impingement from expected vehicles to be launched at KSC. The heat flux from the plume was computed using computational fluid dynamics provided by Ames Research Center in Moffet Field, California. The results from the CFD solutions were mapped onto a 3-D Thermal Desktop model of the flame deflector using the boundary condition mapping capabilities in Thermal Desktop. The ablation subroutine in SINDA/FLUINT was then used to model the ablation of the refractory material.

INTRODUCTION

Under the launch induced environment investigations currently in work at Kennedy Space Center to meet the needs for SLS and other vehicles, a thermal analysis of the flame deflector was needed to predict the amount of refractory material loss due to rocket plume impingement. In the past, the analysis was performed using THERM1D which is one-dimensional ablation analysis software where the analysis is limited to a specific location as opposed to the ablation analysis being performed for the entire surface. An example result of THERM1D analysis indicating surface thickness with respect to time is shown in Figure 1.

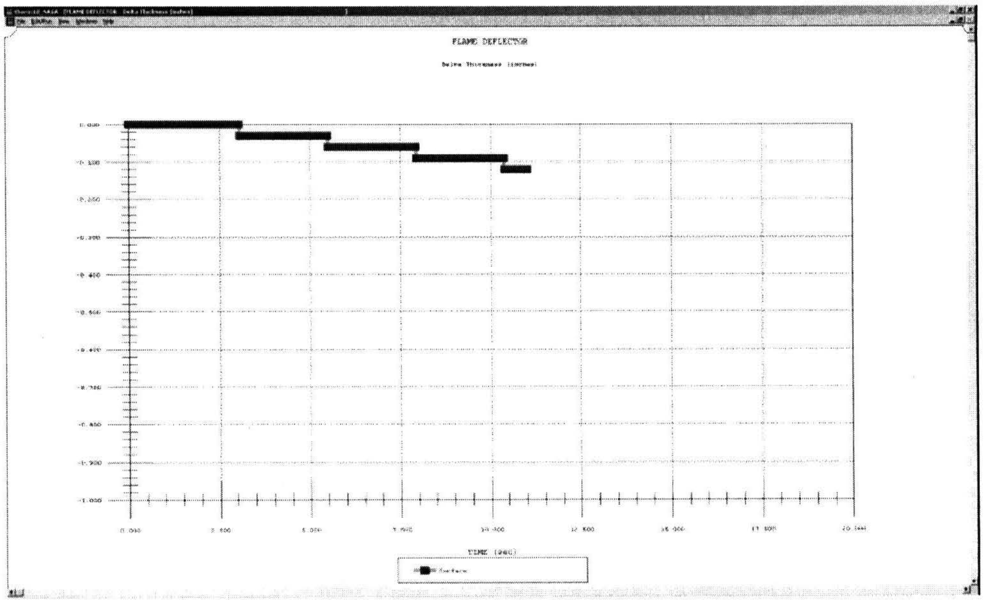


Figure . Example of THERM1D Output.

Although this software has proved to be sufficient in past analyses, by making use of CR Tech's Thermal Desktop software boundary condition mapper and ablation subroutine the one-dimensional ablation analysis can be performed for the entire surface providing the analyst with a contour plot of surface thickness. The model can not only show the maximum ablation but also the location at which we can expect the maximum ablation to occur. The boundary condition mapper allows for highly accurate, transient CFD heat flux data which considers the complex compressible fluid dynamics that impinges on the flame deflector to be mapped to the Thermal Desktop geometry. Once the data is mapped, the Thermal Desktop simulation can be executed to give the ablation over the flame deflector surface. The scope of this ablation analysis does not consider charring or pyrolysis of the material. Figure 2 gives an example of the results obtained by Thermal Desktop.

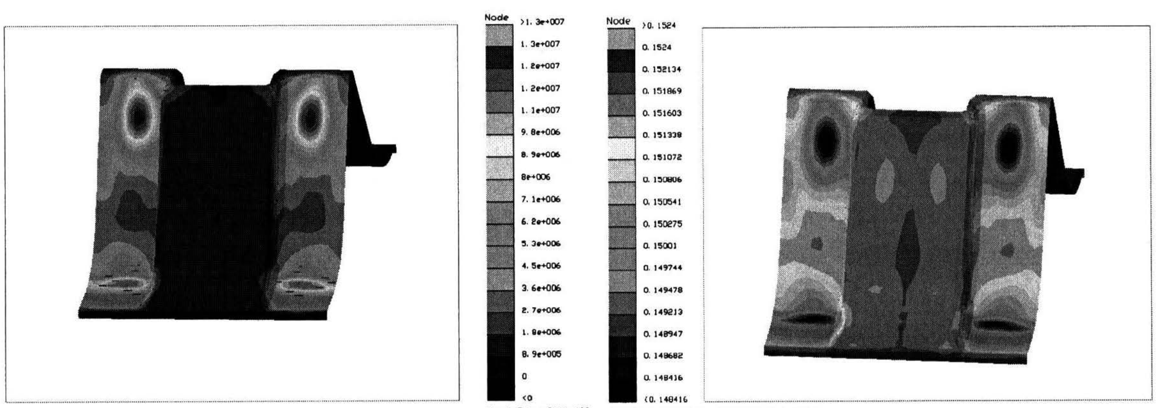


Figure . Thermal Desktop Surface Heat Flux and Surface Ablation Thickness Examples.

Figure 3 shows some of the concepts for the flame deflector which the thermal analysis is performed.

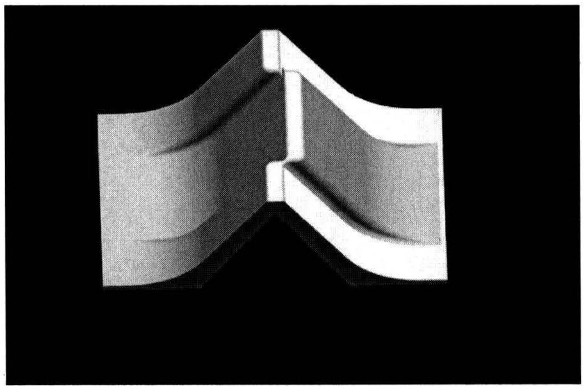


Figure . Flame Deflector Geometries

MODEL SETUP: MESHING

The model setup was started by importing the CAD geometry into NX/NASTRAN and obtaining a surface mesh or solid mesh depending on the analysis. The mesh can then be imported into Thermal Desktop using the import features in the software, as shown in Figure 4.

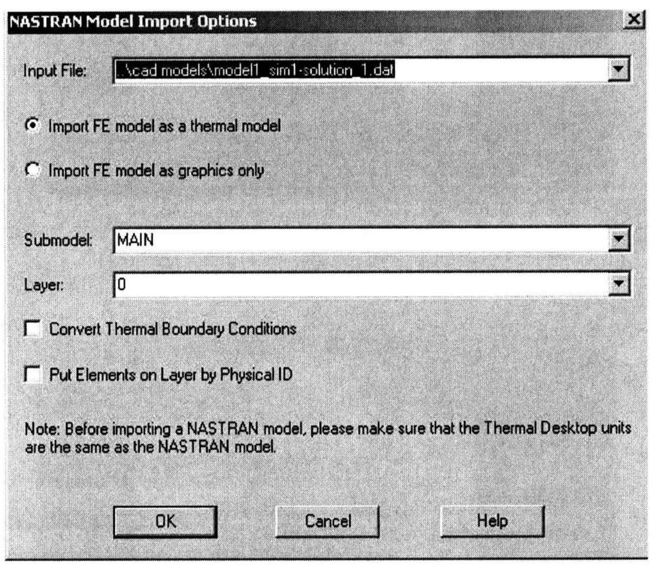


Figure . NASTRAN Model Import Window

Once the analyst imports the mesh, the thermal model should be shown as a AutoCAD® drawing. The thermal desktop models for the flame deflector analysis are shown in Figure 5. A 2-D surface mesh or a 3-D solid mesh can be used depending on the analysis.

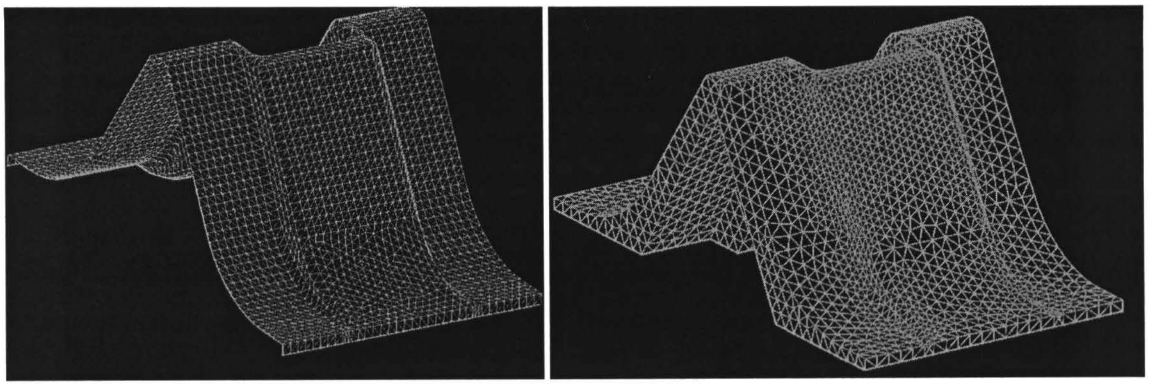


Figure : Imported NASTRAN mesh into Thermal Desktop

MODEL SETUP: THERMOPHYISICAL PROPERTIES & DEFINING ABLATION NODES

Under the thermophysical property manager, the material properties are specified. To take advantage of the ablation subroutine in Thermal Desktop, the analyst must specify ablation for that material. The thermophysical property menu is shown for the refractory material in Figure 6.

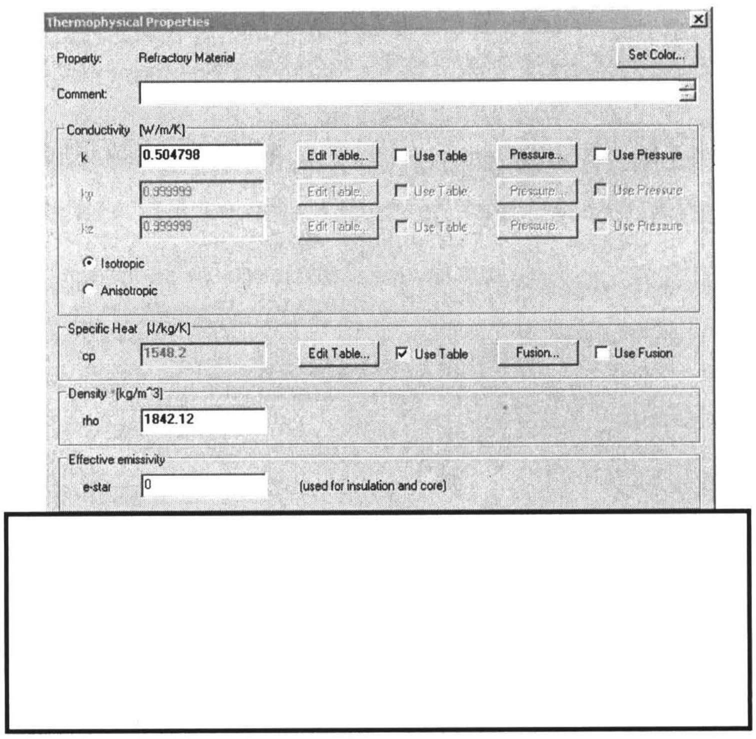


Figure . Thermophysical Properties for Refractory Material

The ablation temperature is 1373 K and the Heat of Ablation is 1.67 MJ/kg describing the refractory material for the analysis of the flame deflector.

The ablation nodes then are specified by editing the Thin Shell Data menu for the surface elements. Under the insulation tab, the insulation can be applied to the top/outside surface.

The material can be chosen from the drop down menu and a thickness can be specified. The flame deflector has 6 inches of refractory material thickness. The number of nodes which the thickness must be discretized also must be specified, this left to the analyst to determine.

BOUNDARY CONDITION MAPPER

The next step is to define the boundary conditions before executing the program and performing the analysis. The boundary condition for the flame deflector heat flux is computed by a transient conjugate heat transfer CFD code that is coupled with the highly complex flow of the 4 RS-25/SSME's and 2 solid rocket boosters impinging on the deflector. The boundary condition mapper feature of Thermal Desktop is capable to take the transient surface heat flux data and map it over the Thermal Desktop model surface.

To begin mapping, the analyst must first have the data in the appropriate format defining the data type, either heat flux or surface temperature, the units of the data, the coordinates of the nodes, and nodes that define the elements, specified as either triangles or quadrilaterals. For this analysis, a MATLAB script was developed in order to take the CFD data, usually provided in a TecPlot® format by ARC, and proceeds to format the data quickly into the required boundary condition mapper format to be read by Thermal Desktop. An example of the boundary condition mapper file format is shown in Figure 7.

TEMPERATURE DEPENDENT HEAT FLUX BCM Sample Input

Note: Please note that all information including and after the '!' is for description and should not be in the actual file.

```
DATA: TEMPERATURE DEPENDENT HEAT FLUX
UNITS LENGTH meters
UNITS TEMPERATURE R
UNITS TIME SECONDS
UNITS DATA W/cm2
TEMPERATURES 2
300.000000
1000.000000
NODE 1 0. 0. 0.
NODE 2 0. 1. 0.
NODE 3 1. 0. 0.
NODE 4 1. 1. 0.
NODE 5 2. 0. 0.
NODE 6 2. 1. 0.
TRI 1 1 2 3
TRI 2 3 2 4
TRI 3 3 4 5
TRI 4 5 4 6
TIME 87.000000
1.01            ! Flux for node 1 at T = 300
1.02            ! Flux for node 1 at T = 1000
2.01            ! Flux for node 2 at T = 300
2.02
3.01
3.02
4.01
4.02
5.01
5.02
6.01
6.02
TIME 90.000000
11.01
11.02
12.01
12.02
13.01
13.02
14.01
14.02
15.01
15.02
16.01
16.02
```

Figure . Example of BCM File Format

Once the formatted file is created, the file can be used as input to the boundary condition mapper. After the file is read into Thermal Desktop, the BCM will be presented as a mesh ash shown in Figure 8. The remaining mapping procedures are shown in Figures 9-11.

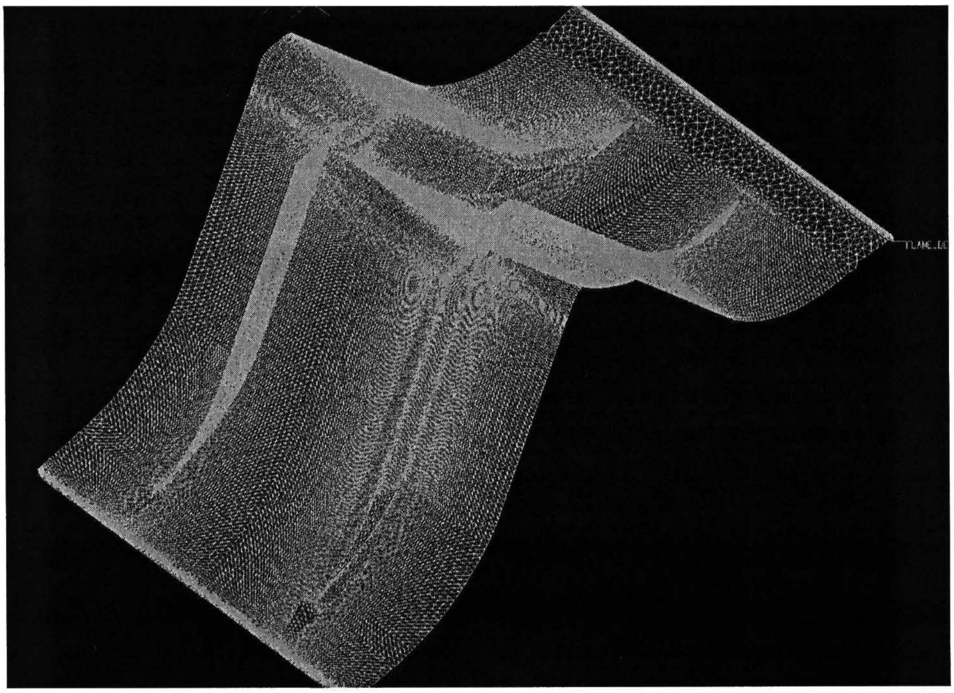


Figure . BCM Mesh Extracted From CFD Model

Using the AutoCAD commands such as align or move, the BCM must be coincident to the thermal model surface to insure an accurate mapping of data.

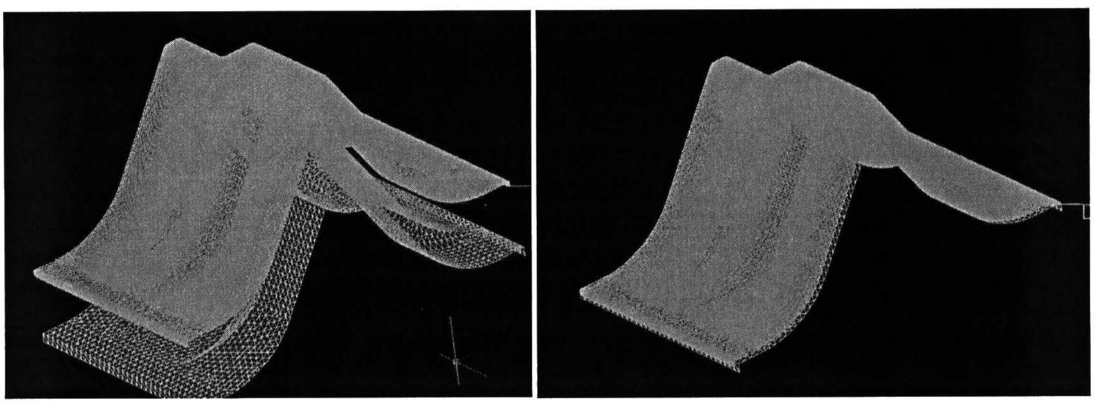


Figure . Align BCM to Thermal Model

The BCM can be edited to point to the desired thermal model elements the data should be mapped onto and to specify variable tolerances. A sufficient range of tolerances should be given to insure that all the points are successfully mapped. In the case of this analysis, the Apply surface thickness to test points should be deselected. Deselecting this option maps the data using the position of the elements where they are currently positioned in the thermal model as opposed to some thickness relative to the surface mesh.

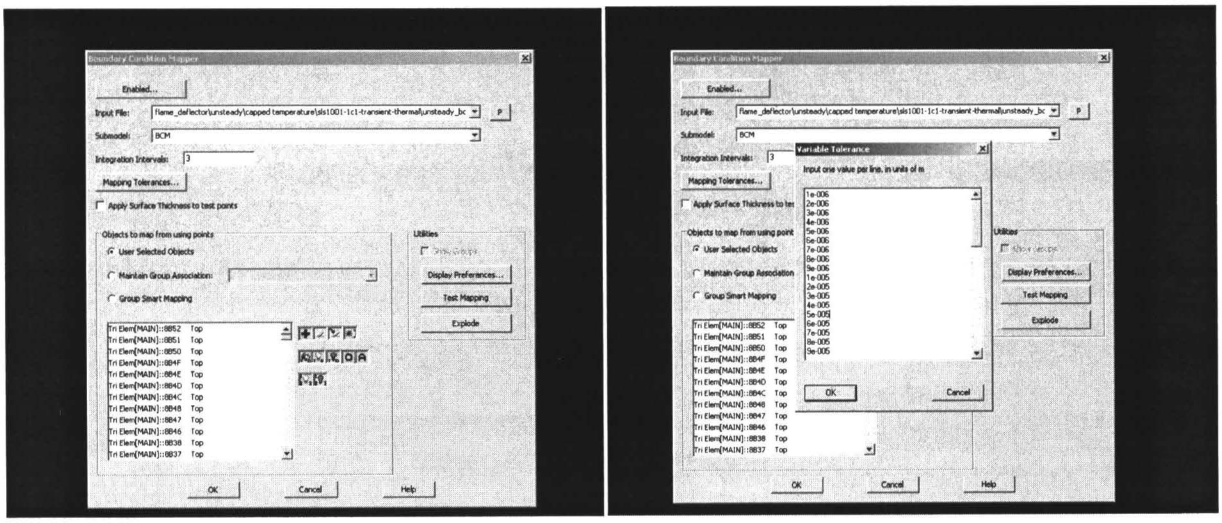


Figure . Boundary Condition Mapper Setup Window. a)Selecting elements and b)Specifying Mapping Tolerances.

After completion, the successful mapping of data should shown as in Figure 12.

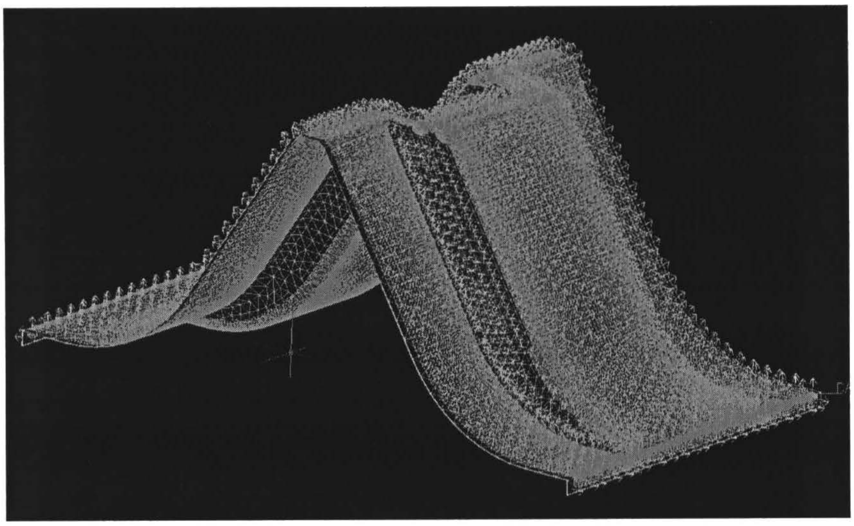


Figure . Successful Mapping of the Heat Flux Boundary

POSTPROCESSING

The post processing of data in Thermal Desktop can be intuitive to the analyst for displaying heat rate, heat flux and temperature contours. For displaying contours of surface thicknesses, the postprocessing is not as straightforward. After completion of the processor the ablation subroutine outputs a text file. The text file must be imported into the postprocessing datasets. These steps are illustrated in Figures 10-12. The postprocessing datasets window in shown in Figure 10.

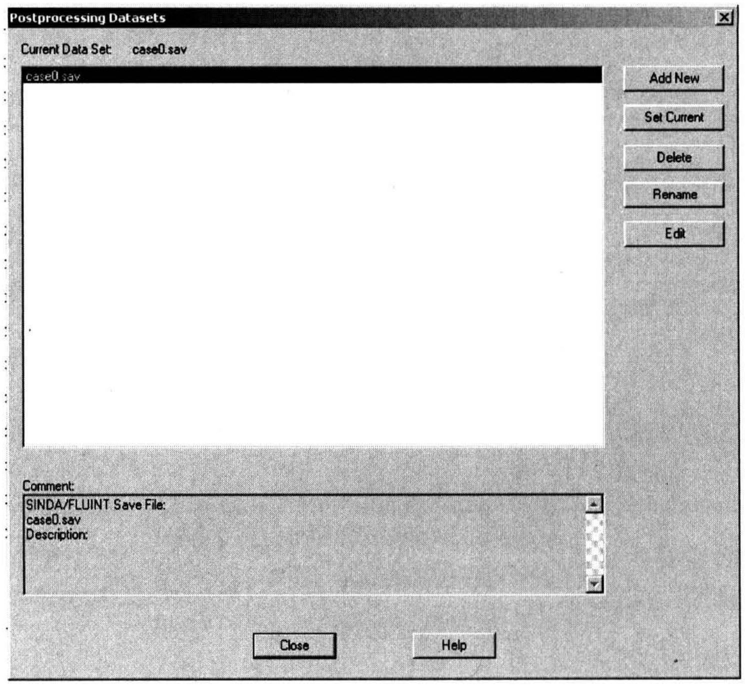


Figure . Post-processing Datasets Import Window

The analyst can add new data sets to be used in the post processor showing color contours. By selecting add new and choosing a text transient file, the surface thickness time history text file can be imported into the post processor. The data set source selection window is shown in Figure 11 as well as the drop down menu to select the file.

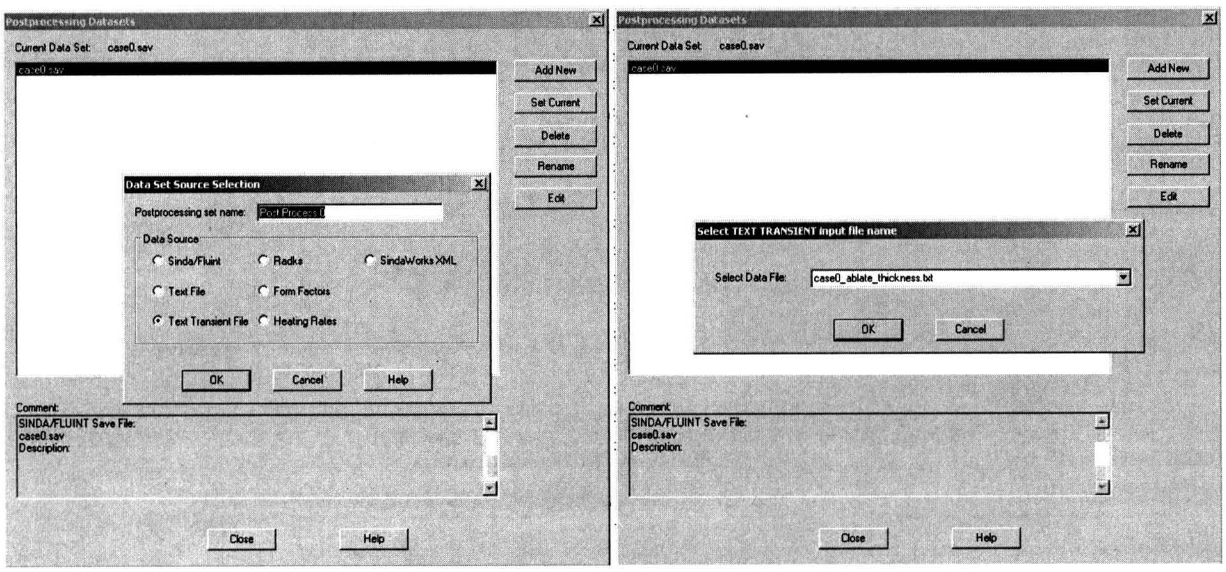


Figure . Text Transient File Import Window.

Once the file has been chosen, the set transient text dataset properties window will appear. Due to the existence of ablation nodes and for any model using some form of insulation, the selection to plot MLI should be made from the drop down menu. The selection will plot the data that exist on the top or bottom sides depending on the selection made. For the analysis of the flame deflector, the selection plot MLI on top out sides was chosen to capture the ablation nodes on the surface. The window for setting the transient text dataset properties is shown in Figure 12.

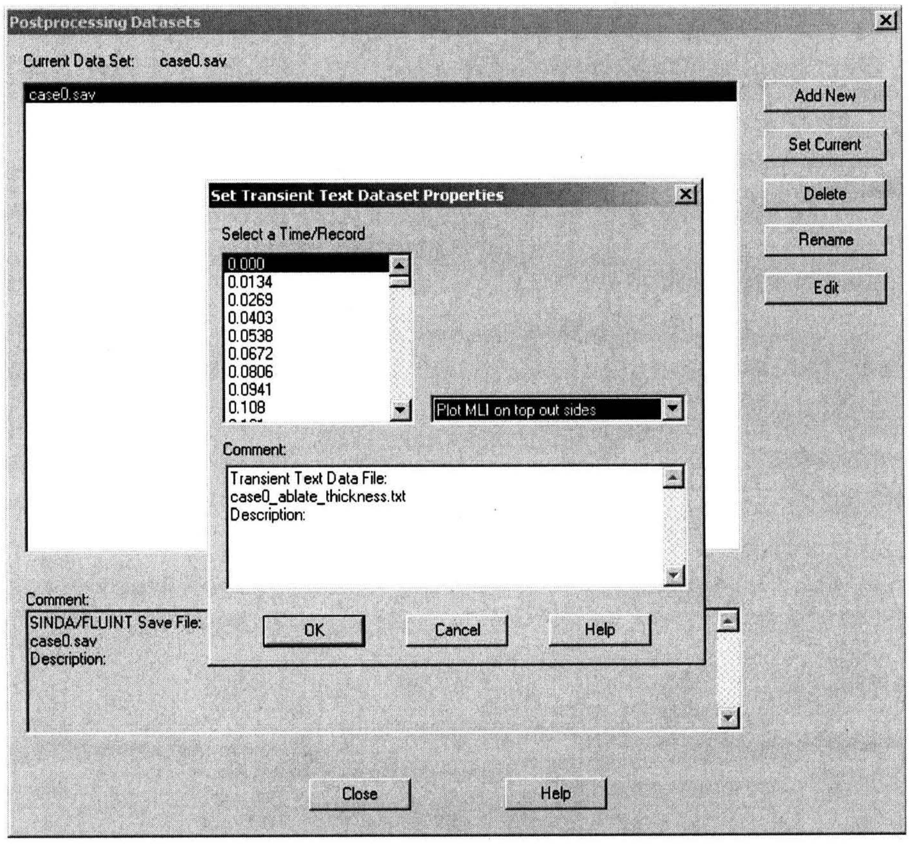


Figure . Set Transient Text Dataset Properties

RESULTS

Heat Flux Data Mapplng Comparison

The heat flux data used in the Thermal Desktop model is extracted from Computational Fluid Dynamic models provided by Ames Research Center. The heat flux data is computed from a conjugate heat transfer model where the maximum temperature is capped at the melting temperature of the refractory material. The melting temperature is approximately 1373 K. The mapping of the heat flux data showing good qualitative comparison between the CFD result and the Thermal Desktop result is shown in Figure 13. The difference in heat flux magnitude is a caused by the difference in area between the elements of the CFD model and the Thermal Desktop model.

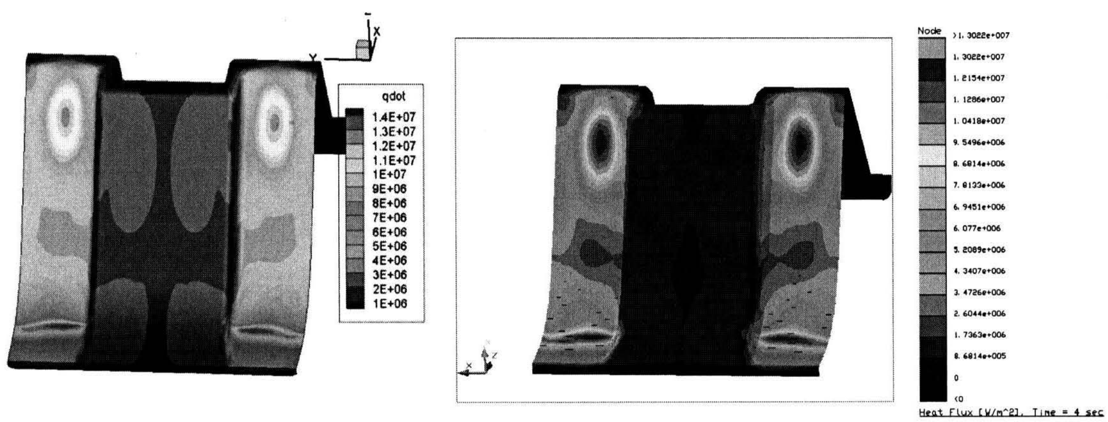


Figure . Heat flux data from CFD solution using TecPlot® and Mapped data to Thermal Desktop® Model.

<u>Surface Thickness Results</u>

From the thermal desktop analysis the analyst can produce results for the mapped heat flux and surface thickness. The base material surface temperature contour can also be produce, but the temperature change of the base material for this analysis was negligible and out of the scope. Figures 17-20 summarizes the results from the analysis.

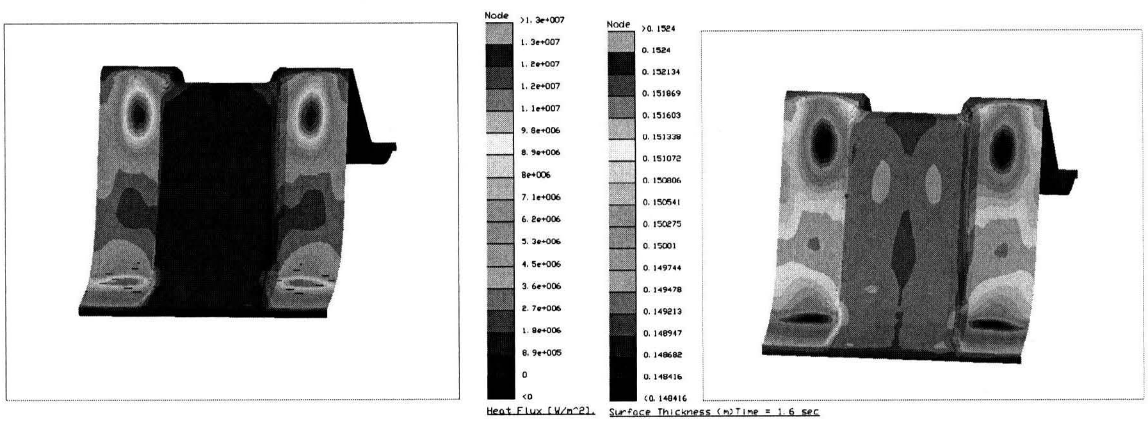


Figure . Heat Flux and Surface Thickness Contours in result of SLS Vehicle

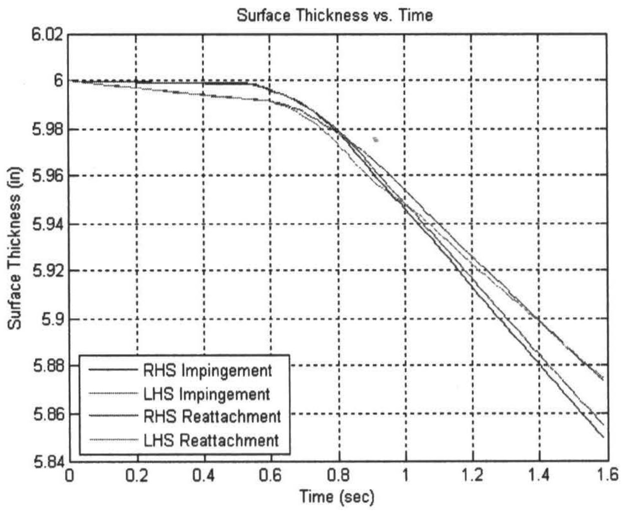


Figure . Surface Thickness versus Time at the Impingement and Reattachment Regions.

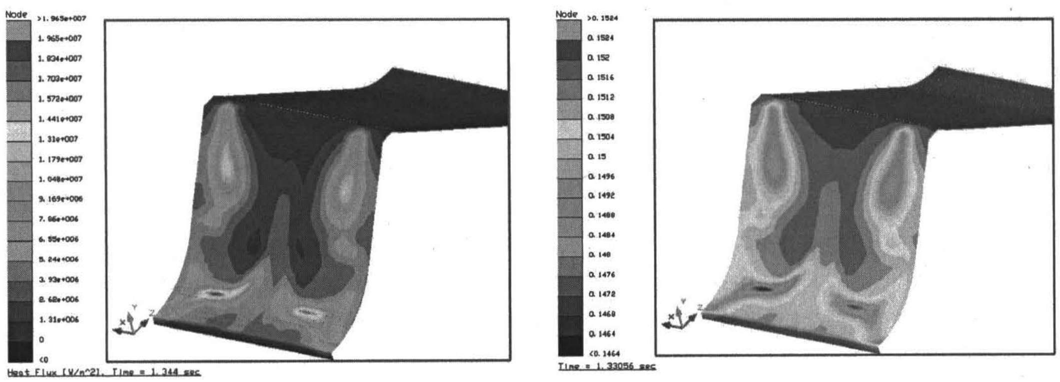


Figure . STS Validation Case

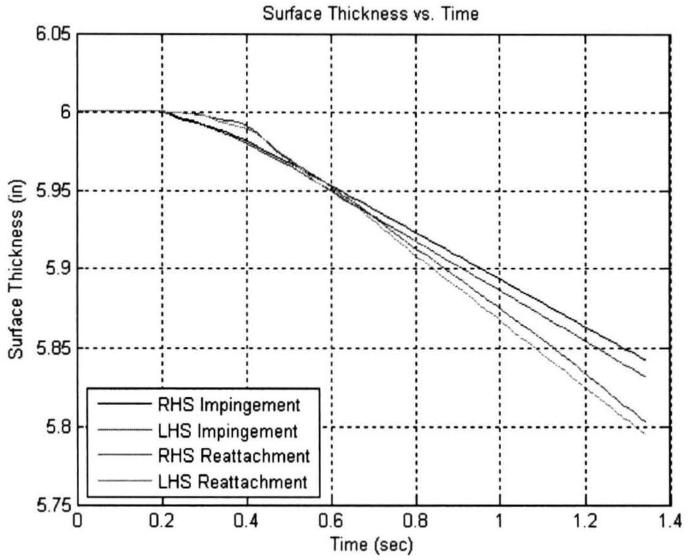


Figure . STS Validation Case Surface Thickness versus Time.

Table . Summary of results

Analysis	Time (sec)	Change in Surface Thickness (in)	Ablation Rate (in/s)
STS Validation	1.344	0.20	0.15
SLS Concept	1.239	0.15	0.12

CONCLUSIONS

The analysis so far has shown the benefits in using CFD and Thermal Desktop tools in tandem by utilizing the boundary condition mapper. The highly transient, highly compressible flow from the rocket plume can be modeled using high fidelity numerical CFD codes. By extracting the thermal data from the CFD models, one can perform thermal analyses that can benefit the determination of insulation required or a thermal structural analysis can be performed to insure minimum stresses. In addition, the knowledge gained using the ablation subroutine gives our analysis group a tool in the future need for an ablation analysis.

The flame deflector results show to be within 20% of the expected 0.25 inch loss measured post-launch of a STS mission. The error is believed to be due to inconsistent times at which the plume impinges on the flame deflector. With the addition of vehicle ascent trajectory, it is believed the results will be within the expected measurement. The new concepts for the flame deflector could benefit the launch environment not only in IOP, acoustics, and vibration, but on a thermal basis allowing for a weaker secondary shock wave to form.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Cetin Kiris and Emre Sozer for their wonderful work on providing heat flux data from their CFD models for this Thermal Desktop analysis. This work was funded by the Mobile Launcher Launch Induced Environment project, Task Order 51.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ARC Ames Research Center

BCM Boundary Condition Mapper

CFD Computational Fluid Dynamics

KSC Kennedy Space Center

REFERENCES

SINDA/FLUINT User's Manual

Thermal Destop® User's Manual

Other suggestions:

To utilize Greek symbols, please use the Symbol font.

Please number figures and tables independently.

Please number equations if they will be referred to in the text.

Modeling of Heat Transfer and Ablation of Refractory Material Due to Rocket Plume Impingement

Michael F. Harris
Bruce T. Vu

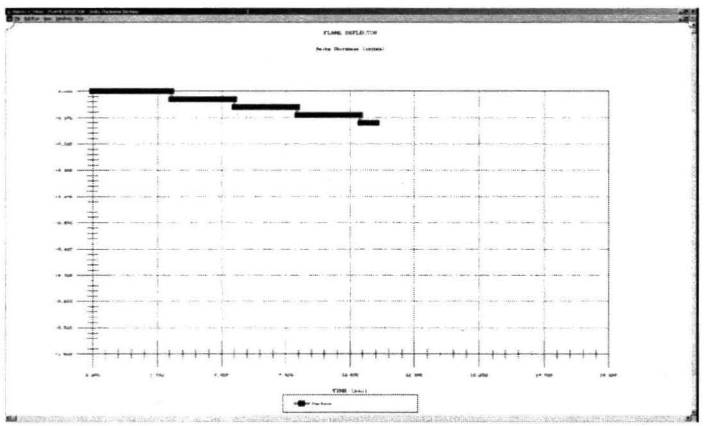
Presented By
Michael F. Harris

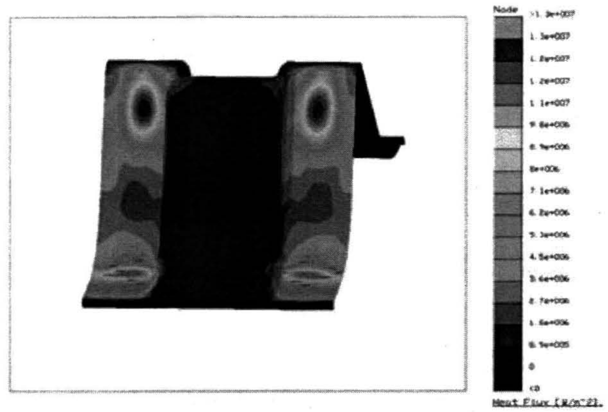
Thermal & Fluids Analysis Workshop
TFAWS 2012
August 13-17, 2012
Jet Propulsion Laboratory
Pasadena, CA

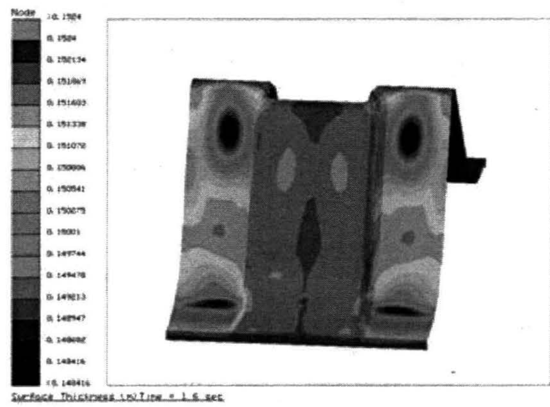
Introduction

- Launched Induced Environment
  - Acoustics
  - Vibration
  - **Thermal**
    - Modeling of the plume heat flux and ablation of the refractory material.
  - Many different concepts and vehicles are being considered
    - Atlas V
    - Delta IV
    - Liberty
    - Space Launch System (SLS)
    - SpaceX Falcon Heavy
- An efficient method of performing the Thermal Analysis of the Flame Deflector was needed.

- Software tools available
  - THERM1D
  - Thermal Desktop®





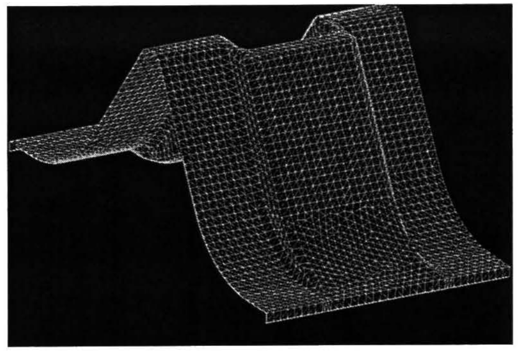


Background

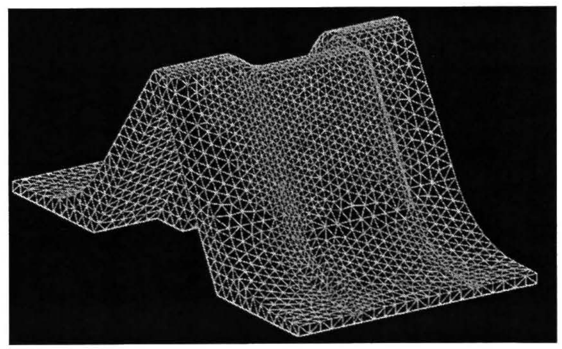
- Therm1D has been sufficient in the past for ablation analysis. The analysis is done at a specifically chosen location.
- Thermal Desktop with SINDA/FLUINT has the capability to perform the same ablation analysis but over the entire surface.
- This will help in rapidly determining locations of highest ablation on the flame deflector

Model Setup: Meshing

- NX/NASTRAN
  - Capability at KSC is used to produce meshes to import into Thermal Desktop
  - 2-D surface mesh using triangle or quad elements
  - 3-D solid mesh using tetrahedral or quadrahedron elements.



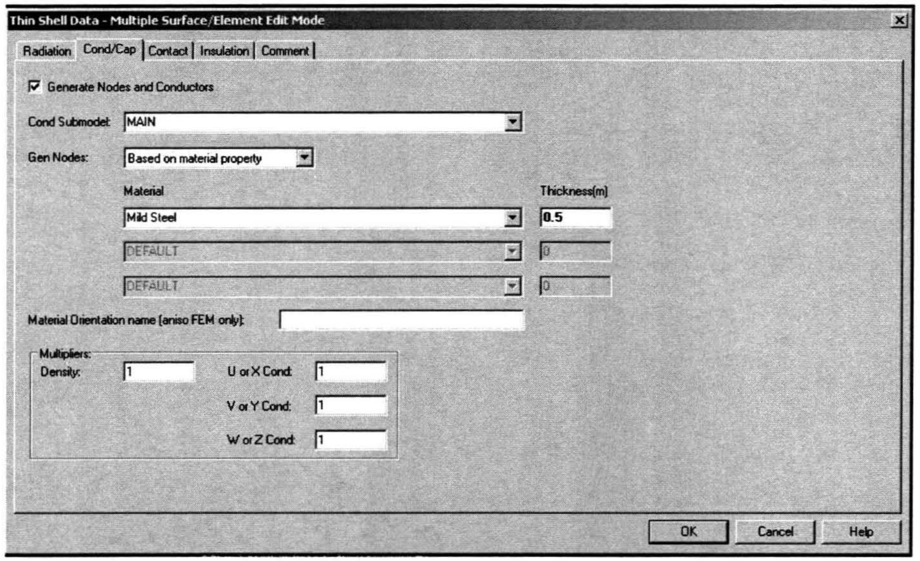
2D Surface Mesh



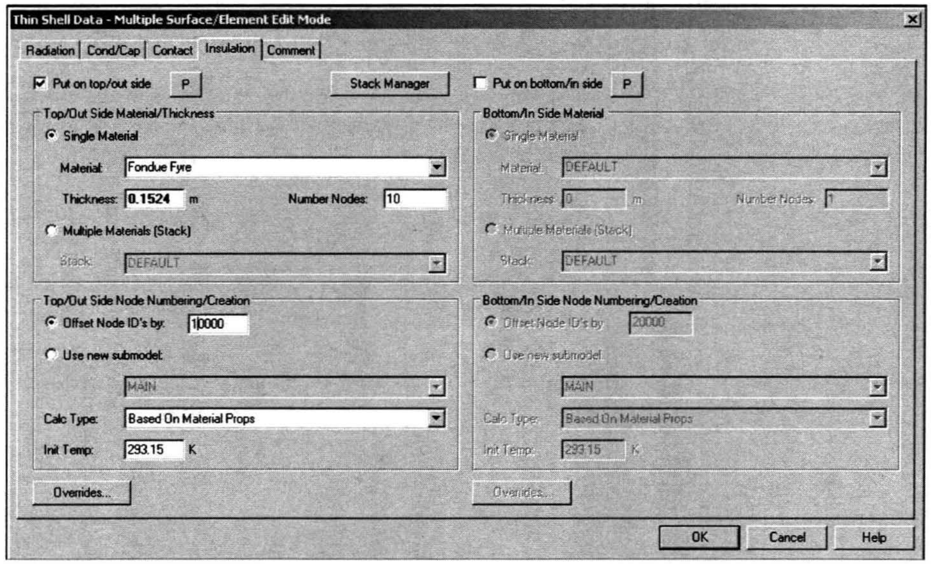
3D Tetrahedral Mesh

Model Setup: Defining Surface Parameters

- Surface Parameters
  - Material
  - Thickness



- Insulation/MLI
  - Defining ablation nodes



Model Setup: Mapping

- Boundary Condition Mapper (BCM)
  - Temperature Dependent Heat Flux (Node Based)
  - Element Based Temperature Dependent Heat Flux
  - Units
  - Node Number and Coordinates
  - Tri or Quad Elements and corresponding Nodes
  - Time and Data for each Node

TEMPERATURE DEPENDENT HEAT FLUX BCM Sample Input

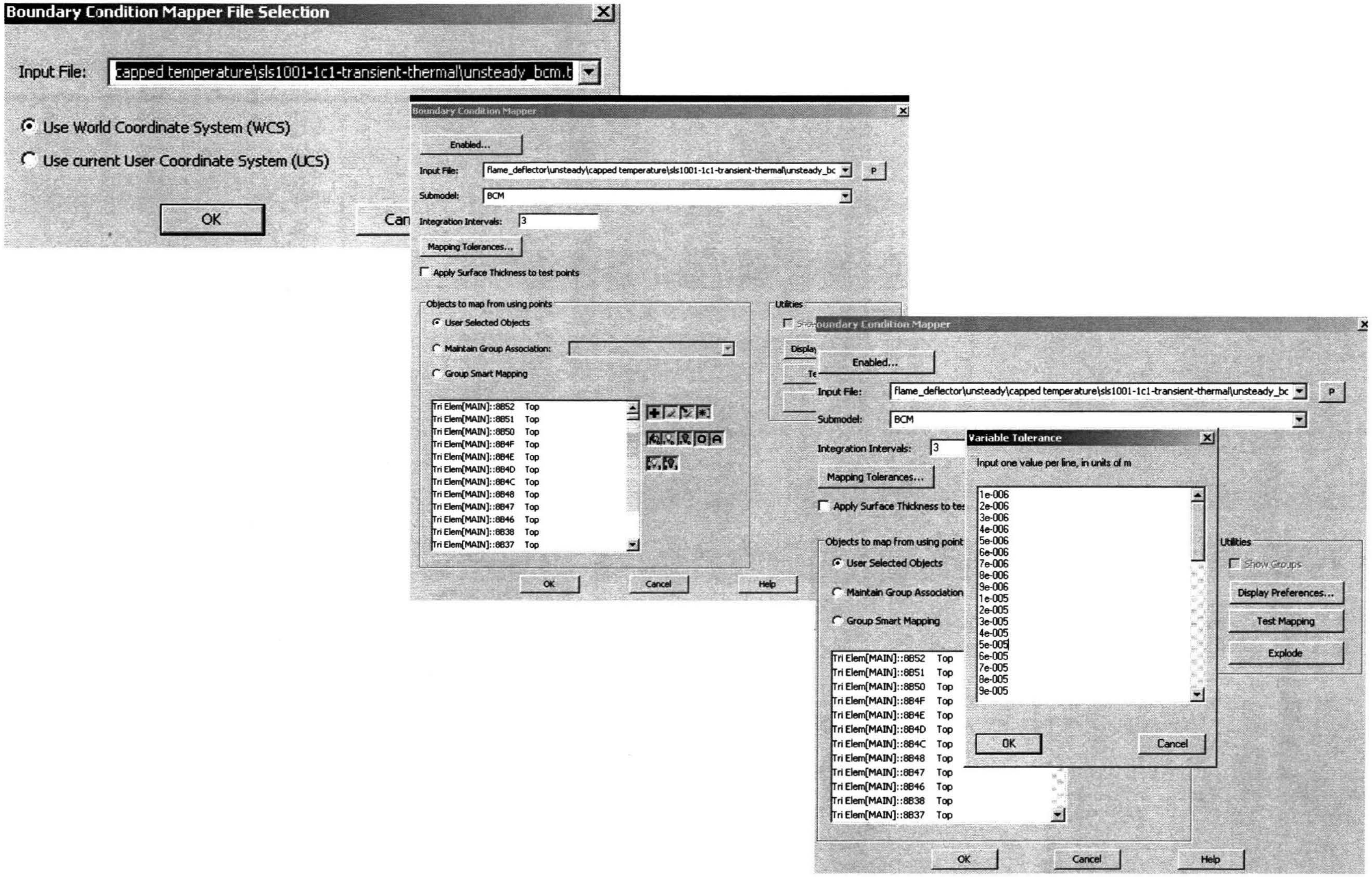
Note: Please note that all information including and after the '!' is for description and should not be in the actual file.

```
DATA: TEMPERATURE DEPENDENT HEAT FLUX
UNITS LENGTH meters
UNITS TEMPERATURE R
UNITS TIME SECONDS
UNITS DATA W/cm2
TEMPERATURES 2
300.000000
1000.000000
NODE 1 0. 0. 0.
NODE 2 0. 1. 0.
NODE 3 1. 0. 0.
NODE 4 1. 1. 0.
NODE 5 2. 0. 0.
NODE 6 2. 1. 0.
TRI 1 1 2 3
TRI 2 3 2 4
TRI 3 3 4 5
TRI 4 5 4 6
TIME 87.000000
1.01            ! Flux for node 1 at T = 300
1.02            ! Flux for node 1 at T = 1000
2.01            ! Flux for node 2 at T = 300
2.02
3.01
3.02
4.01
4.02
5.01
5.02
6.01
6.02
TIME 90.000000
11.01
11.02
12.01
12.02
13.01
13.02
14.01
14.02
15.01
15.02
16.01
16.02
```

Model Setup: Mapping

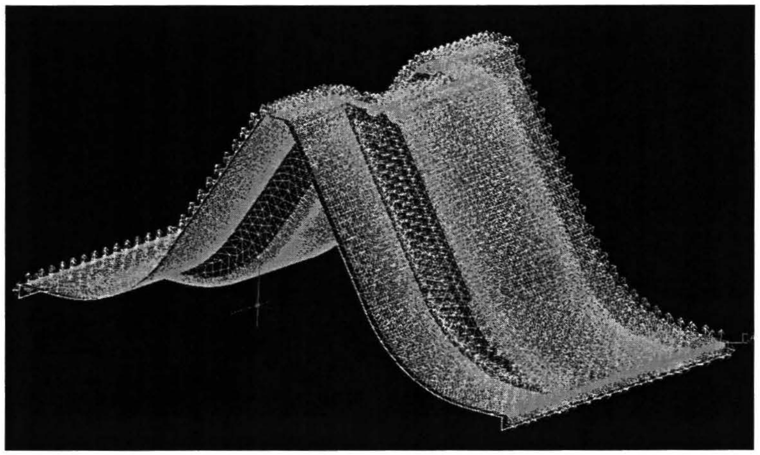
- Large amounts of data needed to be formatted
- Developed MATLAB routine to format TECPLOT® files provided by ARC to Thermal Desktop Boundary Condition Mapper Format

Model Setup: Mapping



Model Setup: Mapping

- ARC results are mapped to the Thermal Desktop model as a boundary condition



Successful Mapping of CFD to Thermal Desktop

Ablation Subroutine

- Theory
  - 1-D finite differencing through the thickness of ablative material
  - Once the ablating node is reduced to 50%, the node is converted to a arithmetic node.
  - The node is collapsed and the capacitance and energy is transferred to the next node.

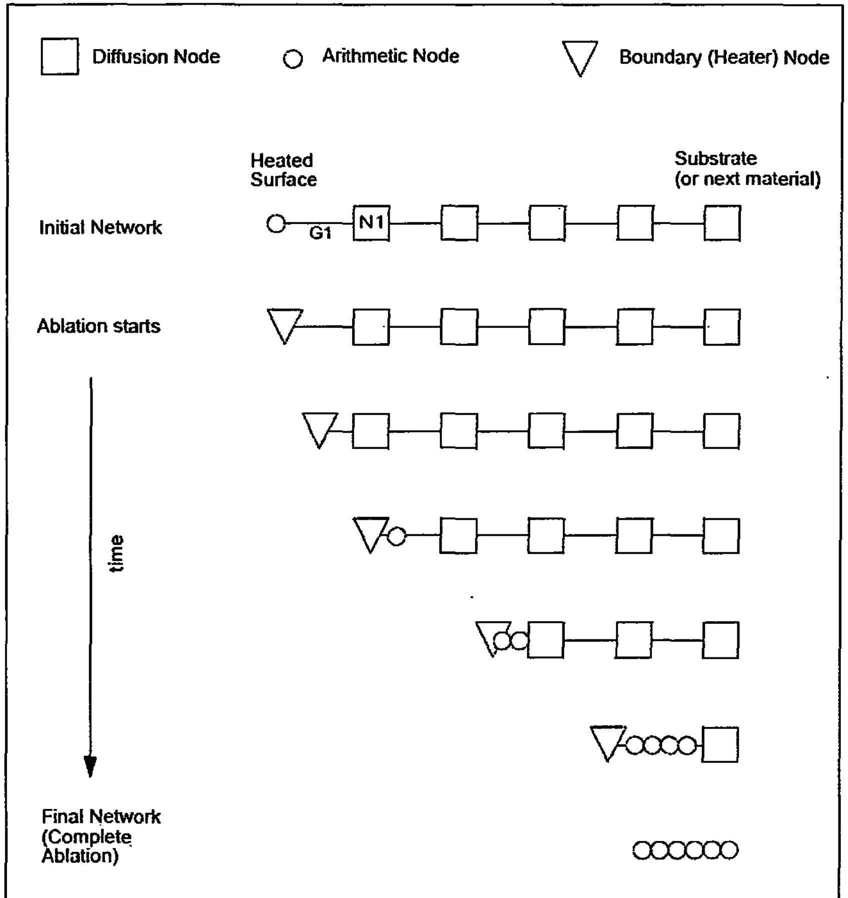
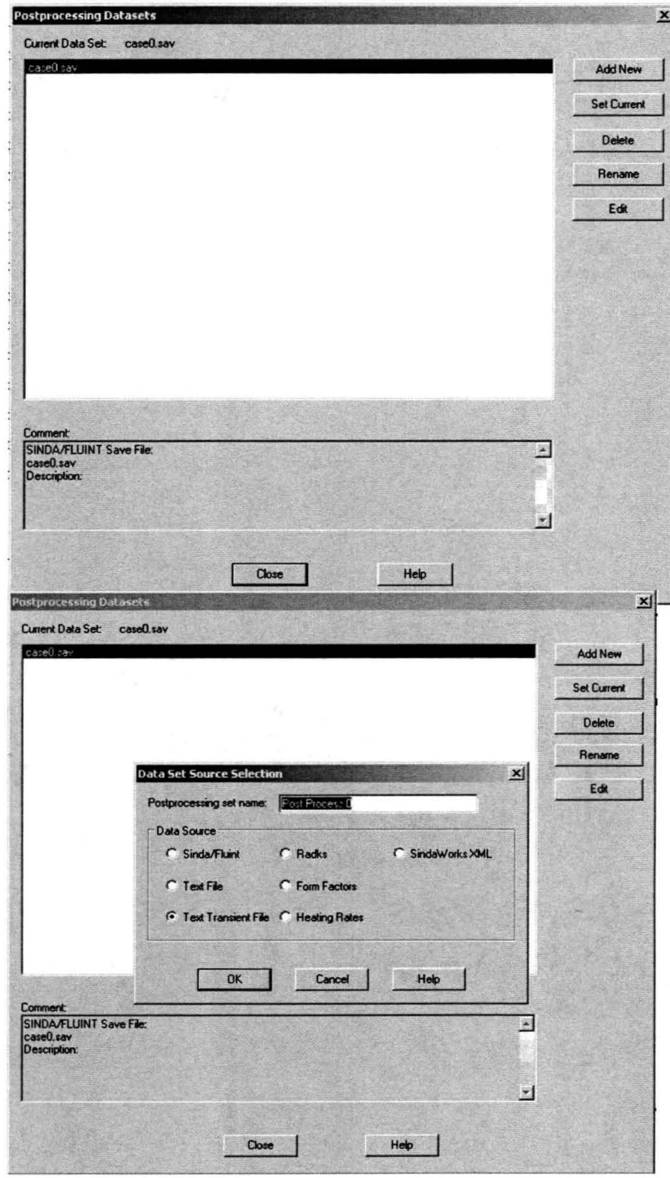


Figure 7-3 Network Changes Invoked by ABLATE for Simulating Mass Loss

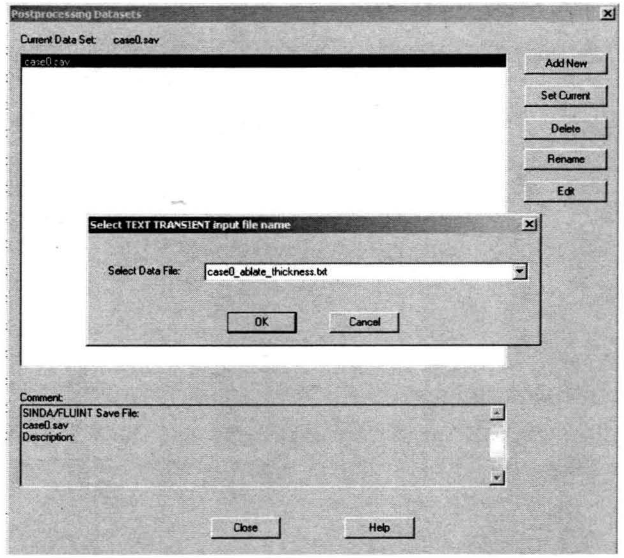
Post Processing

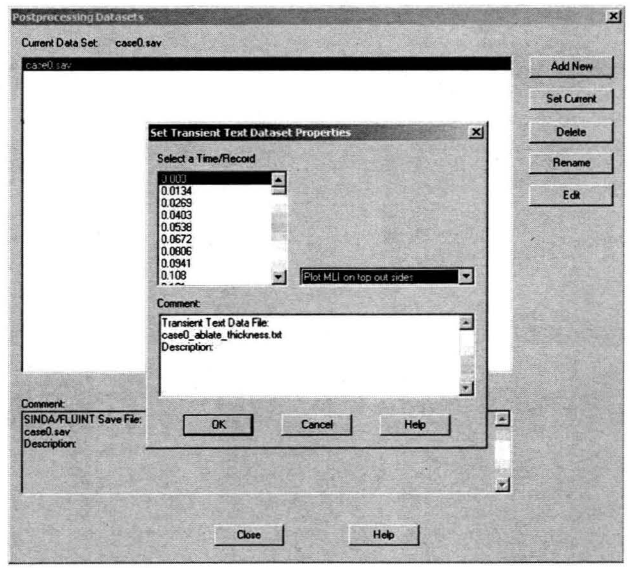
- Ablation subroutine exports a file with the surface thickness time history.
- Post processing Datasets
  - Add New
  - Select Text Transient File
  - Find and Select ablation text file



Post Processing

- Post processing Datasets
  - Find and Select ablation text file
  - Specify Tolerances
    - Give a range
    - 1e-05, 2e-05, 3e-05…..
    - Select Plot MLI on top out sides

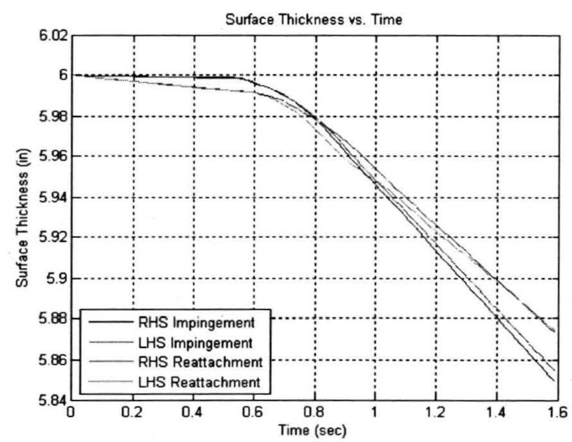




Post Processing

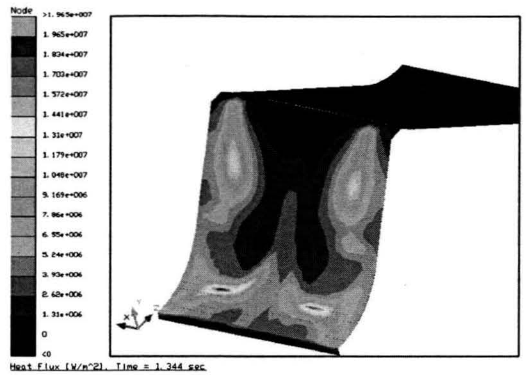
- Surface Thickness vs. Time Plots
  - Difficult to accomplish within Thermal Desktop
  - MATLAB script was developed to read data from surface thickness time history file.

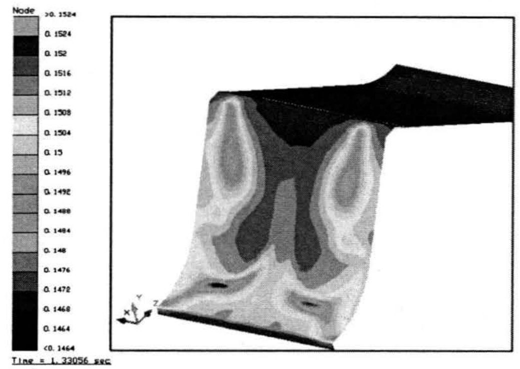
```
clc
clear all
close all

fid = fopen('case0_ablate_thickness.txt');
M = textscan(fid, '%s');
time_records = 102;
numofnodes = str2num(cell2mat(M(1,1)(1)));
nodes = cell2mat(M(1,1)(2:numofnodes+1));
data = M(1,1)(numofnodes+2:((numofnodes*time_records)+time_records));
% data2 = cell2struct(data(1:342895))
for i = 1:342895
    data2(i) = str2num(cell2mat(data(i)));

end
data2 = data2';

j= 1;
i = 1;
stop = 1;
time(i) = data2(j);
for i = 2:102
    stop = j+numofnodes;
    data3(:,i-1) = data2(j+1:stop);
    if i < 102
    time(i) = data2(stop+1);
    end
    j = stop+1;
end

heat = xlsread('Chart1.xls');
figure(1)
[AX,H1,H2] = plotyy(time,data3(3220,:)/0.0254,heat(:,1),heat(:,2));
title('Surface Thickness vs. Time for Fondu Fyre WA-1')
xlabel('Time (sec)')
set(get(AX(1),'Ylabel'),'String','Surface Thickness (in)')
set(get(AX(2),'Ylabel'),'String','Heat Rate (W)')
grid on
```

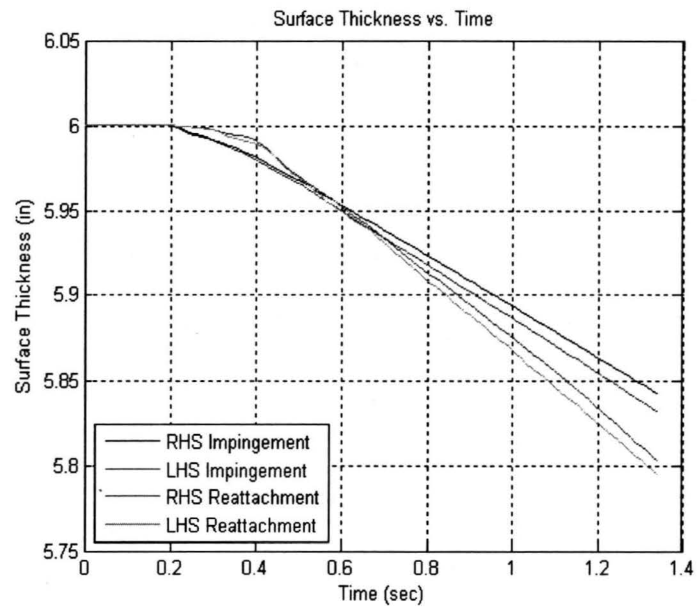


Results: STS Validation

- CFD Heat Flux Boundary Conditions are stopped after Full Thrust is reached.
- Approximately 0.2" of material loss over 1.3 seconds.
- Post Launch Measurements: 0.25" maximum
- About 0.15 in/s loss
- Reattachment shocks give the highest heat flux and maximum ablation.

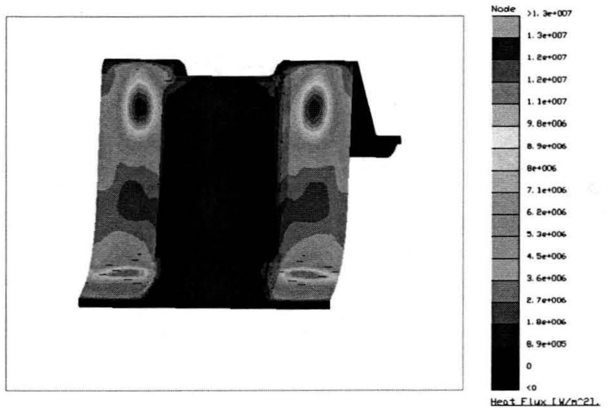


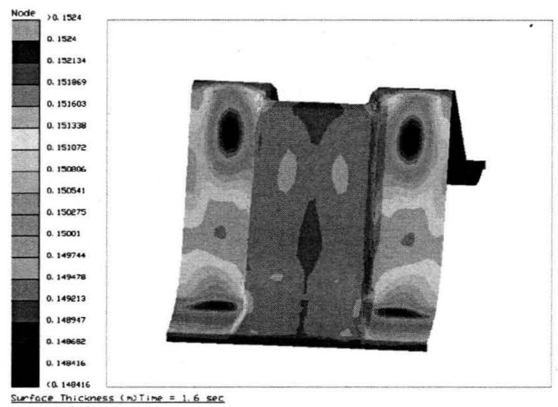


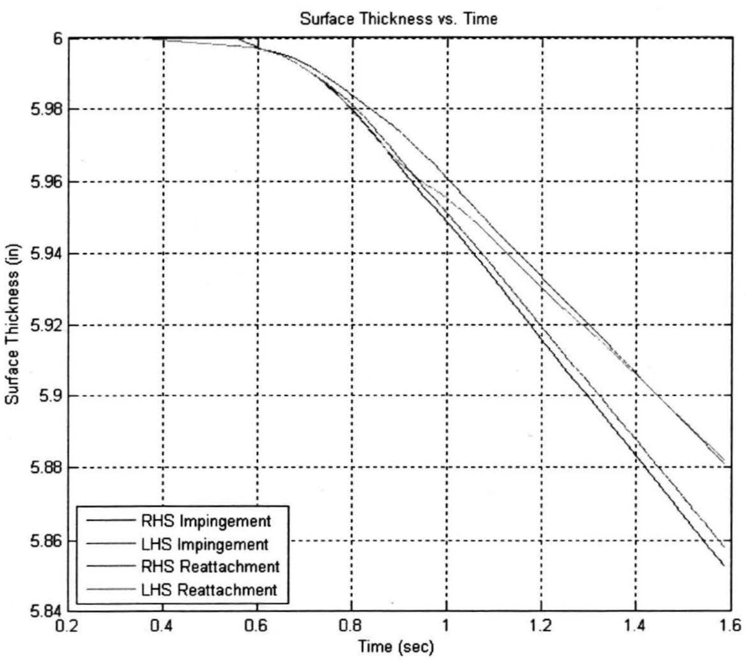


Results: SLS Concept

- Approximately 0.15" loss of material over 1.24 sec duration.
- About 0.12 in/s of material loss
- Reattachment shocks happen to be weaker
- Maximum Heat Flux and Ablation at Plume Impingement







Conclusions

- Developed analysis methods in Thermal Desktop to perform future heat transfer analyses.
  - Gained knowledge and experience for the capability to utilize the Boundary Condition Mapper to map CFD data to Thermal Desktop® Models
  - Gained knowledge and experience for the capability to utilize the ablation subroutine
- Flame Deflector Thermal Analysis
  - The results are within 20% of expected
  - New concepts can be designed to reduce secondary shock wave effects, High Pressure and Temperature.
  - Future analysis will be done to refine results

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Questions?

Thank you!

References

- SINDA/FLUINT User's Manual
- Thermal Desktop® User's Manual