Computed Tomography Scanning and Analysis of the Stardust Heat Shield

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When the Stardust sample return capsule returned to Earth at approximately 3:00 a.m. Mountain Standard Time on January 15, 2006, it made one of the most dramatic re-entries in NASA history (figure 1). The capsule, which was traveling at 12.4 km/s, is the fastest human-made object to re-enter the atmosphere of the Earth. To survive this fiery re-entry, the Stardust capsule was fitted with an ablative heat shield composed of phenolic impregnated carbon ablator (PICA). This material and its re-entry performance are of significant interest to NASA, most notably for the Mars Science Laboratory (MSL) mission and the Orion/Crew Exploration Vehicle (CEV) project. The MSL is currently scheduled to launch with a multi-segmented PICA heat shield in the year 2011. Engineers in the CEV program are also investigating the use of PICA for the forebody of the Orion capsule. Although we have used arc-jet testing to create models for PICA ablation, the Stardust sample return capsule heat shield provides the only actual ground truth with which to validate these models.

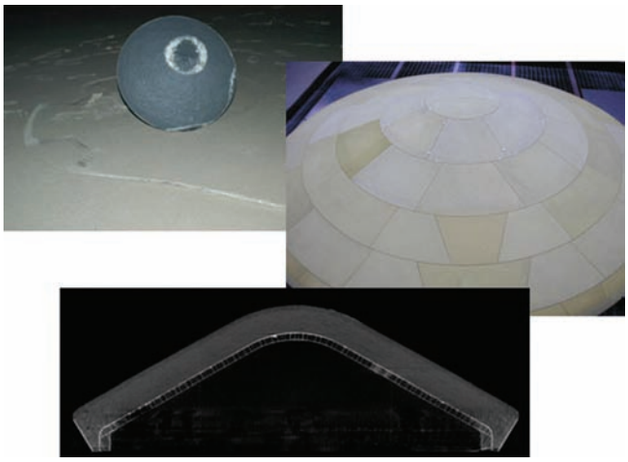

Fig. 1. *View of the landed Stardust heatshield on recovery in the field (top). Multi-segmented MSL PICA heat shield (middle). Cross-sectional (X-Y) computed tomography scan of the Stardust flight heat shield (bottom).*

PICA consists of a preformed, low-density, fibrous carbon structure infiltrated with a phenolic resin. The preform is cast to a proper shape and thickness, fired, impregnated with a phenolic resin, and hand-machined to meet specifications. It is then bonded to an aluminum honeycomb support structure to complete the heat shield. In the case of the Stardust sample return capsule, the steep re-entry angle and speed caused unprecedented peak heat loads that precluded the use of joined sections of PICA to form the outer ablative layer. The handcrafted PICA shell thus consisted of a single solid casting, the design of which was one of the greatest challenges for meeting Thermal Protection System requirements on the Stardust mission.

The Stardust capsule heat shield is the only PICA forebody that has flown a planetary re-entry to date. Its successful recovery on land makes it one of the most interesting re-entry bodies for engineering studies, as it was not exposed to the corrosive environment of the seas (as were the Apollo return capsules). Since the return to Earth of the Stardust sample return capsule in early 2006, the Johnson Space Center (JSC) Space Exposed Hardware (SEH) Group has supported a multitude of studies by NASA, industry, and academic partners. These studies are aimed at forming a better understanding of the performance of the Stardust capsule heat shield. Researchers made residual thickness estimates using at least three independent techniques: (1) mechanical surface height measurements; (2) high-resolution, three-dimensional (3D) laser surface scanning; and (3) thickness measurements based on core abstractions. We performed additional measurements at JSC to address the chemistry of ablation, microstructure, thermal, and mechanical performance.

For MSL, Orion, and other future missions, spatially resolved recession rates are the most critical data that can be amassed to understand heat shield performance. We could not determine the spatially resolved recession rate of the Stardust heat shield based on any of the analyses described above, however – in part because of the lack of pre-flight data for both the bonded and the unbonded PICA casting. Both castings are required to determine overall recession as well as variability, asymmetry, and peak recession. Due to budget, schedule, and scope constraints, we performed, for example, no pre-flight imaging of the heat shield or verification of the thickness, shape, and planarity of the

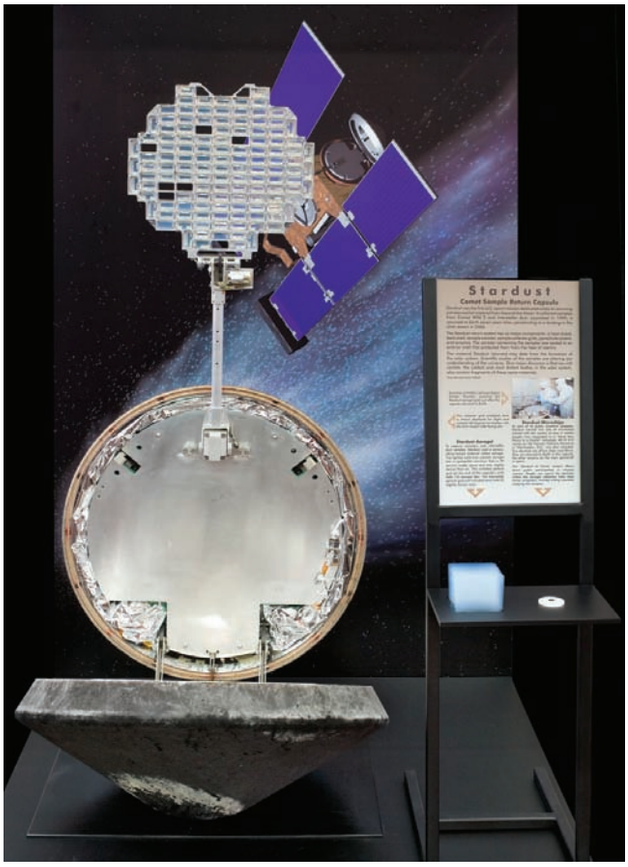

Fig. 2. *The Stardust sample return capsule on display in the National Air and Space Museum.*

surfaces or radii of curvature for the PICA shell. The same is true of the mated PICA form and the support structure.

We might have ended the quest for recession information from the Stardust heat shield there had it not been for a collaborative effort between the JSC SEH Group and the JSC Engineering Nondestructive Evaluation (NDE) Group. The SHE and NDE Groups, which worked with researchers from the Lawrence Livermore National Laboratory, Livermore, Calif., used a new state-of-the-art x-ray system to obtain a complete 3D computed tomography (CT) scan of the Stardust heat shield – one of largest objects ever scanned in a CT system.

Although absolute recession measurements could not be achieved without recourse to pre-flight data, the CT scans provided a 3D thickness map of the PICA layer at a 300-µm resolution that allowed a quantitative comparison of relative recession rates and a qualitative evaluation of arc-jet data and the resulting models. Bondline gaps between the PICA and the aluminum honeycomb substructure can also be clearly measured. These data are absolutely critical to both the MSL and the CEV, both of which will be using multi-segmented heat shield designs. For example, the Stardust heat shield shows extensive bondline separation along the curvature of nearly its entire circumference; this bondline separation could have major impacts on future manufacturing processes. The CT scan also provided values for the PICA density as a function of depth and spatial location. This gives insight into the depth of char and chemical alteration of the PICA, which is important to our understanding of the pyrolysis processes as well as the physical and mechanical performance of the material. Finally, CT scans allow spatial identification of the physical and chemical defects that can alter performance; we can use their results to develop and evaluate manufacturing processes.

Members of the Stardust CT scanning group are continuing to evaluate the data obtained from the flight heat shield. These group members are also planning to perform similar CT scans on the Stardust engineering model (EM) heat shield (figure 2). Although the EM heat shield is not identical to the pre-flight actual, it was manufactured under identical conditions and, thus, should provide insight into pre-flight characteristics and assist in differentiating manufacturing and flight defects.

Completing the NDE of the Stardust heat shield also allowed the JSC SEH Group to work with curators at the Smithsonian National Air and Space Museum in Washington, D.C. to place the reconstructed Stardust sample return capsule on permanent display in the premier “Milestones of Flight” gallery at the museum alongside the Apollo 11 capsule and the Viking lander model. This will be the first NASA artifact to be added to that collection in nearly 25 years.

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