THE RACE TOWARDS LAUNCH: QUALIFYING THE MARS SCIENCE LABORATORY HEATSHIELD IN UNDER TEN MONTHS

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Introduction

The Mars Science Laboratory (MSL) mission will have the largest blunt aeroshell ever built (4.5m in diameter). Due to the aeroshell's size and mass (nearly 3500 kg), the aerothermal environments upon entry will be hotter and have shear forces greater than any previous Mars mission. Furthermore, the boundary layer is expected to be fully turbulent before reaching peak heating. Qualifying a heatshield material to the levels of these extreme conditions proved to be a challenge and required innovative test designs to meet expected flight environments for peak heating, pressure, shear stress, and enthalpy. These tests unveiled a series of failures for the baselined heatshield material (SLA-561V) that could not be fully explained. As a result, the heatshield material was switched to Phenolic Impregnated Carbon Ablator (PICA), and the MSL team qualified, designed, and began manufacturing the heatshield in only 10 months in order to support the original 2009 launch date. The resulting heatshield is now the first ablating tiled design ever built by NASA, proven to be robust and low in risk while meeting all the mission requirements.

Arc Jet Testing

The original heatshield material, SLA-561V, has flown on all previous successful Mars entry missions by NASA. SLA-561V consists of a composite containing glass micro-balloons, phenolic micro-balloons, glass fibers, and chopped cork with a silicone resin binder in a Fiberglas phenolic flexible honeycomb. Earlier arc jet tests of SLA-561V in stagnation showed that the material could tolerate heat fluxes in excess of 300 W/cm^2. However, the material had not been previously tested in a high shear environment and it was not known if glass melt and flow would be a problem for char robustness. Arc jet tests in shear flow typically involve a wedge configuration; however, these geometries are not capable of producing shear stresses in the range appropriate for MSL ($\tau > 250$ Pa) at relevant heat fluxes. A new geometry for testing coupons in shear flow was designed and built that targeted conditions that the MSL heatshield was predicted to experience during entry. This new configuration, a swept cylinder, is capable of producing a heat flux on the sample of $q = 115$ W/cm^2, $p = 0.22$ atm, and peak shear of 300 Pa. Under these conditions, the SLA-561V samples experienced catastrophic failure within the first second after insertion and all of the filler material emptied from the honeycomb, as shown in Fig. 1(a). Other samples at higher heat fluxes using the wedge geometry also demonstrated this same type of failure. After many months of analysis, the team was unable to confirm a specific phenomenon that caused the failures and recommended that SLA-561V not be flown. The decision to switch heatshield materials occurred in October 2007, less than 2 years from the original launch date (September 2009).

(a) (b)

Figure 1. (a) SLA-561V swept cylinder failure during arc jet testing, and (b) successful PICA post-test sample under same conditions.

The only reasonable material that was known to be able to tolerate the entry environment was PICA, a mid-density material developed at Ames which had flown successfully on Stardust. Fortunately for MSL, the Orion mission had spent two years testing and developing material analysis tools for PICA, including gap filler options, and MSL was able to leverage Orion's data. Although the Orion TPS group had tested PICA in shear environments, the samples had not been exposed to the exact conditions which caused SLA-561V to fail. In March 2008, the MSL team arc jet tested PICA swept cylinders and wedges successfully at the same conditions that caused SLA-561V to fail (see Fig. 1(b)).

In all, the MSL team tested a total of 107 samples in 5 different arc jet facilities, including stagnation, wedge, swept cylinder, and panel configurations. No material failures were observed, although there was evidence of some minor flaking in the vicinity of gap fillers from time to time. This flaking did not affect the overall performance of the material.

Analysis

The stagnation tests of PICA showed well-behaved recession rates that followed an Arrhenius form (see Fig. 2). The stagnation coupons were 4” in diameter with a curved surface to ensure a relatively uniform heating profile across the front surface, a shape referred to as “Iso-Q.” Although the resulting heat flux impinging on the front of the sample was uniform, the coupons also experienced sidewall heating which affects the in-depth thermal response. PICA has an in-plane thermal conductivity about twice as large as its through-the-thickness value. This 2D variation needed to be modeled in order to accurately calculate the in-depth thermal response and recession rate for PICA. MSL used TITAN,[1] a 2D response model developed by Orion at Ames, to calculate recession rates for the PICA stagnation coupons. The predicted recession rates agreed within ±20% to the measured values over MSL-relevant conditions except at low heat rates, as shown in Fig. 2.

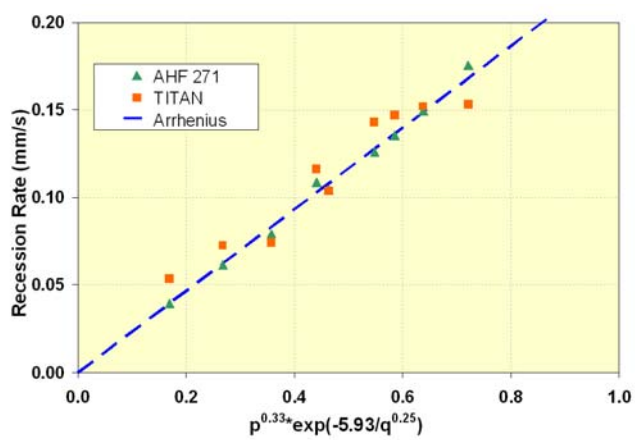

Figure 2. Measured PICA stagnation recession rates agree with predicted values using TITAN.

Comparisons of recession rates for wedge and swept cylinder coupons using a 1D model (FIAT, see Ref. 2) were less favorable and under-predicted recession rates by as much as 150%. Enhanced erosion due to shear stress was not thought to be the cause, as recession did not correlate with shear. Ultimately, a recession bias of 150% was incorporated into the calculated flight-margined thickness for the heatshield to account for this difference.

Because of the intense schedule pressure, the final heatshield thickness was decided in March ‘08 by the maximum allowable TPS mass (1.25” thick PICA) rather than by analysis. This allowed design and qualification to occur in parallel. Hence sizing analysis of margined flight thicknesses occurred after the PICA tiles were cut but before they were installed. Analysis verified that a thickness of 1.25” would ensure a bondline temperature significantly below the maximum allowable bondline temperature of 250 °C.

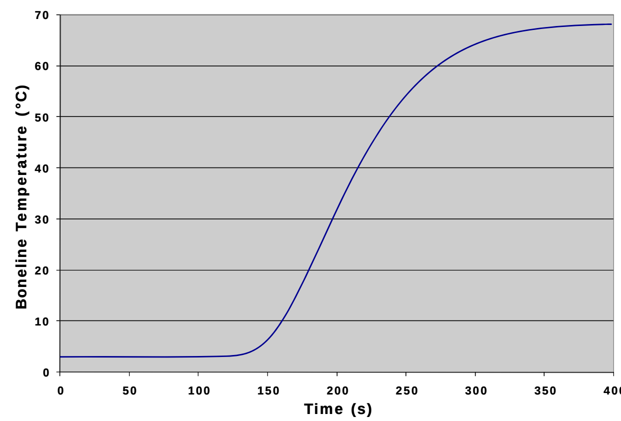

Figure 3. Predicted bondline temperature during atmospheric entry for heatshield region with highest recession.

Future Work

As of June 2009, the MSL heatshield has completed manufacturing. However, other unrelated technical challenges forced a launch slip to 2011. Early analysis of the updated entry environments shows that although the peak heating and total heat load will likely be higher than the 2009 launch trajectories, the as-built thickness is sufficient. There are a few remaining issues still to be investigated, such as the effects of localized augmented heating due protruding to the gap fillers.

References

[1]F.S. Milos and Y.-K. Chen, “Two-Dimensional Ablation, Thermal Response and Sizing Program for Charring Ablators,” AIAA Paper 2008-1223, 46th AIAA Aerospace Sciences Meeting, January 2008.

[2]F.S. Milos and Y.-K. Chen, “Ablation and Thermal Response Property Model Validation for Phenolic Impregnated Carbon Ablator,” AIAA Paper 2009-0262, 47th AIAA Aerospace Science Meeting, January 2009.