AERO-THERMAL DESIGN, ANALYSIS, THERMO-STRUCTURAL TESTING AND QUALIFICATION OF RLV-TD

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Abstract

RLV TD is a lifting re-entry configuration with wing-body mounted on a solid booster. During atmospheric flight of RLV TD, which includes ascent as well as re entry into atmosphere, vehicles encounter severe thermal environment. The vehicle structure should be able to withstand this thermal load. Thermal environments were estimated for RLV TD and hot structures were designed.

To qualify the hot structures, thermo-structural testing has been undertaken. The demonstration of its fly-ability and qualification under the severe environment of thermal and structural loads acting simultaneously is carried out successfully for all hot structures.

Another critical area is the thermal management of electronic packages housed inside RLV fuselage. Thermal management of avionic packages inside RLV fuselage is also critical for the safe functioning of the packages. Detailed thermal analyses to estimate the prelaunch cooling requirements were carried out.

This paper gives the details of aero thermal design of various hot structures, Thermal Protection System (TPS) design of cold structures, thermo structural qualification of structures and thermal management of electronic packages. The comparison of estimated and flight measured temperatures is also provided. Fairly good comparison is seen between estimated and measured temperatures for hot structures and temperature of the windward and leeward region with TPS are well within limits. Safe functioning of packages was also ensured for the cooling design.

***Keywords**: RLV TD, Temperature, Heat Flux, Packages*

Nomenclature

T_f = Temperature of air inside fuselage
T_{si} = Temperature of RLV structure
A_{si} = Internal area of RLV structure
h_{in} = Internal convective heat transfer coefficient
Q_{DISS} = Power dissipation of avionic packages
C_{pf} = Specific heat of fluid
C_{ps} = Specific heat of solid
m = Mass flow rate of coolant
T_{in} = Coolant inlet temperature
Q_{sol} = Incident solar heat flux on RLV structure
α_i = Solar absorptivity of structure
ε_i = Emissivity of structure

h_{out} = External convective heat transfer coefficient

T_{amb} = External ambient temperature

Introduction

RLV-TD is a lifting re-entry configuration with wing-body mounted on a solid booster. During atmospheric flight of RLV TD, which includes ascent as well as re entry into atmosphere, vehicles encounters severe thermal environment. The kinetic energy of air is converted into thermal energy and part of this energy is transferred to the body by viscous diffusion. Thermal environments are quantified and suitable thermal protection is provided for the structures, so that the structures are withstanding the prevailing thermal load.

A design code has been developed for computation of heat transfer rates over a re-entry body and its thermal response along a given trajectory is estimated. This code has been validated for heat flux obtained for similar winged body configurations. Extensive temperature measurements were provided on RLV TD to verify the design. Post flight analysis was carried out and measured temperatures are compared with predicted temperatures. Fairly good comparison is seen between estimated and measured temperature histories and thus validated the thermal design methodology.

RLV-TD consists of electronic packages for Navigation, Guidance and Control systems, Telemetry, Tracking and Command systems and Power systems. In order to ensure their performance till end of flight, temperature levels of these packages have to be maintained with specified limits. Thermal environments for the packages for the prelaunch and flight phases were estimated to compute the package temperatures. Pre-launch cooling design was carried out for high power dissipating packages to limit their temperatures within constraints.

Thermal management of reusuable launch vehicle involves suitable aerothermal design which is further sharpened through analysis and testing. Finally design, analysis and testing are validated through thermal measurements made in flight. This paper presents the entire details of activities related to RLV-TD.

Methodology of Heat Flux Estimation

Based on the trajectory as shown in Fig.1, the altitude and velocity of the re-entry body at any instant of time are known. Free stream properties like temperature, pressure and density are evaluated based on altitude data from standard atmospheric model.

Post-shock conditions are computed by assuming a normal shock ahead of the body and by solving one dimensional conservation equations of mass, momentum and energy across the shock along with state equations.

For obtaining pressure distribution over the module, modified Newtonian method, is used which gives the pressure distribution over the body. Equilibrium air properties are obtained from Hansen Table [1]. Heating rates at the stagnation point of nose cap for ascent and descent phases of the flight are estimated using Fay and Riddell correlation [2]. For any location other than the stagnation point, the heat flux is computed based on Vandriest theory for laminar and turbulent flow [3-4].

The windward central line region was analysed assuming a wedge flow (since the bottom surface is flat) with semi-angle equal to the flow angle of attack. Vandriest method is used for computing the heat transfer rates. Flow in the leeward side is mostly in the separated regime during descent phase, where large angles of attack are encountered. Thermal environment during the descent phase for the leeward region is computed by assuming flow as attached and angle of attack is taken as zero throughout the flight for a conservative design.

Beckwith and Gallagher [5] correlation is used for the wing and vertical tail stagnation point and is treated as an infinite swept cylinder for the flows with an angle of incidence. For control surface like elevon and rudder, normal shock is considered at the wing leading edge (for Elevon) and Vertical tail (for Rudder). Local Mach number is calculated from post shock pressure and local pressure. These conditions are used as upstream for the inner elevon. Newtonian/oblique theory is used to compute the pressure on the elevon/rudder based on deflection angle.

Validation of Methodology

A laboratory measurements program, performed in the Calspan 96-inch Hypersonic Shock Tunnel provides a database for a re-entry sphere cone configuration [6]. The test conditions are: Total temperature of 6000 K, total pressure of 500 atmospheres and M = 9.3. Fig.2 gives the comparison of Calspan Shock Tunnel data with the data computed using the present program. The agreement is fairly good.

Space Shuttle windward centreline heat flux computations were predicted using the above methods and compared with flight data for shuttle [7]. Fig.3 gives the comparison at M=7.19 and at altitude of 45.1 km. Fairly good comparison is seen thus validating the design methodology.

Estimated Heat Flux and Thermal Design

Heat flux is estimated for the flight trajectory. Estimated cold wall heat flux histories, non-dimensionalised with respect to maximum heating at nose cap stagnation point (q_0) at various locations is shown in Fig.4. Thermal response of the structure is evaluated by solving one dimensional conduction equation with suitable boundary conditions. Depending on Peak heat flux and heat load various materials and its thickness were arrived at various regions for withstanding the thermal load. After arriving at optimum material and thickness, three dimensional model of each component is developed and three dimensional thermal response is also carried out using commercial software ANSYS [8]. Spatial as well as transient variation in heat flux is considered for thermal response analysis. Thermal response analysis shows that the configuration can withstand thermal loads. Thermo structural analysis was also carried out and found that the design can withstand structural loads also. Final configuration of RLV TD is shown in Fig.5.

Thermo-Structural Testing

Thermo-structural testing is unique of its kind with capability for simultaneous application of flight heat flux and the structural loads to undertake thermo-structural qualification of proto scale hot structures. It can accurately simulate the spatial distribution as well as the transient nature of both aero-heat flux and structural loading profiles on test articles of varying shapes. This involved major technology developments are development of high temperature strain gauge bonding, measurement of thermal output and strain correction and validation, closed loop control structural loading systems for transient variation and adjustment of structural loads under thermal deformation of structure, and for heat distribution, shaping of reflector, spacing of heater filaments and dynamic movement of entire reflector during the heating phase for achieving the spatial and transient variations. Novel arrangements for deflection measurements under severe heat loads using extension elements were made from structure and adjusting for deformations and providing thermal protection was undertaken. For RLV hot structures, the demonstration of its fly-ability and qualify under the severe environment of thermal and structural loads acting simultaneously was undertaken for all hot structures.

Typical thermo structural testing of wing leading edge is shown in Fig.6. Measured temperature during test is compared with computed temperature. Fairly good comparison is seen and is shown in Fig.7.

Thermo structural testing of hot structures confirmed the integrity under thermal and structural loads experienced in flight.

Post Flight Analysis and Discussions

Various temperature measurements were provided on RLV TD to verify the design. Post flight analysis was carried out and measured temperatures are compared with estimated temperatures. Typical comparison of temperature at Nosecap, Wing Leading Edge, Elevon and Vertical tail is shown in Fig.8. Fairly good comparison is seen between estimated and measured temperature profiles. This shows that thermal behavior was as per prediction and was adequate. Temperature contours of Nosecap, Elevon and Wing Leading Edge are shown from Fig.9 to Fig.11.

Windward region of RLV TD is protected by 22 mm silica tile. Temperature measurements were carried out at different depth of silica tile. Heat flux is estimated by inverse heat conduction from in depth temperature measurements on Silica tile [9-10]. Heat flux estimated for a maximum heating condition during ascent and descent phase is shown in Fig.12.

Peak heat flux on Windward region is ~4 W/cm^2. Thermal response analysis of silica tile carried out with the estimated heat flux and indepth temperature is computed.

Figure 13 shows the comparison of computed and measured in depth temperature measurements on the Silica tile. Heat flux estimated from inverse heat conduction validated the design methodology and silica tile thermal performances were in line with prediction.

Design of TPS for leeward region is carried out by conducting heating tests. Flexible insulation is used as TPS to maintain the temperature of Al. alloy structure less than the constraint of 120°C. Comparison of measured and computed heat flux histories are shown in Fig.14. Ascent

Phase heat flux compares well with prediction. The TPS design was based on attached flow for conservative estimate. However descent phase of flight, since flow is detached measured heat flux is lower compared to computation as expected. Maximum measured back wall is 37°C which is well within the constraint, showing that TPS provided was adequate in the leeward region.

Thermal Management of Avionic Packages in RLV-TD

The Avionics Module of RLV-TD consists of electronic packages for Navigation, Guidance and Control systems, Telemetry, Tracking and Command systems and Power systems. In order to ensure their performance till end of flight, temperature levels of these packages have to be maintained with specified limits. Packages housed inside fuselage are subjected to heat loads due to power dissipation from packages, convection heating from its ambient, and radiation heating from elements including the structure. Avionic packages are mounted on honeycomb decks and are configured as in Fig.15.

Thermal Environments

During pre-launch operations, coolant air at predetermined mass flow rate and temperature is supplied into the fuselage to control the ambient temperatures. A major portion of the heat dissipated by the packages is convected away by the coolant thus keeping their temperatures within their constraints till the end of flight. Solar radiation incident on the external surface is also considered. Flight phase consists of ascent and descent phases. External surfaces are exposed to the aerodynamic heating and re-entry heating during ascent and descent phases respectively.

Theoretical Modelling

Air temperature inside RLV is computed from the following energy balance equation:

$$\rho_f \, \forall_f \, Cp_f \, \frac{d\,T_f}{dt} = \sum_{i=1}^{N} h_{in\,j} \, A_{s\,j} \, (T_{si} - T_f) + Q_{DISS} + \dot{m} \, Cp_f \, (T_{in} - T_f) \qquad (1)$$

RLV structure temperature for different regions is computed from the following energy balance equation:

$$\rho_s \, \forall_s \, Cp_s \, \frac{d\,T_{si}}{dt} = \alpha_i \, A_s \, Q_{sol\,j} + \varepsilon_i \, \sigma \, A_s \, (T_{amb}^4 - T_{si}^4) + h_{out\,j} \, A_s \, (T_{amb} - T_{si}) + h_{in\,j} \, A_s \, (T_f - T_{si}) \qquad (2)$$

Internal heat transfer coefficient is computed using standard correlation for free convection and heat transfer coefficient to external ambient is computed using standard correlation for cross flow over cylinders to consider the effect of wind. Comparison of computed and measured ambient temperatures inside the avionics compartment is shown in Fig.16. Computed temperatures are in agreement with measured data.

Finite element model of the package was developed using commercial software NX9.0 [11]. Avionic packages have been modelled as cuboids and their location, mass, power dissipation and surface finish have been accounted. Convective heat exchange with the ambient during pre-launch phase and radiation exchange with the structure during flight phase is simulated. Computed temperature contour of avionic packages is shown in Fig.17. Comparison between measured and computed temperatures of a typical package is shown in Fig.18.

Summary

- Aerodynamic heating rates for a re-entry mission are computed using an in-house design code. The design code employs engineering methods to compute heat fluxes on different structure components, both in ascent and descent phases. The code has been well validated with shock tunnel data.
- The thermal design adopted for both hot and cold structures was adequate for the successful mission of RLV TD.
- Thermo-structural testing and qualification under the severe environment of thermal and structural loads acting simultaneously is carried for all hot structures and confirmed the structural integrity.
- Temperature measurements indicated that design of hot structures was adequate.
- Temperature measurements on the silica tile in the windward region validated the design methodology and proved its adequacy.
- Silica tile and flexible insulation also analyzed and found that all temperatures are within the constraint.
- Thermal management of avionic packages inside RLV-TD was carried out considering the thermal environ-

ments experienced in flight. Pre-launch cooling design ensured the safe functioning of all packages till end of flight.

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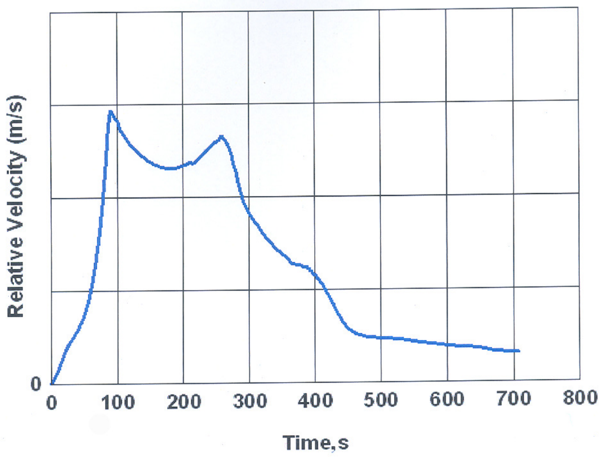

Fig.1 RLV TD Flight Trajectory

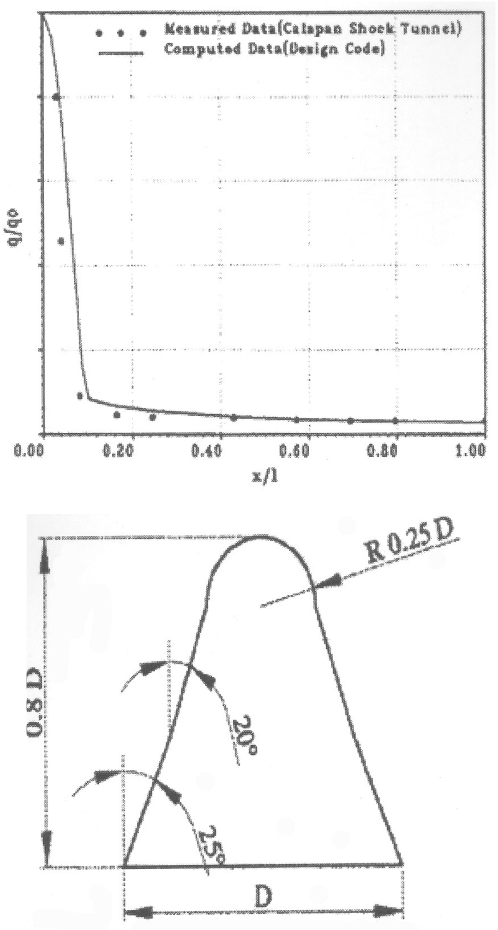

Fig.2 Comparison of Heat Flux on Spherically Blunt Cone of a Typical Re-entry Module

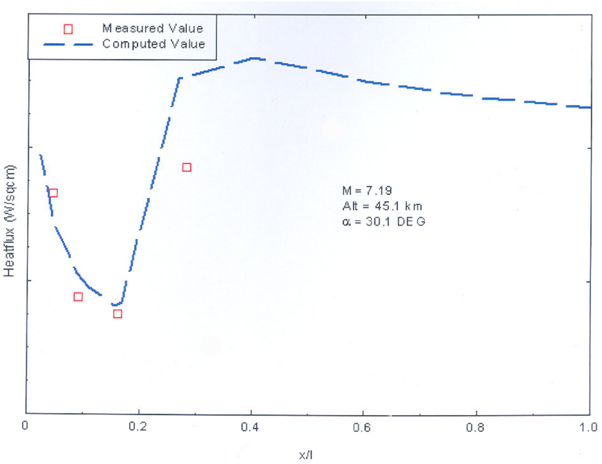

Fig.3 Comparison of Heat Flux on Windward Centerline of Shuttle

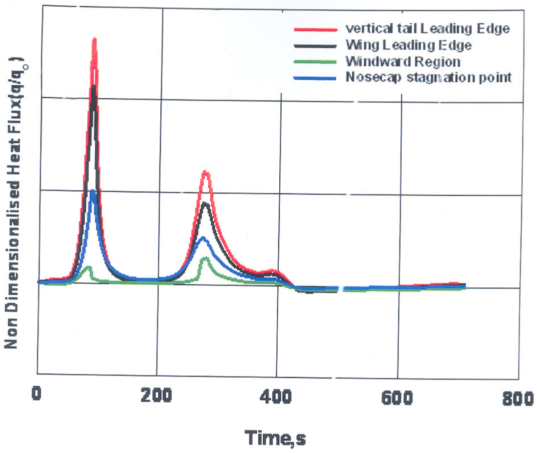

Fig.4 Cold Wall Heat Flux Estimated at Various Location of RLV TD

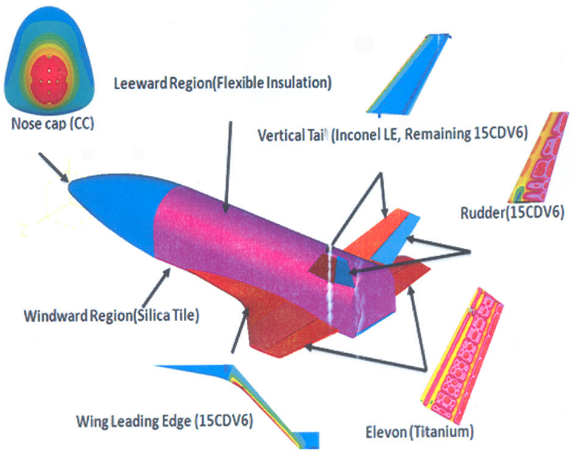

Fig.5 Various Structures of RLV TD

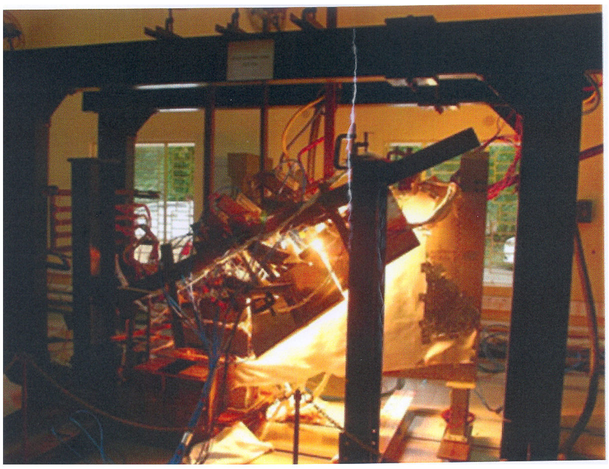

Fig.6 Wing Leading Edge Thermo-Structural Test

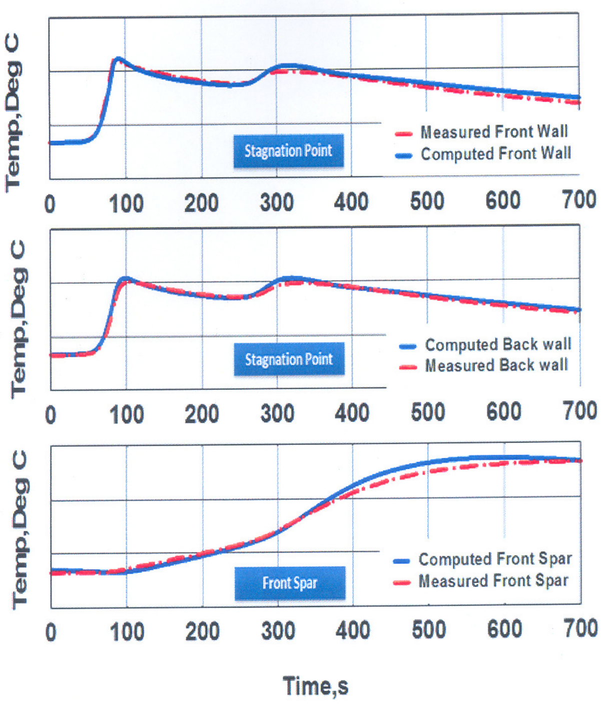

Fig.7 Comparison of Measured Temperatures and Computed Temperature During Thermo Structural Testing

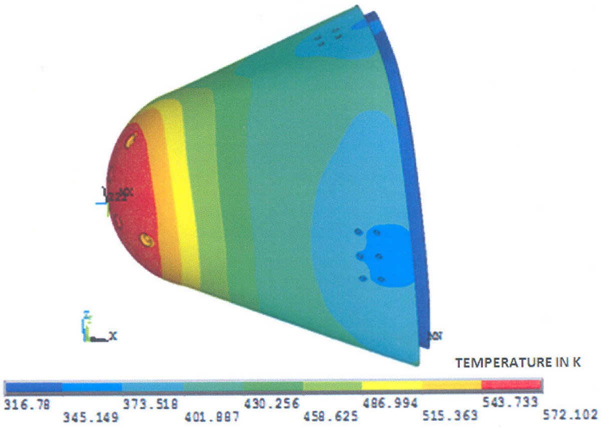

Fig.9 Temperature Contour of Nose Cap

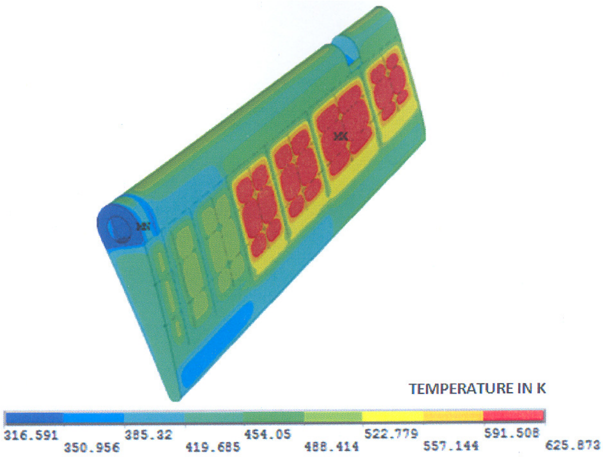

Fig.10 Temperature Contour of Elevon

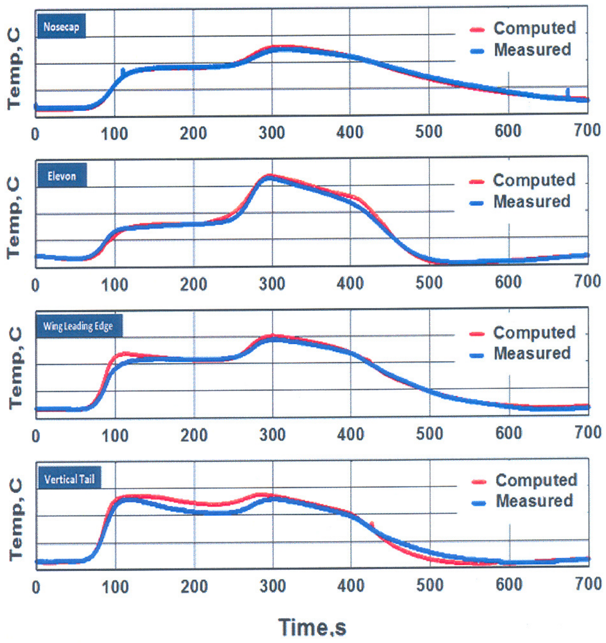

Fig.8 Comparison of Computed and Measured Temperature Histories

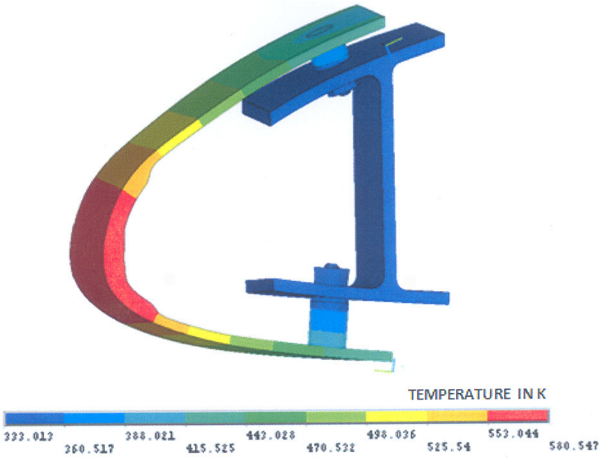

Fig.11 Temperature Contour of Wing Leading Edge

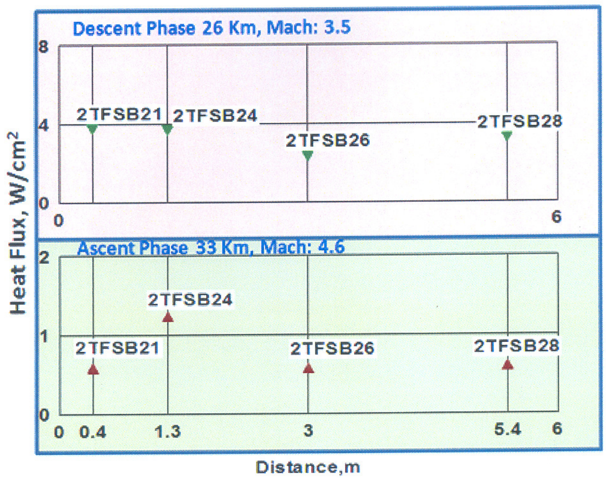

Fig.12 Heat Flux Estimated for a Maximum Heating Condition During Ascent and Descent Phase

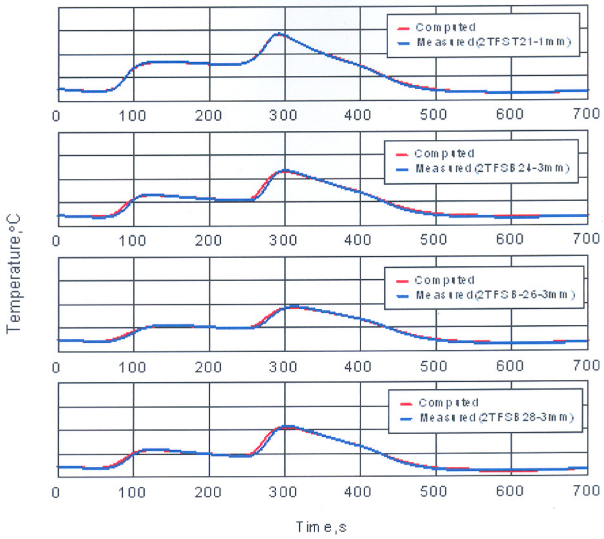

Fig.13 Comparison of Computed and Measured Temperature Histories on Silica Tile

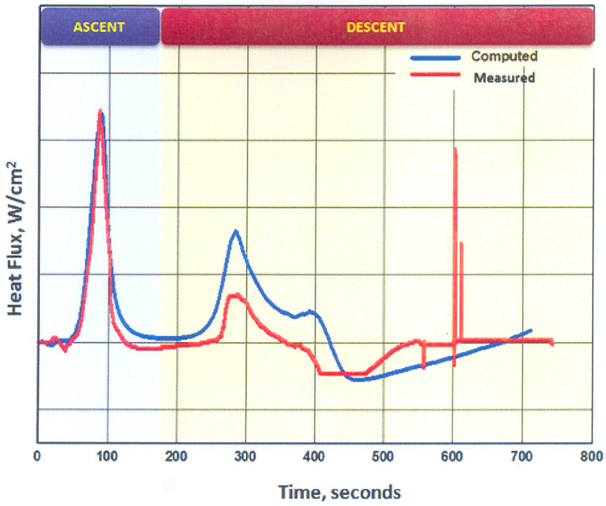

Fig.14 Comparison of Measured and Computed Heat Flux Histories in the Leeward Region

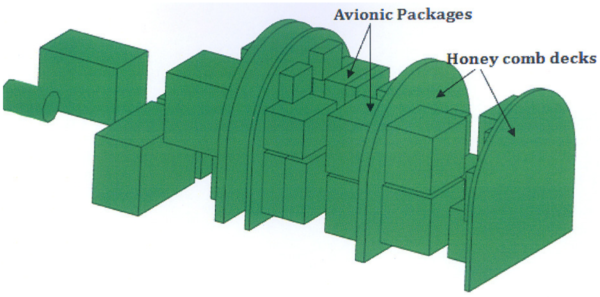

Fig.15 Avionic Package Configuration in RLV

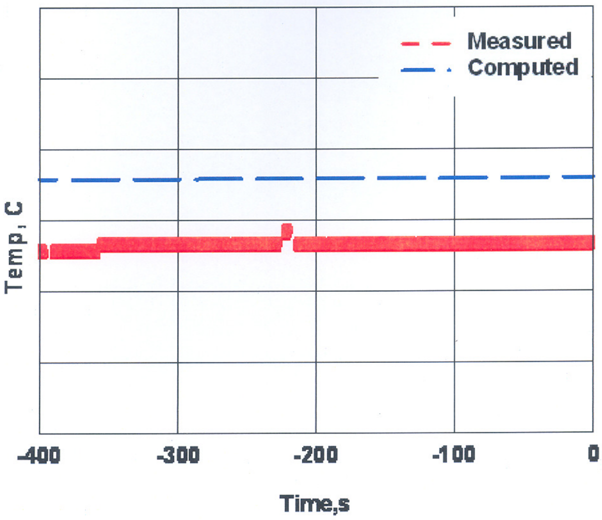

Fig.16 Comparison of Computed and Measured Ambient Temperatures Inside Avionics Compartment in RLV TD

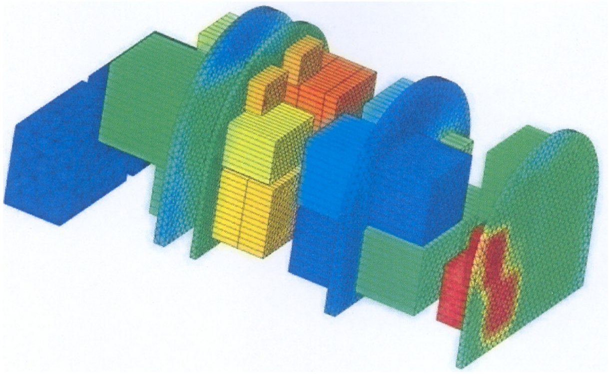

Fig.17 Computed Temperature Contour of Avionic Packages

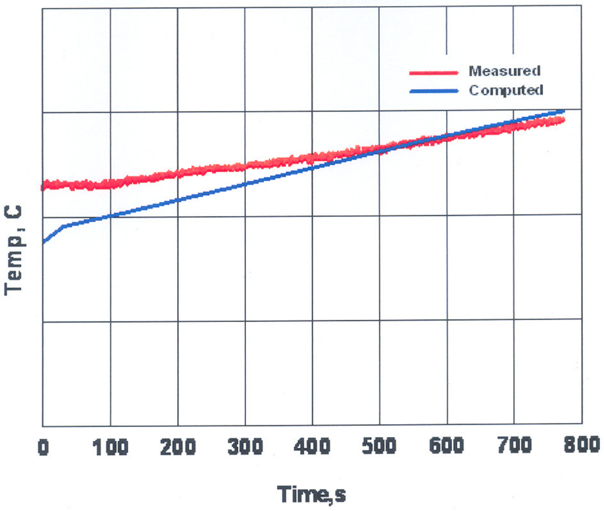

Fig.18 Comparison of Computed and Measured Package Temperature Inside Avionics Compartment in RLV TD