X-33 Base Region Thermal Protection System Design Study

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Introduction

The X-33 is an advanced technology demonstrator for validating critical technologies and systems required for an operational Single-Stage-to-Orbit (SSTO) Reusuable Launch Vehicle (RLV). Currently under development by a unique contractor/government team led by Lockheed-Martin Skunk Works (LMSW), and managed by Marshall Space Flight Center (MSFC), the X-33 will be the prototype of the first new launch system developed by the United States since the advent of the space shuttle.

This paper documents a design trade study of the X-33 base region thermal protection system (TPS). Two candidate designs were evaluated for thermal performance and weight. The first candidate was a fully reusable metallic TPS using Inconel honeycomb panels insulated with high temperature fibrous insulation, while the second was an ablator/insulator sprayed on the metallic skin of the vehicle. The TPS configurations and insulation thickness requirements were determined for the predicted main engine plume heating environments and base region entry aerothermal environments. In addition to thermal analysis of the design concepts, sensitivity studies were performed to investigate the effect of variations in key parameters of the base TPS analysis.

Requirements

The first step in the X-33 base region thermal protection system design study was the definition of requirements and constraints. Starting with SSTO RLV system requirements, X-33 vehicle-specific design specifications have been defined by the government and its contractor team (Ref. 1). This information was used to develop specific criteria for evaluation of base TPS designs.

Thermal protection of internal structure and temperature-sensitive components is the basic function of the base TPS and must be considered the primary design discriminator. SSTO vehicle designs are highly sensitive to vehicle mass-fraction, hence minimization of weight is a key design requirement. Although the X-33 is not intended to be an orbital vehicle, weight is still an important consideration. Other factors that must be considered for the RLV base TPS include reuse with little/no maintenance, reliability/durability of the TPS, the capability for quick repair or replacement.

Configurations

Two design concepts were evaluated in this study. The first uses metallic honeycomb panels with high temperature fibrous insulation affixed to the internal face to reduce the temperatures experienced by internal components and structure. The anticipated thermal environment in the base region of the X-33 lead to selection of Inconel as the baseline material for the base region metallic honeycomb.

The second design concept considered in this study was an ablator/insulator coating over a metallic honeycomb skin. The metallic skin in this configuration was Titanium honeycomb, which was limited to much lower temperatures than the Inconel material considered in the first design concept. Several ablative materials were evaluated to determine required thickness and resulting system weights.

Design Heating Environments

The base region of the X-33 will experience severe radiant heating from the linear-aerospike main engine exhaust plume during ascent. Later in the ascent trajectory, as the local pressure around the base of the vehicle falls, the exhaust plume will expand and envelope the aft portion of the vehicle. Convective heating from the hot exhaust plume gases then becomes the dominant mode of heating for the base TPS. The X-33 base region plume heating environments were developed at MSFC using a combination of CFD predictions and extrapolations from flight measurements of previous launch vehicles (Ref. 2). After main-engine cut-off (MECO), the X-33 will experience aerodynamic heating (or cooling, as the case may be) during the remainder of the trajectory. This aerodynamic heating in the base region is relatively benign and not a design driver. Post-MECO aerothermal environments were supplied by LMSW using data generated by NASA/Ames Research Center. Internal vehicle compartment conditions were obtained from a separate thermal model of the vehicle. These internal environments were applied to the backside of the TPS and the underlying support structure. Figure 1 below shows a typical heating environment for a selected point on the base of the X-33 vehicle.

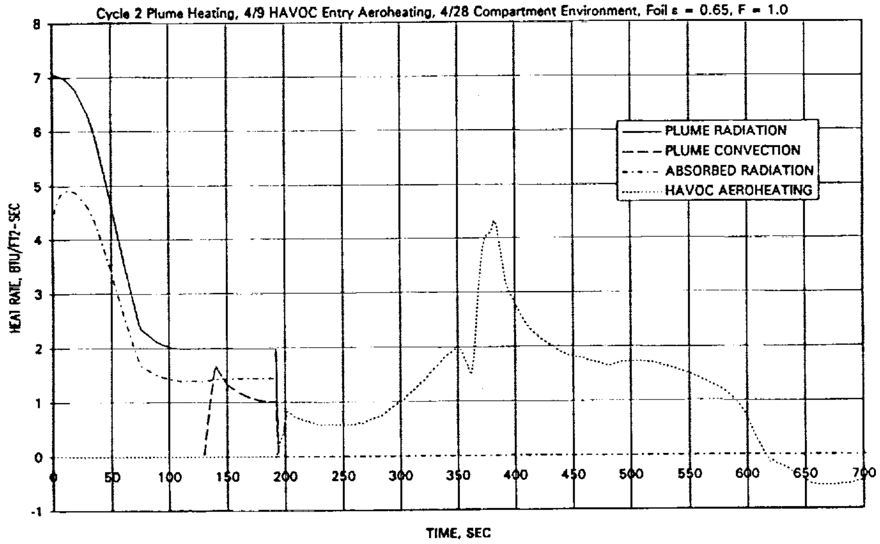

Figure 1. Design Heating Environment for a Typical Point on the Base of the X-33

Thermal Analysis

The X-33 base region TPS designs were modeled and analyzed using the SINDA/G thermal analyzer (Ref. 3). Thermal properties for all materials considered in this study were obtained from the NASA/Ames TPS-X database. The variation in thermal conductivity with temperature was included for all materials. The pressure-dependent thermal conductivity of the Q-felt insulation used with the metallic TPS panels was also included.

The thermal models considered all modes of heat transfer present in the flight case. The calculation of ablating surface recession in depth with conduction was included for the ablative TPS design. Additional details of the analysis procedure will be described in the full paper.

Results

TPS design concepts for the base region of the X-33 vehicle were evaluated for operation in main engine exhaust plume heating environments and entry aerodynamic heating and internal compartment heating. The transient temperature response for the TPS and underlying composite structure was calculated for 10 body points on the fuselage base. A typical solution for the metallic TPS is shown in Figure 2.

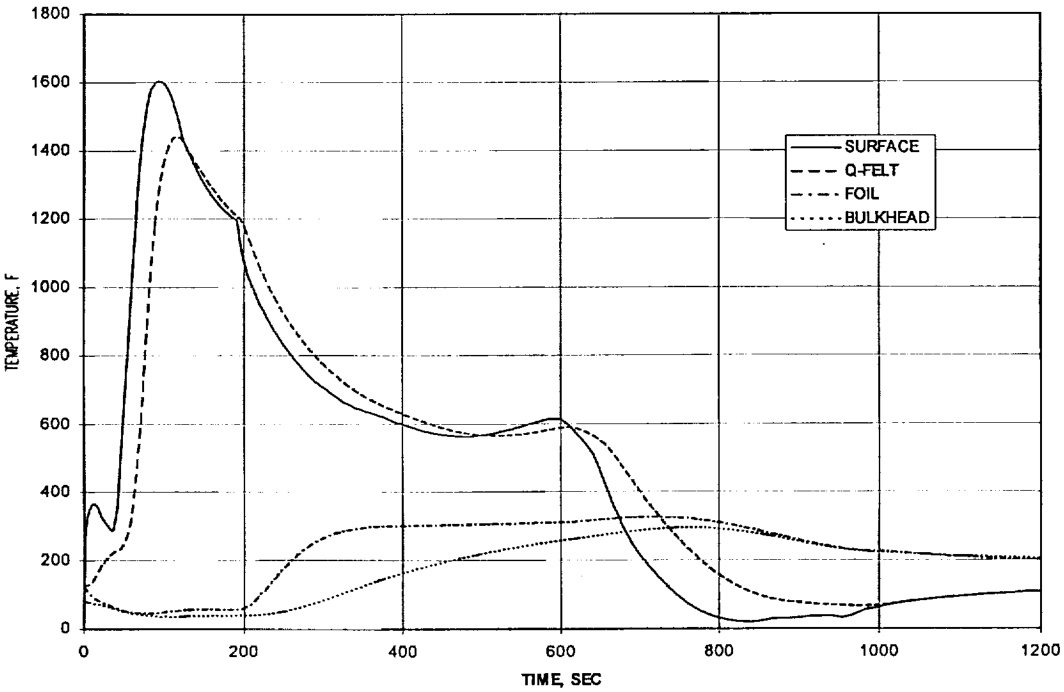

Figure 2. Typical Transient Solution for X-33 Metallic TPS Temperature Response

Inconel 617 honeycomb over 1.25 inch of Q-felt insulation was found to meet requirements for all fuselage base body points. Peak temperatures on the base are approaching the upper limit for Inconel honeycomb and this structure must be evaluated closely as new aerothermal and plume heating environments are generated. A second design concept using ablative materials over the metallic honeycomb skin was also analyzed. Ablator thicknesses were determined and the transient temperature response of this TPS configuration was calculated at the same 10 body points on the base of the vehicle. Overall system weights were calculated and compared for the two design concepts. In addition to the thermal analysis of the baseline design, sensitivity studies were performed to investigate the effect of variations in key parameters of the base TPS.

Additional details, including thermal analysis results for the metallic and ablative TPS designs, weight estimates, etc. will be provided in the full paper.

References

1. X-33 Vehicle Design Specification, Lockheed-Martin Skunk Works Document 603D0007 (Preliminary), July 1996.

2. Seaford, Mark et al, "Revised Informal Release of Lockheed Martin Skunk Works (LMSW) X-33 Malmstrom4 Ascent Post-PDR Cycle 2 Plume Heating," NASA/MSFC memorandum ED32(XX-97), February 28, 1997.

3. SINDA/G User's Guide, ver. 1.6, Network Analysis Associates, 1994.

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Subject: RE: COTR Identification
Date: Mon, 11 May 1998 10:59:43 -0500
Mime-Version: 1.0

Yes I am. Please send them to EA02/Peggy Hueter.
Johnny
544-6712

> ----------
> From: Betty Fowler[SMTP:betty.fowler@msfc.nasa.gov]
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> To: Johnny F Stephenson
> Subject: COTR Identification
> Importance: High
>
> Are you the COTR for Sverdrup under Contract NAS8-40386?
>
> I have received 2 clearance requests from Sverdrup. May I send them to
> you?
>
> Betty Fowler
> Technical Publications
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