DESIGN, DEVELOPMENT AND QUALIFICATION OF CARBON-CARBON NOSE CAP FOR REUSABLE LAUNCH VEHICLE APPLICATION

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Abstract

Reusable Launch Vehicles are the ultimate solution to reduction in cost of access to space. To demonstrate the technological capabilities of Indian Space Program in the realm of such reusable launch vehicles, one of the prime focuses was design and development of Carbon-Carbon(C-C) composite for thermal protection system of the vehicle. This paper outlines the detailed design, development cycle and qualification of C-C Nose Cap for the RLV-TD mission of ISRO. Critical technological challenges overcome for the purpose include: the development of carbon-carbon material and processing the final hardware, the 3D FE thermo-structural design and analysis, and the developmental and qualification tests.

***Keywords**: Carbon-Carbon Composite, Nose Cap, Reusable Launch Vehicle, Thermo-structural Analysis, FE Analysis*

Introduction

Reusable Launch Vehicle (RLV) is a winged body re-entry spacecraft envisaged by ISRO (Fig.1). The RLV Technology Demonstration (TD) flight was a prototype to assess the technological challenges in a winged body space flight. RLV-TD spacecraft performed re-entry without going into a full orbit. The mission included hypersonic flight, a virtual landing over sea and the vehicle ultimately impacted in Bay of Bengal.

An aerodynamically contoured nosecap is required at the frontend of RLV to reduce drag and enable smooth flow over the fuselage. The RLV-TD flight regime required a nosecap, which would withstand the high aerodynamic thermal and pressure loads simultaneously. For mitigating heat flux generated during a mission, conventional materials with Thermal Protection System (TPS) like thermal paints, ceramic tiles with strain-isolation pads are generally used. During re-entry into earths atmosphere, the heat flux at the stagnation point can reach up to the maximum level of around 325W/cm^2, with dynamic pressures of the order of 88 kPa. When the temperatures are of such higher order the TPS requirements are very high; and for meeting such requirements of the mission, ceramic matrix composites like carbon-carbon, C-SiC or C-C-SiC are the best candidate materials from the spectrum of materials available. These materials are thermo-structurally stable even at higher temperature. Thus, Carbon-Carbon material is selected for the design and development of the Nosecap for RLV-TD.

Development of carbon-carbon and SiC coating was carried out in tandem with the design and analyses of the nosecap. Another challenge of using high temperature material is designing the interface for thermo-structural compatibility for the complete flight regime with varying range of thermal loads. The developmental tests conducted provided feedback to the design and also confirmed the performance of the hardware as predicted by the FE Analyses. This paper outlines the design and development of the first ever carbon-carbon nosecap for a winged body reusable-launch vehicle of India.

Description

The aerodynamic profile of the nosecap is configured with a spherical section of 120° cone, which extends tangentially into a conical triangular section - filleted at the three sides. This shape is called as ogive shaped geometry which has axi-symmetric blunt cone with semi-cone angle of 14° and 125 mm spherical radius. It will experience maximum heat flux of ≈40 W/cm^2, maximum dynamic pressure of ≈60 kPa and maximum angle of attack of 3°. The overall envelope of C-C Nose Cap is 450 mm x 420 mm height (Fig.2). The interface plane of the nosecap with the fuselage is a slant section, given that the angle of attack during re-entry phase remains positive (where the role of nosecap gets emphasized). The nosecap interfaces with the fuselage through a set of brackets made of Molybdenum mounted directly onto the Fore-End Ring of aluminum.

Being an experimental flight, the nosecap has also been furnished with nine numbers of Flush Air Data System (FADS) Adaptors in the spherical region, for monitoring the pressure data and determining flight parameters. A thermal barrier plate of aluminum, for shielding thermal radiation, is provided at the ring interface plane with a slot meant for FADS Tubes.

Material selection for re-entry application is governed by thermo-structural performance of not just the nosecap material, but also the combination of interface materials. Material options for nosecap include carbon-carbon composite, ceramic matrix composite and high temperature alloys. Any ablative material cannot be used due to its susceptibility to erosion, which will lead to an improper nosecap contour creating aerodynamic problems. High temperature alloys pose the issue of mass penalty.

From the gamut of prospective material candidates, carbon-carbon composite stands as the best option because of its light weight and near-zero in-plane Coefficient of Thermal Expansion (CTE). Also carbon-carbon can retain its mechanical properties at higher temperatures than any other conventional material, which made it suitable material for nosecap application. Carbon-SiC or CC-SiC could have been other favorable options, but the material development timeline extended beyond the mission timeline. Hence, carbon-carbon was selected as the nosecap material.

Carbon-carbon nosecap is interfaced with the fuselage through four L-shaped brackets made of Molybdenum, which are fastened directly to the aluminum ring on one side and nosecap on the other side. For thermo-structural integrity/performance of the interface, it is essential that the coefficients of thermal expansion in the operating temperature range are of similar order as that of carbon-carbon. Hence, the choice of material for brackets and fasteners and similarly for FADS adaptors was a primary concern for design and analyses.

Design of C-C Nose Cap

Design and Analysis

The structure is designed for maximum dynamic pressure, maximum thermal and thermal gradient conditions at the interfaces. Design of nosecap is primarily governed by the maximum thermal and maximum pressure conditions during flight, which occur at two different instances during the flight. The presence of metallic Flush Air Data System (FADS) adaptors mounted at the tip of nosecap makes it further challenging as it is the stagnation region that experiences maximum temperature and pressure.

The CTE difference between C-C and metal had to be accounted for during the design, so as not to cause severe thermal stresses. Nosecap is interfaced with the fuselage, through an aluminum ring, using four metallic brackets fastened to nose cap. Here again the CTE mismatch could cause severe in-plane stress, as well as loosening/tightening of fasteners. Since C-C is a conductive material, the effect of high temperatures on components interfaced with nose cap also required to be studied [1].

Through buckling calculations [2] and fabrication feasibility perspective, a uniform thickness of 14mm was decided for the nosecap. Super-invar and molybdenum were selected as options for interfaces. For management of any thermal performance mismatch, graphite spacer pad between CC-Nosecap and bracket flange was also studied as an option. Ultimately molybdenum was selected as the material for the interface brackets and fasteners, as it met both the thermal and structural requirements of the mission.

A 3D Finite Element (FE) model was generated to study the temperature and stress variation through the C-C nosecap. All geometries, including FADS and interface fasteners, were modeled using 8 and 6 node solid elements (Fig.3). Nosecap was modeled in several layers to study the through thickness variation of temperature and induced stresses. At cap-bracket and bracket-ring interface, the fasteners were again simulated with solid elements, with suitable contact at interfaces (Fig.4). Exact preload was simulated in all the fasteners using special nodal ties, which are available in the FE Software package - MSC Marc. With this, the increase or decrease of preload could be easily studied. Only the tested mechanical and thermal properties (Table-1), including the variation with tempera-

Table-1 : Typical Generic Properties of C-C Nosecap

Sl.No.	Property	Value
1	Density	1.6 h/cc
2	Tensile Strength (Fiber Direction)	110 MPa
3	Compressive Strength (Fiber Direction)	150 MPa
4	Tensile Modulus (Fiber Direction)	60 GPa
5	Compressive Modulus (Fiber Direction)	50 GPa
6	Inter-laminar Shear Strength	15 MPa
7	In-Plane Shear Modulus	60 MPa
8	In-Plane Shear Modulus	9 GPa
9	CTE (RT to 800°C) : (a) Fiber Direction (b) Thickness Direction	 0.5μm/m/°C 7μm/m/°C
10	Thermal Conductivity : (a) Fiber Direction (b) Thickness Direction	 25 W/mK 8 W/mK
11	Specific Heat	700 J/kgK

ture, were used for the analysis. Suitable contact was simulated at all interfaces. Except at bolt-nut interface, all other interfaces were analyzed with a realistic 'touch' contact. Contact analysis gave a proper estimation of stresses caused by CTE mismatch.

As the flight experiences both thermal and mechanical loads simultaneously, a thermo-structural analysis was conducted for proper estimation of stresses and fastener loosening. The 3D FE Model of nosecap was analyzed for 8 flight cases with different pressure and temperature conditions. The same FE model was first used for a thermal simulation to extract temperatures at all the nodes at various time instants of flight. These nodal temperatures were then used for a combined thermo-structural analysis. Aero and thermal analyses had estimated maximum pressure of 128 kPa, which occurs at 61s time instant of flight and maximum temperature of 721K occurs at 299s time instant (Fig.5, 6 and 7).

It was found that using molybdenum (Mo) as the material for brackets causes an increase in preload of fasteners with temperature rise, as CTE for Mo is more than the through thickness CTE of C-C. Stresses at all locations were benign, except at the metal-C-C interface, where the expanding metal pressed against C-C and caused severe stresses. Stresses at metallic components attached to nosecap were also found within limit. Minimum local margin in the CC-Bracket interface holes was 0.4 and that for the metal counterpart was 0.5 for molybdenum and 0.7 for aluminum fasteners; while the available global margins were sufficiently high. Free vibration frequency for first mode of Nosecap was 216.1 Hz. Buckling load factor for Nosecap was 13.3.

Development of C-C Nose Cap

Material Development

Unlike other composites, the material development for C-C composites was unique and involved lot of challenges. To develop C-C composites for a particular application, the main requirements are raw material (carbon fabric/carbon fiber) and the facilities available within the country. Selection of suitable raw material poses a greater challenge, since the options available for the carbon fabric and carbon fibre were very limited for C-C composites unlike other composites. A spun-yarn graphitized carbon fabric was finally selected, as its processing temperature is greater than 2000°C under vacuum.

The minimum density required for the C-C Nosecap was 1.6g/cc to suit the mission requirements. To obtain the required density level, the carbon-matrix has to be derived either from Chemical Vapor Infiltration (CVI) process or from a Resin/Pitch precursor. It is well understood that no single process would yield the end attributes for RLV-TD mission. Hence, ISRO worked on a strategic route of judiciously combining various processes to meet the end attributes for the mission, with the available resources in the country. An optimum process route was charted to develop C-C Nosecap, where carbon matrix was derived from resin as well as pitch, as depicted in Fig.8.

Various experiments were conducted before finalization of the process route, like finding the optimum impregnation parameters for the carbon fabric, optimum resin percentage for the high strength fiber for cross-stitching, mould concepts for initial lay-up and minimization of post-curing defects, methodology of lay-up to reduce the process abnormalities during curing, determining the post curing temperature, optimization of the resin carbonization cycle, design and development of toolings for the pitch impregnation process followed by optimum pitch carbonization cycle, optimum temperature for high temperature heat treatment, design of tooling for machining, etc.

In order to establish the physical, mechanical and thermal properties of the new material, which were required for the initiation of thermo-structural design, extensive characterization tests were carried out on C-C specimens. Generic laminates were developed using the generalized process route both for establishing the repeatability of the process and for characterization. All the properties were evaluated at room temperature as well as at elevated temperature. The typical values are listed in the Table-1.

Product Development of C-C Nosecap

As mentioned in the previous section, a female metallic mould was selected, designed and fabricated, to reduce the process abnormalities in the curing process of C-C Nosecap (Fig.9a). Segmented petals of prepreg were laid up in the mould to form a layer. Layers of (0/45)n were laid up over each other in a circumferentially staggered manner to meet the designed thickness of 14mm. The petals of prepreg were stitched using high strength carbon fiber by specially designed needles.

The wet preform was cured at 25 bar and 160°C followed by long post curing at 180°C and slow carbonization process under inert atmosphere from RT to 900°C with special graphite fixtures. This porous C-C was subjected to repeated pitch impregnations (230°C and 10bar) and carbonizations under inert atmosphere from RT to 900°C, followed by an intermediate and the final heat treatment cycle (1700°C under vacuum).

Final machining was carried out using specially designed fixtures for shape and thickness corrections (Fig.9b). Since C-C is prone to oxidation at high temperature, anti-oxidant coating (SiC) was provided on the outer surface of nosecap through pre-ceramic slurry route (Fig.9c).

Qualification of C-C Nose Cap

CC Nosecap being a new development of its kind with no heritage at ISRO, extensive tests were carried out to prove its capability and robustness. For RLV-TD mission, the following tests were carried out.

- Testing of SiC coated C-C Laminate under flight thermal loads.
- Testing of Interfaces: C-C Nosecap to Molybdenum Brackets under thermal and shear loads.
- Testing of C-C Nose Cap under pressure load and thermal load.

Testing of SiC Coated C-C Laminate Under Thermal Environment

The objective of this test was to evaluate the thermal response of SiC coated C-C laminates under the flight thermal load for 1036s duration as shown in Fig.10. The processing adapted for the specimens was identical to the one implemented for the final product.

After the test, SiC coating on C-C laminate was intact and negligible mass loss was observed. The maximum front wall and back wall temperature of 686K at 322s and 672K at 360s respectively were observed. From this test, the capability of SiC coating and C-C nosecap, and their mutual compatibility were evaluated.

C-C Nosecap and Molybdenum Bracket Interface Test

This test was carried out in Plasma Wind Tunnel facility to evaluate the C-C Nosecap interface along with Molybdenum Bracket and Aluminum FE Ring, under heat flux and shear loading condition, using a double wedge shear flow model (Fig.11). The main objectives of this test were:

- To evaluate the thermal response of C-C Nosecap and Molybdenum interface, wherein materials having different co-efficient of thermal expansion are joined together.
- To evaluate the integrity of the interface (between C-C, silica tile and molybdenum bracket) subjected to heating and shear flow conditions.
- To measure the interface temperature between these joints.
- To evaluate the health of the C-C specimen after thermal test.

In this test, 9W/cm^2 heat flux along with shear stress of 58Pa was simulated for 22s. Post test NDT of the specimen showed that the interface remained integral and no defects developed in the specimen.

Testing C-C Nose Cap Under Structural Load and Thermal Load

For qualifying the hardware and proving it to be flight worthy, the realized nosecap was subjected to the maximum pressure and thermal loads, which were to be encountered during flight. As two maxima occur at two different time instants during the flight, the hardware was subjected to pressure and thermal loads separately (Fig.12); especially as the pressure at the maximum temperature instant was benign. Test data was in close accordance with the simulated predictions, qualifying the carbon-carbon nosecap for the flight. All the interfaces were intact and the hardware had developed no defect after the tests.

Data obtained from flight has been used to obtain the temperature distribution over the hardware and re-simulated to find the strains witnessed. During flight the maximum temperature of 572 K was witnessed by the nosecap at 281s into flight. Strains were of the order of 100 micro-strains, with the maximum value of 200 micro-strains.

Conclusions

Carbon-carbon nosecap is successfully designed, developed and tested for the Technology Demonstration flight of Reusable Launch Vehicle (Fig.13). The design is validated through thermo-structural qualification tests both at specimen and full-scale hardware level, correlating the measured strains and displacements with predictions. The post-flight analysis, based on the temperature and strain flight data obtained at four locations inside nosecap, show a close correlation; thus validating the model used for design and analysis. The technology demonstration of advance composite for future re-entry missions has been successfully accomplished.

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2. "Buckling of Thin Walled Doubly Curved Shells", NASA-SP 8032.

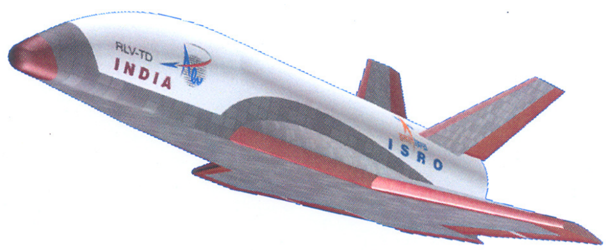


Fig.1 Reusable Launch Vehicle - Technology Demonstrator

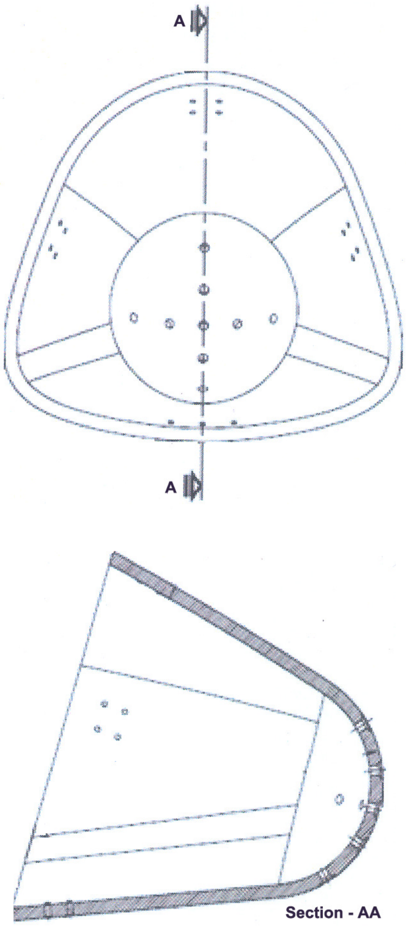


Fig.2 Nosecap Configuration

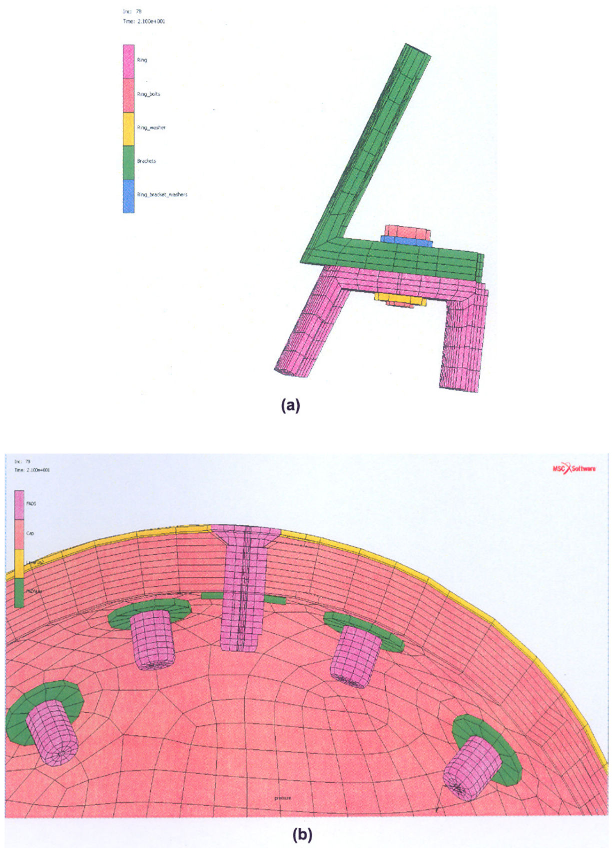


Fig.4(a) Section of FNB Ring and Clamp Joint
(b) Section View of FADS at the Nosecap Tip

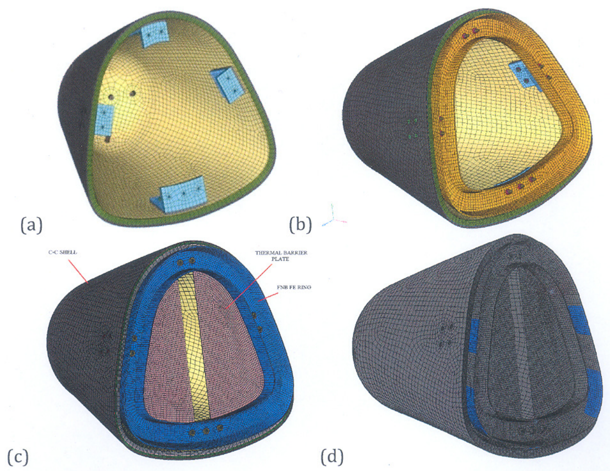


Fig.3(a,b,c) Finite Element Model of Nosecap (d) Fixity Locations for Nosecap Assembly at FNB Ring (in Blue)

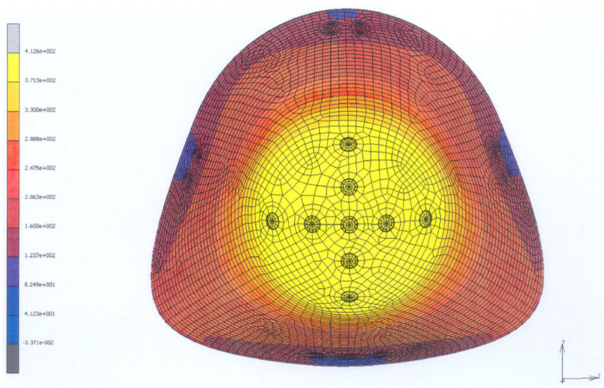


Fig.5 Temperature Profile for Max. Temperature Load Case (299s) Max. Temperature = 442°C (Figure shown ΔT only)

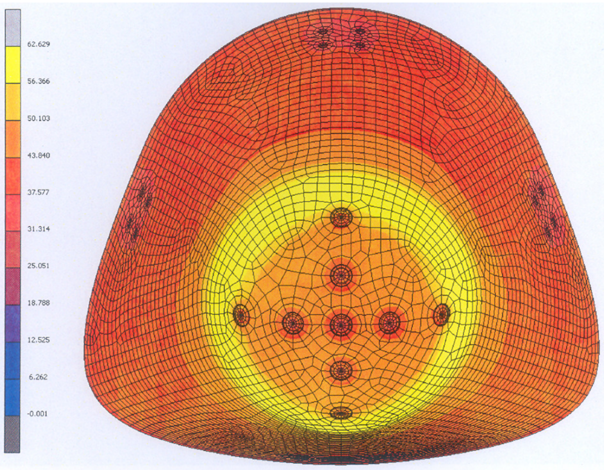


Fig.6 Temperature Profile for Max. Pressure Load Case (61s)

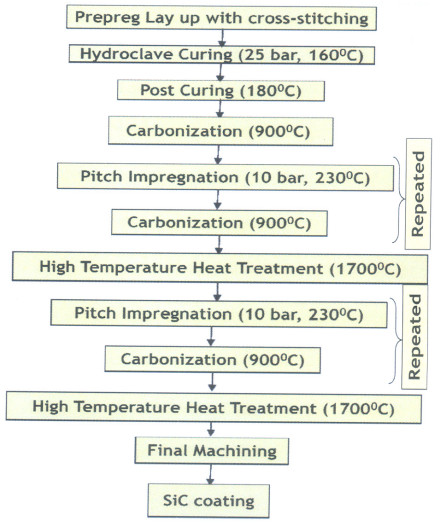


Fig.8 Generalized Process Route for C-C Nosecap

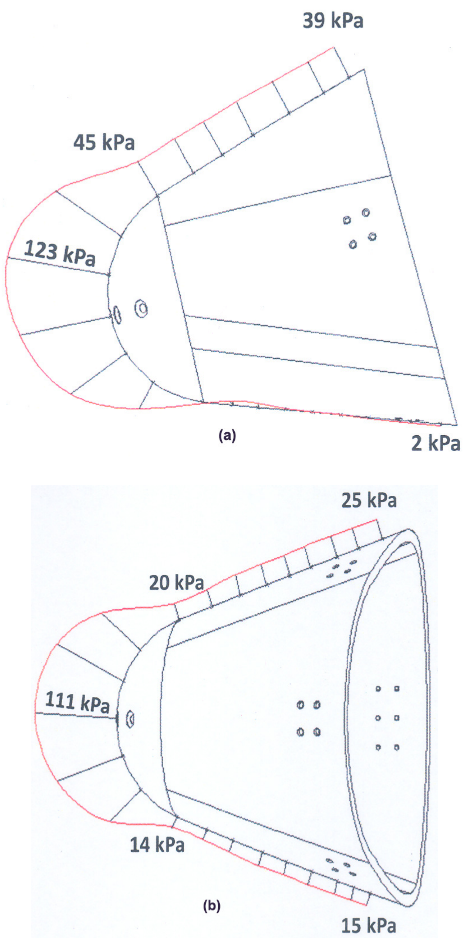


Fig.7 Pressure Profile on Nosecap for Max. Dynamic Pressure Loadcase (a) Side View (b) Top View

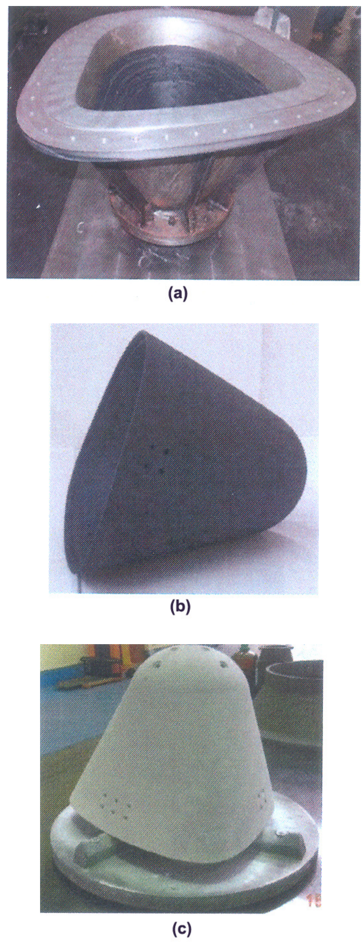
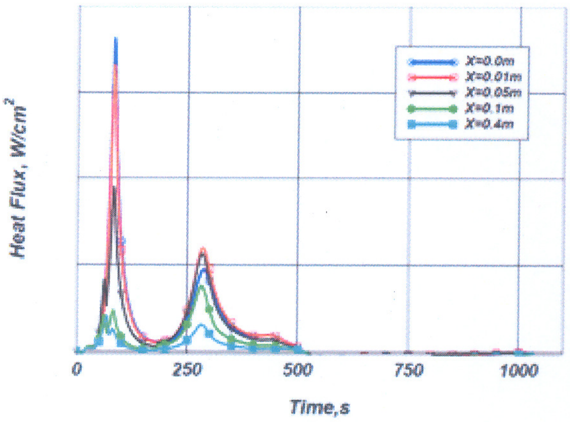


Fig.9(a) Female Mould (b) CC Nosecap (After final machining) (c) CC Nosecap (After SiC Coating)



Fif.10 Predicted Heat Flux History of RLV C-C Nosecap

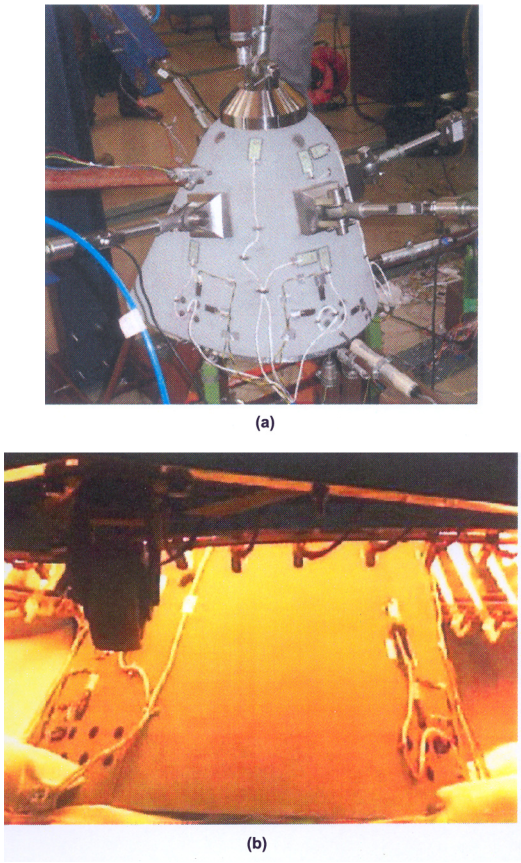


Fig.12(a) C-C Nosecap with SiC Coating Under Pressure Qualification Test (b) C-C Nosecap with SiC Coating Under Thermal Qualification Test

Fig.11 Test Article in the Test Chamber During Test and After Test

Fig.13 Carbon Nosecap with SiC Coating Ready for Assembly to RLV-TD Fuselage