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Engineering Note

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Evaluation of High-Temperature Multilayer Insulation for Inflatable Ballute

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Introduction

INCREASED emphasis has been placed on the reduction in spacecraft (S/C) subsystem mass and stowed volume, because of the high cost for access to space. An innovative technology that offers these benefits is inflatable structures, and a novel application in S/C is for aeroassist. Increased use of this landing approach (e.g., for Mars) is planned by NASA and its contractors with up to 65% of the missions for the 1995–2005 time frame showing aeroassist as a primary mission element.[1] Significant payoffs of an aeroassist landing approach include reduced weight and mission cost through the reduction or elimination of the propellant required for a traditional retrorocket landing.

An early concept, the attached inflatable decelerator (AID), was originally analyzed and experimentally studied 30 years ago by Mikulas and Bohon[2] and Anderson et al.[3] The original concept was developed to increase drag during entry into a low-density planetary atmosphere (e.g., Mars) and thereby eliminate the need for heavy towed supersonic decelerators (i.e., parachutes). In these studies, several different AID configurations were considered, with variations in the designs to accommodate different heat shield shapes. To reduce the inflatable volume (and thereby subsystem mass), the recommended method was to fold back some of the canopy and reattach it to the payload at the rear of the S/C. This "tuck-back" configuration also results in a blunter nose configuration and a higher drag coefficient.

A previous publication by the authors described analytical modeling and fabrication of a prototype inflatable ballute for packaging and inflation demonstration.[4] The objective of the work presented here is to design and fabricate a test article with a prototype multilayer insulation (MLI) and conduct thermal testing to enable comparison with analytical modeling.

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Results and Discussion

Thermal Analyses

Table 1 lists the thickness, areal density, mass, and predicted temperatures for each segment of a flexible, high-temperature (HT) MLI designed for use on an inflatable ballute surface. The design consists of ceramic fabric (aluminoborosilicate, Nextel™), carbon cloth, metal foils, metallized polyimide, and bare Kapton™ (inflatable bladder). Also listed in Table 1 are peak temperatures, predicted by SINDA, for different HT-MLI configurations on the bladder surface. The complexity and number of layers were reduced with distance away from the highest heating rate zone, from a 25-layer design [4.29-mm (0.169-in.) total thickness] to a four-layer design [1.76-mm (0.069-in.) total thickness] for the maximum diameter position on the ballute. These tailored HT-MLI designs were effective in keeping the induced temperature on the inflatable bladder below the recommended maximum of 205°C. A peak temperature of 1150°C was predicted for the ballute surface at the location of the rigid aeroshell/ballute interface.

Mass estimates for each segment of the tailored HT-MLI, also listed in Table 2, suggest the HT-MLI system weighs only about 30.2 kg, which is about 43% lighter than an equivalent area and thickness for a traditional heat shield impregnated with a silicone-loaded ablator (SLA-561V). An analytical trade indicated that if the allowed bladder temperature could be increased to 350°C (from 204°C) then the HT-MLI segment areal density could be reduced by about 30%.

Table 1 Calculated masses and predicted temperatures for each segment of ballute

Zone[a]	No. of plies	Total thickness, mm (in.)	Areal density, g/cm^2	Area, cm^2	Mass, kg	Calc. peak temperature on bladder, °C
Joint[b]	25[b]	4.29 (0.169)	0.364	27,063	9.9	182
Midcone	25	1.38 (0.054)	0.227	27,063	6.1	200
Max. diameter	7	1.86 (0.073)	0.131	27,063	3.6	204
Aft. of max. diameter	4	1.75 (0.069)	0.130	81,189	10.6	194
Total			——	——	**30.2**	——

[a]Zone location from position listed to position listed in next zone.
[b]Layup: 1) two layers of Nextel 312 (each 0.31 mm thick) separated by Ti mesh (0.10 mm thick), with embedded TC (#1); 2) one layer of C-cloth (0.86 mm thick) with Ti mesh (0.10 mm thick) separator; 3) one layer of Ti foil (0.05 mm thick) with Ti mesh (0.10 mm thick) separator; 4) one layer of C-cloth (0.86 mm thick) with Ti mesh (0.10 mm thick) separator and embedded TC (#2); 5) three layers of Ti foil (each 0.05 mm thick) with Ti mesh (0.10 mm thick) separators; 6) four layers of Al foil (each 0.13 mm thick) with Ti mesh (0.10 mm thick) separators; 7) one layer of aluminized (one side) Kapton (0.05 mm thick) with Nomex™ scrim separator; 8) 11 layers of aluminized (both sides) and embossed Kapton (0.008 mm thick) with Nomex scrim separators; 9) one layer of aluminized (one side) Kapton (0.05 mm thick) with Dacron™ scrim separator and embedded TC (#3); 10) one layer of Kapton (0.18 mm thick).

Table 2 Summary of peak temperature data for three plasma-jet test runs

Run	Avg. flux, W/cm^2	Surf. pyro. temperature, °C	TC1[a] °C	TC2[a] °C	TC3[a] °C
1	35.3	1307.6	507	499.2	91.0
2	35.5	1281.8	775	497.6	81.5
3	35.1	1279.3	775	503.0	83.0
Avg.	35.3	——	——	499.9	85.2

[a]TC locations listed in Table1.

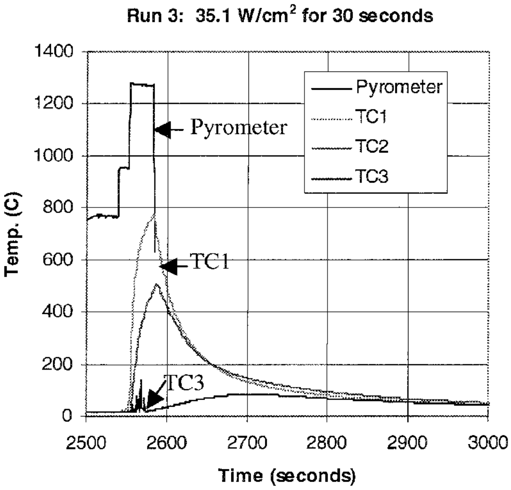
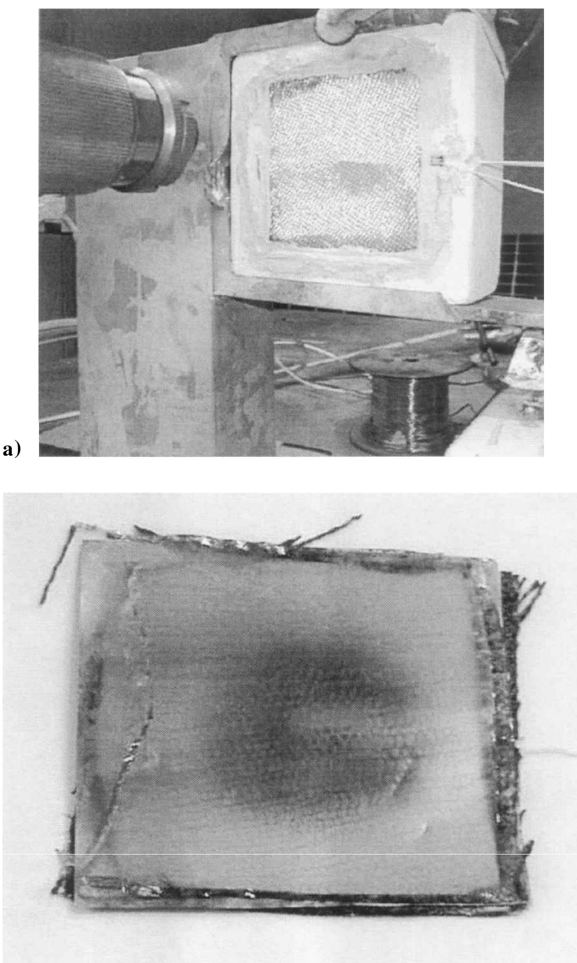


Fig. 1 Graphical plot of temperature vs time for plasma-arc run 3, showing rapid temperature rise for all thermocouples and pyrometer and then steady decrease after plasma termination.



a)

b)

Fig. 2 Photographs of a) test article after plasma-jet exposure showing no significant surface damage and b) internal Ti foil (and Ti mesh) showing discoloration at site of plasma-jet incidence.

Plasma-Jet Tests

The HT-MLI test article was subjected to three plasma-jet tests [hot gas (Ar & H_2) plasma at 35 W/cm^2 for 30 s] to measure induced temperatures for comparison with the SINDA model predictions. The plasma-jet test is used as an inexpensive screening method to test candidate thermal designs and does not preclude more rigorous arcjet testing. Peak temperatures recorded for all three tests are listed in Table 2, and Fig. 1 shows a typical time-temperature graphical plot for test run 3. The data in Table 2 suggest the HT-MLI system is effective in keeping the temperature at the inflatable bladder (location TC3) below the maximum recommended temperature of 205°C for the Kapton material. The measured surface temperature (from an optical pyrometer with emissivity set at 0.65) for runs 2 and 3 exhibited fairly good agreement with the predicted surface temperature of 1150°C (11% deviation). However, the measured temperature for the bladder was lower than for the predicted bladder temperatures. Potential reasons for this discrepancy include, among others, 1) use of an Ar and H_2 environment in the test vs a partial CO environment in the model; 2) nonuniform plasma-jet exposure area, which may increase lateral losses; 3) addition of scrim separator materials between layers, which would provide additional conduction paths; 4) effects of TC wires and mass; 5) radial conduction across the HT-MLI layers; and 6) lateral conduction across compressed edges of HT-MLI layup.

Posttest Characterization of Test Article

The tested HT-MLI layup did not reveal any significant damage, such as fiber breakage, weave unravel, or discoloration, on the top ceramic surface layer (Fig. 2). The test article was disassembled for additional examination of in-depth layers, which showed a lack of serious degradation to the insulation layers. The forward-most Ti metal foil sheet was slightly discolored with a ~2.5-cm (1-in.)-inner-diameter circle having a bluish-white tint and a larger diameter circle [~5.1 cm (2 in.)] having a brownish tint (Fig. 2b). It is likely this discoloration is from oxidation or nitriding of the Ti foil that occurred during the plasma-jet test.

Summary

A tailored HT-MLI thermal protection system (TPS) design for an inflatable ballute for S/C deceleration was developed using analytical modeling and fabricated for testing in a plasma-jet environment. The tailored TPS consisted of ceramic, carbon fabric, metal foil, and metallized Kapton layers. At areas removed from the highest heat flux, the TPS configuration consisted of fewer layers and thus had a lower areal density. The HT-MLI design is 43% lighter than an equivalently sized SLV-561V ablator TPS.

Plasma-jet testing of a fabricated test article was performed to measure induced temperatures for comparison with analytical predictions. Measured temperatures were lower than predicted and can be caused by several factors, including the different atmospheres used in the experiment vs the model and radial conduction in the test models. However, it appears the HT-MLI design will provide thermal protection for a lower temperature capable bladder material. No significant damage to the test article was observed after three plasma-jet tests.

Acknowledgments

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