TRANSIENT ANALYSIS OF THERMAL PROTECTION SYSTEM FOR X-33 VEHICLE USING MSC/NASTRAN

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ABSTRACT

X-33 is an advanced technology demonstrator vehicle for the Reusable Launch Vehicle (RLV) program. The thermal protection system (TPS) for the X-33 is composed of complex layers of materials to protect internal components, while withstanding severe external temperatures induced by aerodynamic heating during high speed flight. It also serves as the vehicle aeroshell in some regions using a stand-off design. MSC/NASTRAN thermal analysis capability was used to predict transient temperature distribution (within the TPS) throughout a mission, from launch through the cool-off period after landing.

In this paper, a typical analysis model, representing a point on the vehicle where the liquid oxygen tank is closest to the outer mold line, is described. The maximum temperature difference between the outer mold line and the internal surface of the liquid oxygen tank can exceed 1500°F. One dimensional thermal models are used to select the materials and determine the thickness of each layer for minimum weight while insuring that all materials remain within the allowable temperature range. The purpose of working with three dimensional (3D) comprehensive models using MSC/NASTRAN is to assess the 3D radiation effects and the thermal conduction heat shorts of the support fixtures.

1. INTRODUCTION

In July 1996, NASA entered a partnership with Lockheed-Martin to develop and demonstrate the technologies required to build a next generation fully reusable launch vehicle (RLV) that will provide lower launch costs. The X-33 is a technology demonstrator which will test the application of advanced technology, including real gas effects of hypersonic flight, in the design of a next generation RLV. A conceptual view of X-33 is shown in Fig. 1.

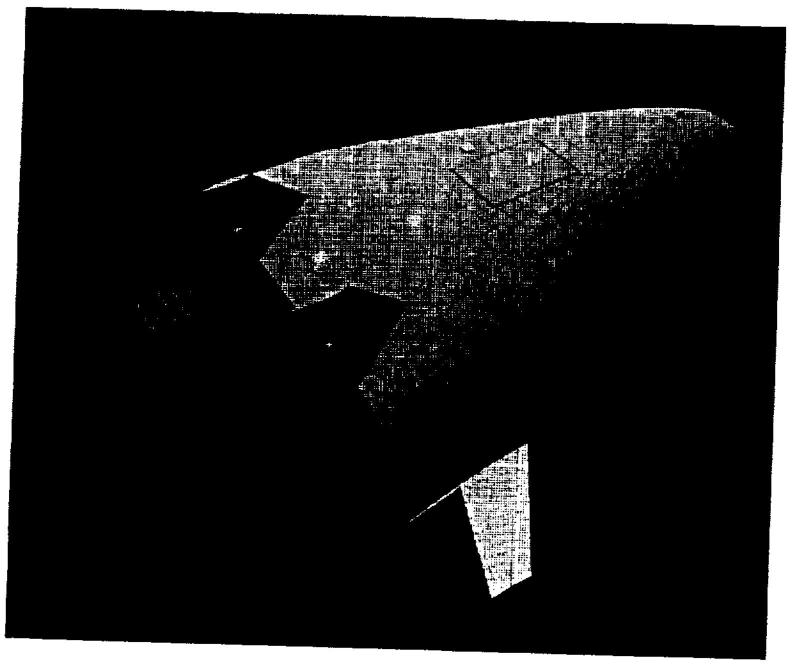

Fig. 1 X-33 Technology Demonstration Vehicle

The external thermal load profile varies widely over the surface of the vehicle, hence different types of thermal protection systems are deployed over the surface to achieve minimum weight while maintaining structural and thermal integrity. Accurate prediction of the external thermal loads over the specified flight trajectory is a very difficult task, even with modern computational fluid dynamics (CFD) codes. Especially difficult is the prediction of transition from a laminar to turbulent boundary layer which has severe impact on the amount of aerodynamic heating experienced by the vehicle. However, a number of CFD analyses have been carried out at certain discrete points for a design database and a program that is capable of interpolating a thermal load at any point on the trajectory has been developed. When the flight test data become available to provide calibration of the CFD results, the result will be a better calibrated database for design of the RLV.

Most of the internal volume of X-33 is occupied by storage tanks for cryogenic fuels, i.e., liquid hydrogen (LH2) and oxygen (LOX). These tanks serve as the primary load carrying structures. The internal tank wall is in contact with either LH2 or LOX at the beginning of ascent. After most of the fuel is depleted in the first few minutes of flight, the tank internal wall is exposed only to the gasified fuel.

Since the shape of the tanks is not conformal to the vehicle external mold line, internal structures deployed between the tank and the external surfaces vary in length depending on the distance between two surfaces. In this paper, a typical location is considered where the distance between external surface and LOX tank is about 10 to 12 inches.

2. MODEL DESCRIPTION

The layers of thermal protection system at the point considered are schematically shown in Fig. 2. The external surface is formed by an assembly of approximately 18" x 18" x 0.5" Inconel honeycomb sandwich panels. The internal surface of each panel is covered by 1 to 1.5 in. of fibrous insulation enclosed by a thin Inconel foil pan. The LOX tank wall is made of aluminum alloy and is covered by a light weight foam insulation approximately one inch thick.

At the specific location considered here, there is not enough clearance between the two surfaces to install standard stand-off composite honeycomb structural elements. Therefore, thin walled longitudinal titanium beams are placed on the LOX tank external ring frames and metal clips, referred to as rosettes, are attached to these beams. Subsequently, each corner of the honeycomb sandwich panel is attached to the end of a rosette leaf.

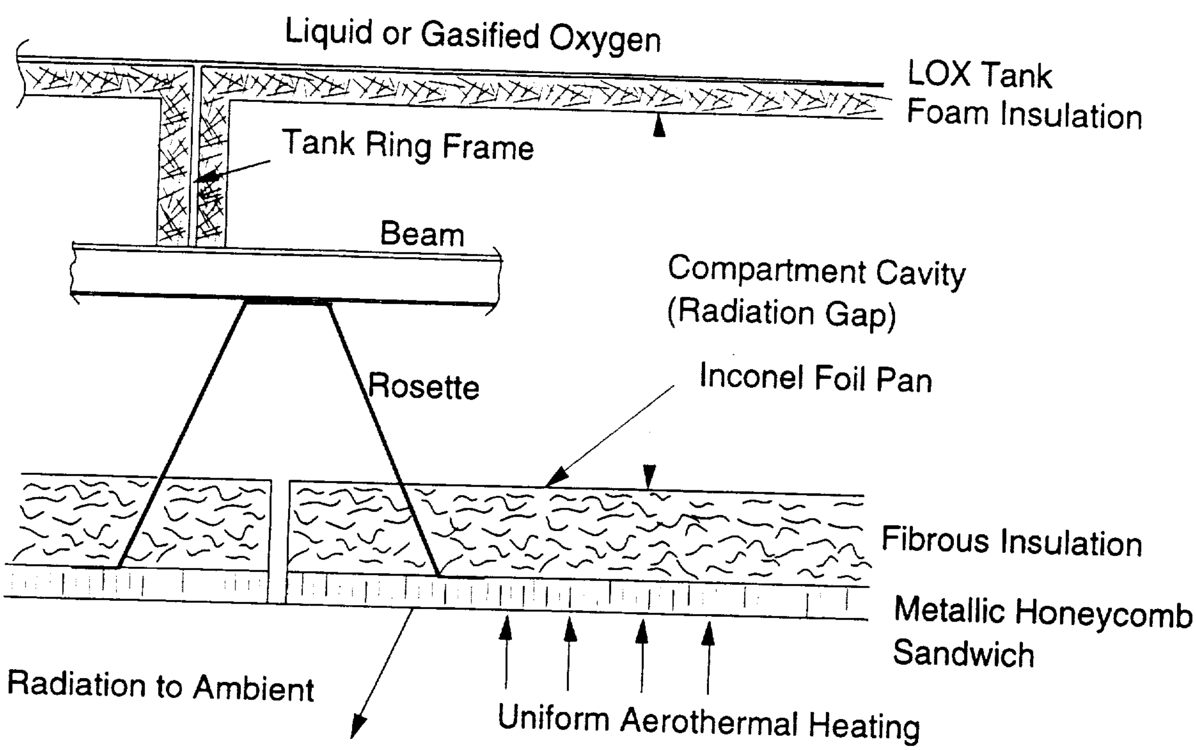

Fig. 2 Finite Element Model

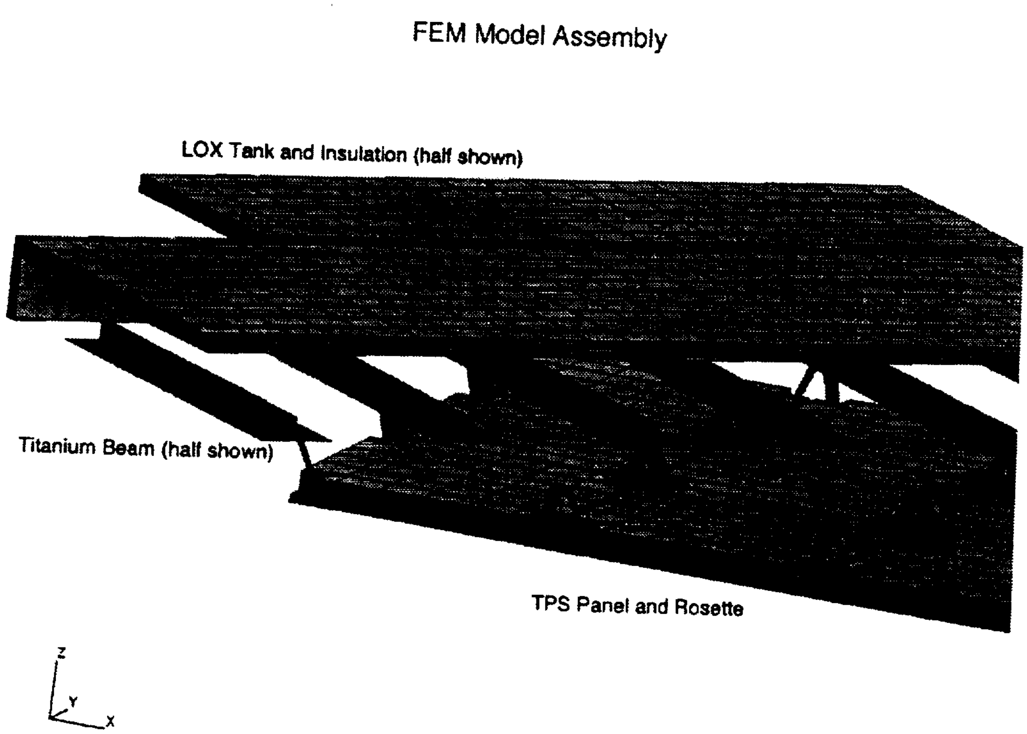

Fig. 3 Finite Element Model

The finite element model generated for this study is shown in Fig. 3. To expose the internal support fixtures, a half of the tank wall and support beams are removed in this figure. Although a nine-panel array was constructed, the results presented are taken from the center panel so as to reduce the edge effects of radiation in the model.

2. 1 Material Properties

2. 1. 1 Metallic Honeycomb Sandwich

The metallic sandwich panel is modeled in three separate components: external face sheet, honeycomb, and back face sheet. Approximate homogenized thermal properties of honeycomb are provided by the manufacturer. Thermal conductivity is orthotropic and temperature dependent. Specific heat is isotropic and temperature dependent. Emissivity of the oxidized external surface is also temperature dependent.

2. 1. 2 Fibrous Insulation

Various candidate materials are available with different density, allowable temperature range, and thermal properties. Regardless of the selection of a specific material, thermal properties for these type of materials are temperature and pressure dependent.

2. 1. 3 Foam Insulation for Tanks

Various candidate materials are available and tested. In addition to the thermal conductivity and specific heat, both of which are temperature dependent, the upper bound for the surface temperature for tank insulation is a key design criterion.

2. 1. 4 Conduction through Support Fixtures

The fixtures that support the surface panel are all considered to be metallic in this study. Essentially, the metallic honeycomb sandwich panels are supported at four corners by rosettes which are attached to beams, which in turn are attached to the tank ring frame. All the attachments use mechanical fasteners. Heat conduction from the vehicle surface to the tank was modeled to reflect the geometry of these fasteners. Contact resistance for mechanical connections was not modeled.

2. 2 Boundary Conditions and Thermal Loads

2. 2. 1 External Surface

External thermal loads are assumed to be uniform for the nine panels considered. Aerodynamic heating is treated as convective heat transfer through the thermal boundary layer, given the recovery temperature and equivalent film coefficient as functions of time. This is modeled as a convection to an ambient point through a time dependent film coefficient and a time dependent temperature assigned to an SPOINT representing the ambient. At or near the peak aerothermal heating, the majority of the thermal energy coming into the external surface is radiated back to space, thus only a small fraction of the energy of aerothermal heating penetrates through the surface. Therefore, it is important to model this radiation to an ambient point as accurately as possible, hence temperature dependent emissivity is used instead of an average constant emissivity.

2. 2. 2 Radiation in Compartment Cavity

Radiation heat transfer through the compartment cavity is modeled by a cavity enclosure. In reality, the gap distance is not constant, but it is assumed to be constant since the variation is moderate and smooth. The difficulty is to eliminate, or at least decrease, the edge effects of radiation through the gap at the open ends of the model. MSC/NASTRAN does not support a reflective boundary condition which requires ray tracing analysis in the cavity. This effect may be reduced by modeling nine TPS panels instead of only one, and consider the computed thermal responses reliable only for the center panel. The radiation through the gap at the open ends of the cavity is handled as radiation exchange with an ambient point. The default temperature of this ambient point is absolute zero, thus it absorbs all the radiation energy emanating from the open gap. For this reason, portions of the model near the edges and corners tend to be cooler than the center. It is possible to specify the temperature for this ambient point and it may be adequate to assign compartment temperature (time dependent) to this point in the future.

The shading from the support beam needs to be taken into account since the beam flanges cover about 40% of the area. There is no problem in modeling the shading involving beam flanges, but the CPU time for the analysis increases if shading is implemented for all nine panels and tank surfaces. To remedy this situation, shading is introduced only at the immediate neighborhood of the center panel, since capturing the thermal responses of the center panel is the primary interest of this study.

2. 2. 3 Convection in Compartment Cavity

For various reasons, such as the small amounts of hot gas leaking through the panel seals, convective heat transfer of the air moving through the compartment must be taken into account. As an approximation, available vehicle data are used which provide the average temperature of the compartment air and convective film coefficient both as the functions of time.

2. 2. 4 Convection at the LOX Tank Wall

The tank is full of liquid oxygen at the time of launch.. Due to the small thermal resistance between the liquid oxygen and the tank wall, the tank surface is at the same temperature as the liquid oxygen at launch. As soon as the liquid oxygen is depleted during ascent, the free surface level moves down to leave the internal surface in contact with gasified oxygen. These rather complex dynamic phenomena are approximated in this model as convection to an ambient point, with time-dependent temperature through time-dependent convection film coefficient.

3. RESULTS OF ANALYSES

3. 1 Steady State Analysis

To find the appropriate initial temperature over the entire model, steady state analysis is performed with SOL153, simulating the ground-hold condition prior to launch. A hot day condition was applied by keeping the external surface at 103 °F. It turned out that the use of temperature dependent emissivity in the cavity enclosure, together with shading options, dramatically increased CPU time, even for this relatively simple model. This is due primarily to recomputing the radiation exchange matrix for every nonlinear iteration. Based on the results of one dimensional analyses and preliminary test data, it is reasonably sure that none of the primary surfaces exposed to the internal surface of this enclosure exceeds 500°F. Therefore, it was assumed that emissivities of all the enclosure surfaces remain constant to complete the computation within a reasonable time and budget. This assumption is applied also to the computationally more expensive transient analyses.

3. 2 Transient Analysis

Starting from the initial temperature distribution obtained from the steady state analysis, SOL159 is used to estimate the internal temperature distribution over the entire flight and including the cool-off period after landing. For the trajectory studied here, the actual flight takes less than 25 minutes, but analyses are performed usually up to 3,000 seconds, even though the temperature profile

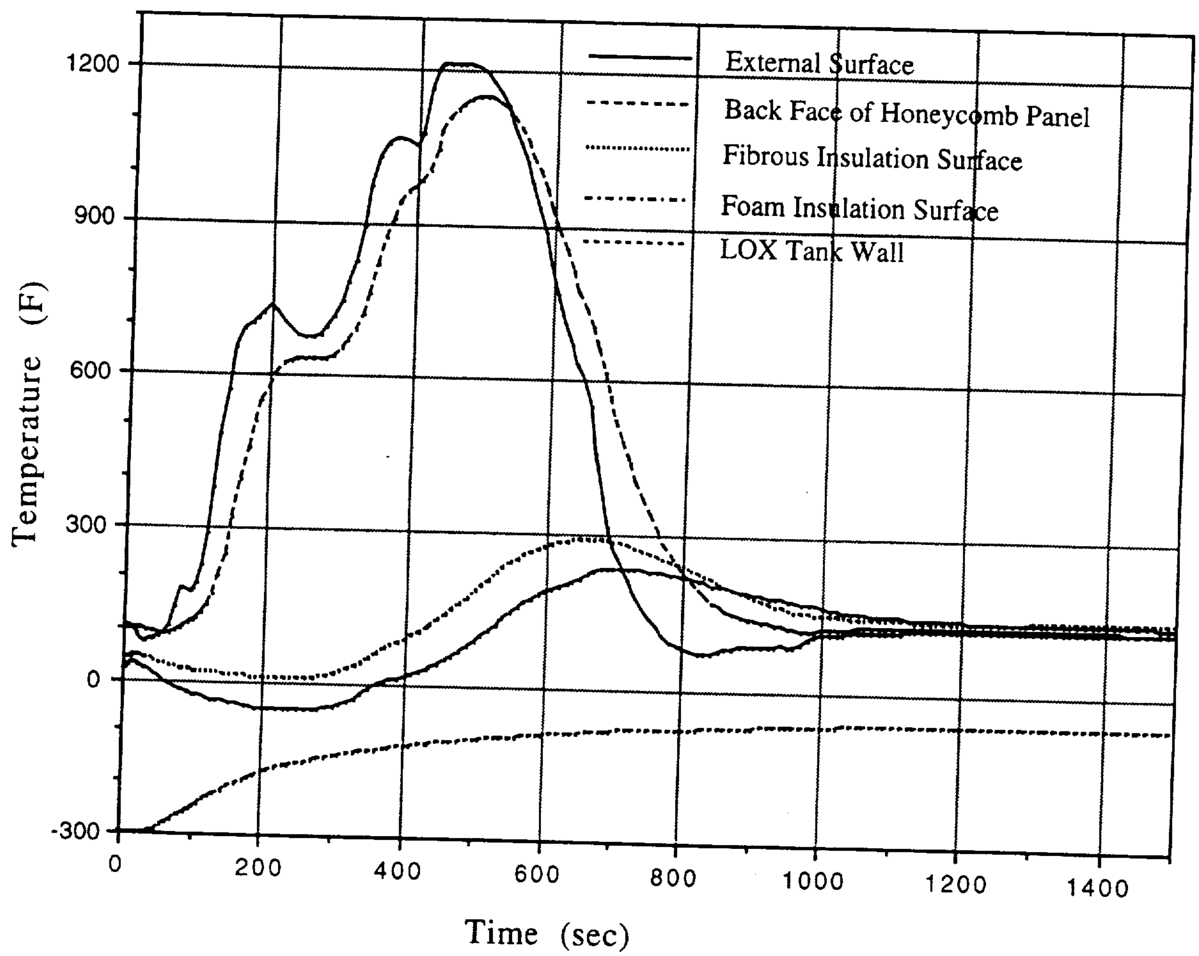

Figure 4. Temperature Profile through the Middle of the Center Panel

is changing very slowly after 1,500 seconds. Because of very low thermal conductivity in the fibrous and foam insulation materials, this system does not arrive at a steady state during this entire period. It asymptotically approaches steady state towards the end of the analysis. Fig. 4 shows the temperature history of the points through the middle of the center panel in the range 0 - 1,500 seconds. For this flight trajectory, the maximum altitude is reached at about 245 seconds and the maximum temperature at the surface is reached after the boundary layer goes through transition from a laminar to turbulent boundary layer. After about 530 seconds, the location with the highest temperature in the entire model is no longer on the surface; instead it is inside the fibrous insulation. The external surface quickly cools down after about 500 seconds, but the thermal energy stored in the insulation material is released to the vehicle slowly.

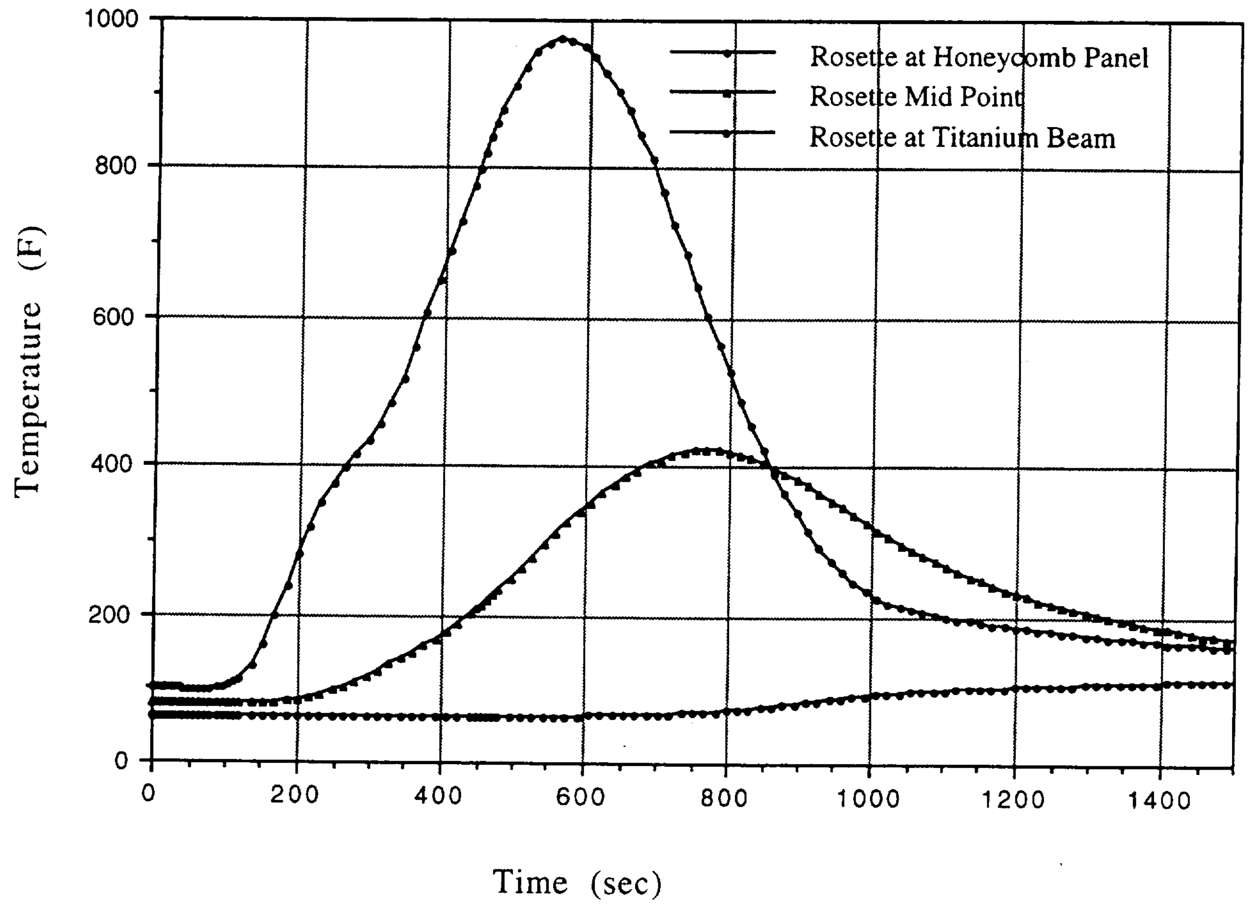

Fig. 5 Temperature Drop through Rosette Leaves

The thermal path through the support structures appears to be well designed to achieve a very significant temperature drop through the rosette leaves, as shown in Fig. 5. This plot also indicates that the beam is kept cool by the LOX tank ring flanges, since it is made of aluminum alloy with a high thermal conductivity.

If the contact resistance at the mechanical fastener surfaces are modeled, the temperature drop through rosette may increase further.

CONCLUDING REMARKS

Thermal analysis capability of MSC/NASTRAN was applied in the analysis of the complex layers of thermal protection system being designed for the X-33 advanced technology demonstrator vehicle. Nonlinearities associated with the temperature dependent material properties, presence of internal radiation cavity with shading, prescription of various time dependent thermal loads, and boundary conditions all contributed to the complexity of this model. Fortunately, various approximations, which were introduced to reduce the computation time, did not have significant effects on the critical transient responses. The thermal analysis capabilities implemented in MSC/NASTRAN served well the analysis of this model for the evaluation of an alternative proposed designs and material combinations.

ACKNOWLEDGMENTS

The prime industry partner for the development of X-33 is Lockheed Martin Skunk Works and the responsibility for the development of the thermal protection system is assumed by Rohr Inc. The compartment database is provided and updated by NASA Marshall Space Flight Center. The authors are grateful for technical as well as administrative cooperation provided by these institutions.

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