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Mars Exploration Rover Heatshield Observation Campaign

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Abstract

For the first time ever, engineers were able to observe a heatshield on the surface of another planet after a successful entry through the atmosphere. A three-week heatshield observation campaign was conducted in December 2004 after the Mars Exploration Rover *Opportunity* rover exited "Endurance Crater." By utilizing the rover's scientific instruments, data was collected to make a qualitative assessment of the performance of the heatshield. This data was gathered to gain a better understanding of how the heatshield performed during entry through the Martian atmosphere. In addition, this unprecedented look at the heatshield offered engineers the opportunity to assess if any unexpected anomalies occurred. Once a survey of the heatshield debris was completed, multiple targets of interest were chosen for the collection of imaging data. This data was then used to assess the char depth of the thermal protection material, which compared well with computational predictions. Extensive imaging data was collected and showed the main seal in pristine conditions, and no observable indications of structure overheating. Additionally, unexpected vehicle dynamics during the atmospheric entry were explained by the observation of thermal blanket remnants attached to the heatshield.

Introduction

The Mars Exploration Rover (MER) mission successfully landed two rovers on the surface of Mars. The first, named *Spirit*, landed near Gusev Crater on January 3, 2004 (PST) and the second, named *Opportunity*, landed on Meridiani Planum on January 24, 2004 (PST). The goal of the identical rovers was to learn about ancient water and climate on Mars. Led by principal investigator, Steve Squyres, professor of astronomy at Cornell University, discoveries made by the MER mission were chosen by *Science* magazine as "Breakthrough of the Year" in its December 17, 2004 edition. This top honor was awarded for the mission's discovery of evidence of salty, acidic water on the planet's surface that may have been hospitable to sustaining life. Originally slated for a primary mission of 90 sols (or martian days), the two rovers have far exceeded expectations, and now are now well past 1000 sols of successful operation, and still going strong.

Figure 1 shows the entry, descent, and landing (EDL) timeline for the mission.[1] The MER mission leveraged off of the successful Mars Pathfinder landing system by utilizing a bridle descent from the entry vehicle and air bags to protect the rover upon surface impact. As shown in Figure 2, the entry vehicle forebody, like Viking and Mars Pathfinder before it, was a 70 degree half-angle sphere cone, with a diameter of 2.65 m. Figure 3 shows the entry vehicle mated to the cruise stage with half of the external thermal blanket installed. Successful entry into the Martian atmosphere relies on thermal protection systems (TPS) to protect the rover, inside the entry vehicle, from the harsh heating environment experienced during atmospheric entry. The heatshield thermal protection system utilized on MER was SLA-561V, a Lockheed-Martin ablative material that was used on the Viking and Mars Pathfinder missions. The SLA-561V material is composed of phenolic honeycomb cells that are packed with organic compounds and fillers. The material is designed to ablate as a heat rejection mechanism, as shown in Figure 4. An ablative material contains organic resins, which through an endothermic process, decompose (or pyrolyze) and escape from the material surface in the form of pyrolysis gases that then thickens the boundary layer. In addition, carbonaceous products from the decomposition process deposit on the material surface to create a char layer with a high emissivity, which re-radiates back into the boundary layer. The net heat flux is then conducted through the material thickness to the spacecraft structure.

The heatshield TPS thickness is designed to ensure adequate thermal protection of the structure so that the structure maintains its mechanical integrity throughout EDL. A computational thermal model of the TPS is used to predict the material thermal response to the entry environment. These computational models are anchored to data from arc jet testing of the material, but uncertainties still exist. For example, arc jet tests are conducted in air as opposed to carbon dioxide, of which the Martian atmosphere is composed. Typically, margin and factors of safety are added to TPS thickness designs to account for any "unknown unknowns" that may occur during the actual Martian entry. Very little flight test data exists for Martian entries and thus there has been little basis for reducing these material design margins from mission to mission. Some instrumentation was flown on Mars Pathfinder, but limited correlation to computational predictions was achieved.[2]

Once the MER heatshield successfully performed its function of protecting the spacecraft structure, it was jettisoned to allow the rover to descend on a bridle and impact the Martian surface within a protective airbag landing system. Once safely on the surface of Mars, the *Opportunity* rover spent time exploring and analyzing the unique bedrock outcrop nearby and entered "Endurance" crater in June 2004.

In early December 2004, once the *Opportunity* rover exited "Endurance" crater, engineers were given the unique opportunity to utilize the rover to observe the heatshield on the surface of Mars. There was no instrumentation on the MER heatshield to provide data on its performance, and this opportunity offered an unprecedented look at a heatshield after a Mars entry. There were several instruments on-board the rover that could be utilized to gain useful information regarding the performance of the heatshield and this data then has the potential to impact future heatshield designs.

Opportunity Rover Assets

The MER rovers have high-resolution cameras and a Microscopic Imager (MI) that were used for this observation campaign. Two Navigation Cameras (Navcams) and four Hazard Avoidance Cameras (Hazcams) were primarily used for traverse planning and rover fine positioning for the Instrument Deployment Device (IDD). The Navcams are mounted on the rover 1.54 m above the Martian surface and have an optimum best focus depth of field of 1.0 m. The Navcams can provide 360° panoramas, as well as stereo and monoscopic images. The Hazcams are mounted on the rover 0.5 m from the surface and are specified to provide about 15° of sky in the top portion of the images. The Hazcams have a best focus depth of field of 0.5 m.[3]

The Panoramic Camera (Pancam) is a high resolution, color, stereo panoramic imaging system consisting of two digital cameras mounted on a mast 1.5 m above the Martian surface. The mast allows a full 360° image in azimuth and ±90° in elevation. The Pancam was designed and optimized to assess the high-resolution morphology, topography, and geologic context of each MER landing site.[4] For the heatshield observation campaign, the Pancam provided high-resolution (~1 mm/pixel at a range of 3 m from the rover) color images of the hardware and debris field.

The rover's science payload includes a five degree of freedom IDD arm that carries four tools: the MI, an Alpha Particle X-ray Spectrometer (APXS) for elemental chemistry, a Mössbauer Spectrometer (MB) for the mineralogy of iron-bearing materials, and a Rock Abrasion Tool (RAT) for removing dusty surfaces and exposing fresh rock underneath.[5] The RAT and the MI were considered for use in the observation campaign. The MI could be used for close-up magnification (fixed at 0.4) of the heatshield surface and the RAT could be used to remove a certain depth of material to obtain images of the material char layer. Laboratory tests were conducted with an engineering RAT unit and a charred SLA-561V material sample to evaluate if this tool could be used on the heatshield. Test results showed that the RAT abrasion process on the char surface layer produced a large amount of carbon dust that then prevented an assessment of char layer depth within the resultant cross-section. This char dust also contaminated the engineering RAT and thus was unacceptable for *Opportunity*'s RAT since it may cross-contaminate future science investigations on Martian rocks. Thus it was decided that the RAT would not be used for the heatshield observation campaign. The MI could still be utilized, however, as long as the MI surface did not come in contact with the heatshield. The rover and location of these science assets are shown in Figure 5.

Heatshield Observation Plan

A team was formed from MER team members at JPL, Lockheed-Martin, and NASA Ames Research Center, and included engineers familiar with the TPS design and spacecraft hardware. This team created a prioritized investigation plan that the MER Operations team would implement:

1. Obtain imaging data to determine char depth of localized area of material. This information can be used to directly compare TPS performance vs. computational predictions.
2. Obtain imaging data to look at global charring patterns on heatshield. Surface color variability and surface feature observations (e.g. surface roughness) can allow a qualitative comparison to Computational Fluid Dynamics (CFD) aerothermal heating prediction trends and ground test results.
3. Obtain imaging data to evaluate the performance of the main thermal seal. This main thermal seal prevented hot gas ingestion into the spacecraft during entry at the interface between the heatshield and the backshell. Imaging data can be used to assess the integrity of the seal and evaluate if any burn-through occurred.
4. Obtain imaging data of the internal structure. Observation of structure color variability may indicate thermal gradients and structure over-heating, if it occurred.

In order to begin the observation campaign, a comprehensive imaging survey of all heatshield debris was planned. In addition to assisting in the determination of targets of interest, this information could be used to evaluate if any anomalies occurred.

The Approach

Once *Opportunity* exited "Endurance" crater, the rover began driving towards the heatshield. Figure 6 shows a PanCam image of the heatshield taken on Sol 322 as the rover was about 130 m away. At this point, it was clear that the heatshield was not intact after impacting the surface at about 75 m/s (170 mi/hr). The shiny, reflective material was determined to be internal multilayer insulation (MLI) blankets, which were integrated to the inside of the heatshield. Images were taken on Sol 324, shown in Figures 7 and 8, as the rover was about 30 m away the heatshield. These images provided a clear view of the impact divot, the main heatshield, and a secondary debris site. This image provided the information needed to implement the prioritized investigation plan. The images provided a clear view that the heatshield was unexpectedly inverted, or "inside out". This is seen from the fact that the internal thermal blankets are observed on the outside of the heatshield debris (the silvery, glinting region in Figures 7 and 8).

It was hoped that the stagnation point, or "nose", of the heatshield, which corresponds to the highest heating location on the heatshield, was located at the secondary debris site, named the "flank" piece. Since this is a critical location on the heatshield, the plan was to drive the rover to the "flank" piece first and obtain imaging data. The MI would then be used to obtain char depth information, if a target of acceptable quality was identified. After the flank piece was evaluated, the plan was then to survey the main heatshield debris by circling around to obtain imaging from each main direction. The rover would then drive in close to the exposed seal location to obtain imaging of the seal and internal structure. If a worthy target was identified on the main heatshield piece, the MI would be utilized to gather char depth information from the resulting images.

The "Flank" Piece

Sol 329 and 330 imaging of the "flank" piece provided a survey of the broken heatshield and structure at this location, and Figure 9 identifies these pieces. Circling around the flank piece gave intriguing vantage points and color images of the debris by utilizing the PanCam (shown in Figures 10 and 11). MI data was obtained on a couple of areas, including the stagnation piece, as seen in Figures 12 and 13. At the stagnation piece, the IDD was not able to position the MI to obtain a true cross-sectional view of the exposed edge. Therefore char depth could not be evaluated at this location on the heatshield. None of the "flank" piece debris offered areas where char depth evaluation could easily be obtained, so it was decided to move to the main heatshield.

The Main Heatshield

Before it was determined that the heatshield was inverted, it was hoped that observation of the global charring pattern on the exterior surface of the TPS would offer insight into heating gradients and transition to turbulence. Images were taken from various angles around the main heatshield, and at different times of the Martian day, to attempt to distinguish color patterns on the TPS. Unfortunately because of the inversion and the fact that the interior was always shadowed, clear images of the TPS exterior could not be obtained, as seen in Figure 14. However, this side of the main heatshield offered excellent cross section targets to obtain char depth measurements.

The heatshield shoulder is shown in Figure 15 and a close-up is shown in Figure 16. Figure 17 shows an intriguing view of the IDD and MI in position at the target location. This location turned out to be an excellent cross sectional view, and the image (Figure 18) was examined for the slight color difference between the char and the virgin material. Estimated char depth from the image was consistent with pre-flight predictions, yielding confidence in the ability of the computational material response model to predict the material's ablative response. This data allowed engineers to achieve one of the main objectives of the heatshield observation plan. An interesting view and color image of the shoulder area is shown in Figure 19.

Figure 20 shows the internal MLI blanketing, a separation spring, and fortuitously, a rock that intrigued the MER scientists. An additional image of the impact divot (Figure 21) shows various aeroshell hardware, including separation springs and ballast mass that had been attached to the inside of the heatshield. A color image from Sol 357 (Figure 22) revealed the heatshield composite structure, fractured and rippled from the high-speed impact into the Martian surface. These color images showed no observable discolorations on the structure or internal MLI blanketing that would indicate overheating. This result achieved the fourth main objective of the observation plan.

This vantage point and the same color image also show that the main seal appeared to be in pristine condition, with no observable sign of hot gas penetration through the seal. There were also no observable discolorations that would indicate overheating, and this observation achieved the third main objective of the observation. Further images taken on Sol 357 proved to be some of the most valuable images of the entire observation campaign.

A Major Discovery – External MLI Blanket Remnants

Figure 23 shows a close-up of the main seal area, and clearly shows remnants of the aluminized mylar tape interface and thermal blanket "keeper strips" that were used to attach the external MLI blanket to the heatshield. This external MLI blanket was needed for thermal control of the spacecraft during cruise. The observation of these remnants led engineers to explore the possibility that this may be an explanation for a mystery that had plagued the MER flight reconstruction efforts.

Figure 24 shows the entry attitude reconstruction for *Opportunity*. This plot shows angle of attack oscillations much earlier, and at magnitudes far in excess of what was expected. This behavior was not seen in the post-flight reconstruction of the Mars Pathfinder spacecraft. Thus this unexplained behavior was causing consternation for design engineers who were designing the EDL system for the next Mars mission, Phoenix. Aerodynamicists studied the effect that this tape strip could have had on the entry dynamics. This work is detailed in Reference 6, and it was concluded that this tape strip remnant could have been enough of a disturbance in the flow field to explain the anomalous angle of attack oscillations during entry. This discovery has thus drawn attention to the design of external MLI blanket attachment schemes for future Mars missions. Fortunately, the Phoenix spacecraft did not need an external thermal blanket for thermal control during the cruise phase. It is now clear that the blanket attachment design must ensure complete burn-off during atmospheric entry, or mechanical removal, of the blanket and any attachment strips to avoid any possible flow field disturbance that would adversely affect entry dynamics.

"Heatshield Rock"

Opportunity's heatshield fortuitously landed near a unique, basketball-sized rock (Figure 25), aptly named "heatshield rock" by MER scientists (and affectionately nicknamed "SpongeBob" by the MER operations team). During the heatshield observation campaign, the scientists took a detour around the heatshield to gather spectroscopic data on the rock to aid in its identification. Surprisingly, it was determined to be an iron-rich meteorite, and the first meteorite of any type ever to be identified on another planet. This unexpected science "gem" could open up research possibilities for future robotic and sample return missions.

Conclusions

The observation of a heatshield, post-atmospheric entry on another planet, was an unprecedented opportunity for engineers in the aerothermodynamic and TPS community. Designing an EDL system is challenging, and without TPS instrumentation, there is no information on how well the TPS performed in comparison to predictions, how well engineers were able to predict the aerothermal environment, and the appropriateness of the margin approach used in the TPS design. Without this information, it is difficult to feed-forward improvements to TPS design for future missions.

The ability to visually observe *Opportunity*'s heatshield after atmospheric entry proved extremely valuable in making qualitative assessments with respect to the TPS and main seal performance. This observation campaign successfully met three of the four main objectives:

1. Obtain imaging data to determine char depth of localized area of material. Objective met - MI imaging at the shoulder allowed an assessment of char depth that compared well to pre-test predictions.
2. Obtain imaging data to look at global charring patterns on heatshield. Objective not met – Due to the inversion of the main heatshield debris, images could not be obtained that would allow an assessment of global heating patterns.
3. Obtain imaging data to evaluate the performance of the main thermal seal. Objective met – Clear, color images of the main seal show no observable signs of overheating or gas penetration through the seal; seal appears to be in pristine condition and confirms adequacy of the seal design.
4. Obtain imaging data of the internal structure. Objective met – Images of the internal structure, though fractured from impact, show no observable signs of discoloration that would indicate overheating.

The critical discovery of external thermal blanket remnants on the heatshield can directly feed-forward to future mission designs. Aerodynamic analyses have shown that these remnants could have been enough of a disturbance in the flow field to explain the previously unsolved mystery of unexpected angle of attack oscillations during entry. It is clear that external thermal blanket attachment designs need to ensure complete removal so as not to adversely affect entry dynamics.

This observation campaign was extremely successful in gathering an abundance of visual data to allow qualitative assessments of TPS performance and the main seal design. The data gathered showed a char depth consistent with pre-flight predictions and a main seal in pristine condition. In addition, there was no indication of overheating on the structure or internal thermal blankets. The MER scientists also got a bonus in the discovery of the first meteorite ever identified on another planet. Though limited and qualitative, this observation campaign yielded critical results that can feed-forward to future missions.

Acknowledgements

This opportunity would not have been possible without the support and advocacy from Rob Manning, Wayne Lee, and Doug McCuistion. The authors are also grateful to the MER science team, especially Steve Squyres and Ray Arvidson, for allowing weeks of rover operations dedicated to obtaining this critical data. Last, and certainly not least, many thanks go to the incredible MER operations team, who carefully drove *Opportunity* through the challenging debris field, operated the rover in non-standard manners, and obtained all of the incredible images that allowed the accomplishment of the heatshield observation campaign objectives. This campaign was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1. Desai, P.N., Lee, W.J., "Entry, Descent, and Landing Scenario for the Mars Exploration Rover Mission," International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Sciences, Lisbon, Portugal, October 2003.
2. Milos, F.S., Chen, Y.K., Congdon, W.M., Thornton, J.M., "Mars Pathfinder Entry Temperature Data, Aerothermal Heating, and Heatshield Material Response," AIAA Paper 98-2681, 1998.
3. Maki, J.N., et al., "Mars Exploration Rover Engineering Cameras," *J. Geophys. Res.*, *108*(E12), 8071, doi: 10.1029/2003JE002077, 2003.
4. Bell III. J.F., et al., "Mars Exploration Rover Athena Panoramic Camera (Pancam) Investigation," *J. Geophys. Res.*, *108*(E12), 8063, doi: 10.1029/2003JE002070, 2003.
5. Squyres, S.W., et al.., "Athena Mars rover science investigation," *J. Geophys. Res.*, *108*(E12), 8062, doi: 10.1029/2003JE002121, 2003.
6. Tolson, R.H., Willcockson, W.H., Desai, P.N., Thomas, P., "Anomalistic Disturbance Torques During the Entry Phase of the Mars Exploration Rover Missions – A Telemetry and Mars-Surface Investigation," 29th Annual AAS Guidance and Control Conference, AAS 06-087, Breckinridge, CO, February 4-8, 2006.

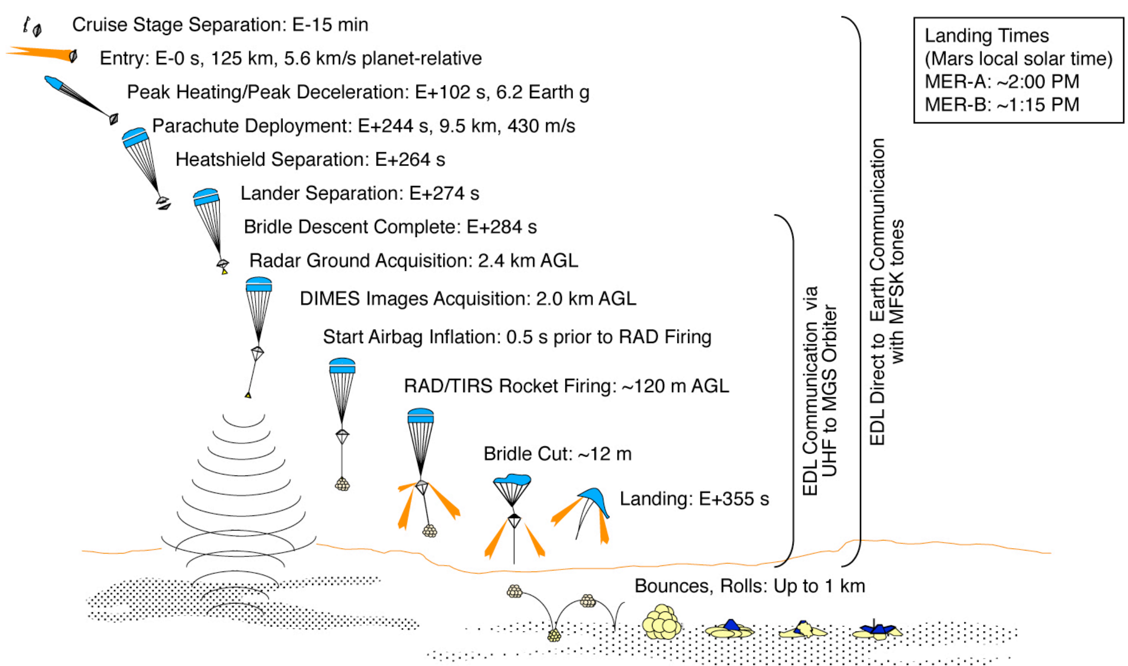

Figure 1: MER Entry, Descent, and Landing Timeline (MER-A, *Spirit*; MER-B, *Opportunity*)

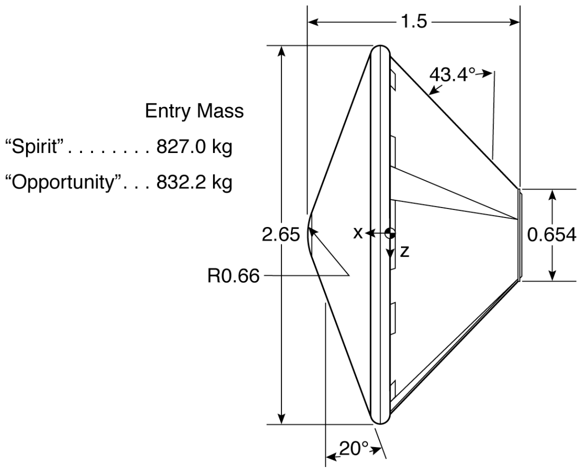

Figure 2: MER Entry Vehicle Configuration (dimensions in meters)

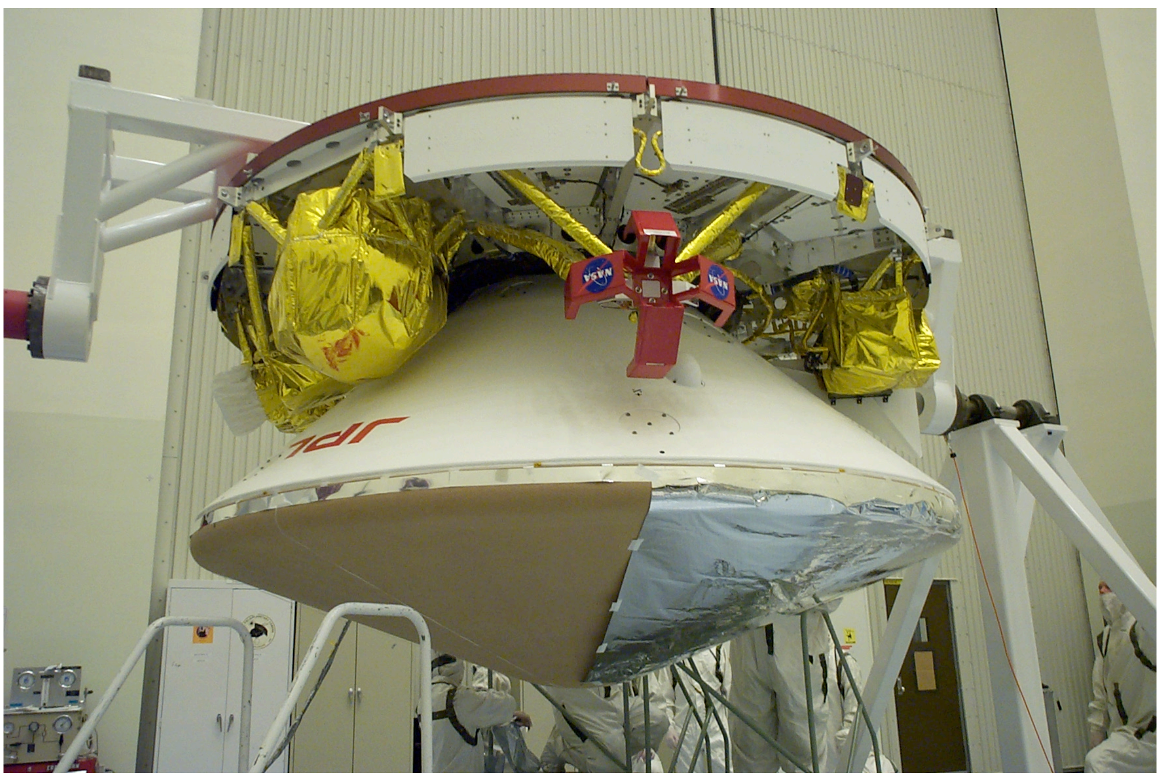

Figure 3: MER spacecraft mated to cruise stage (half of external thermal blanket installed)

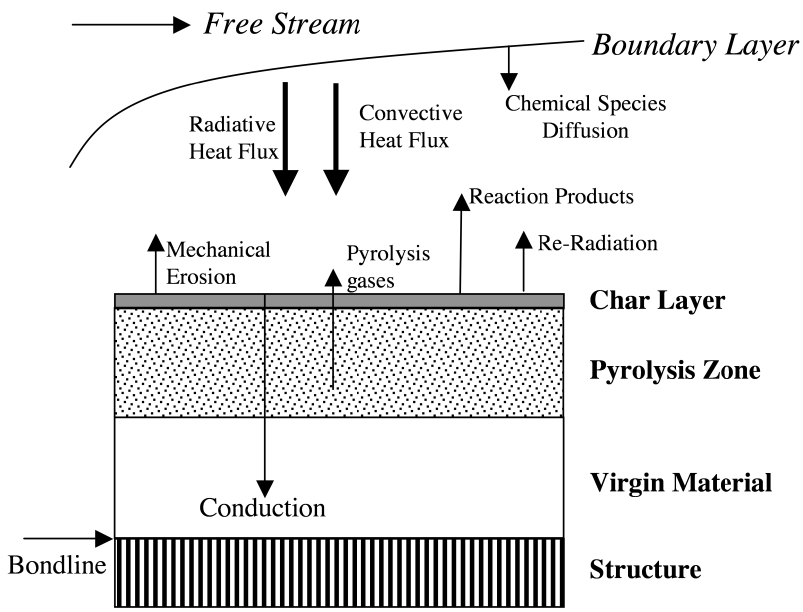

Figure 4: The ablation process of a thermal protection material

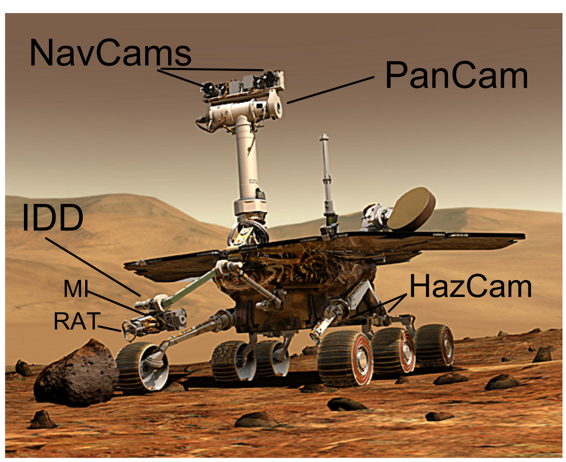

Figure 5: Mars Exploration Rover and Heatshield Observation Science Assets

Figure 6: Heatshield Debris Image from Sol 322 (Rover approximately 130 m away)

Figure 7: Images of the heatshield debris field taken on Sol 324

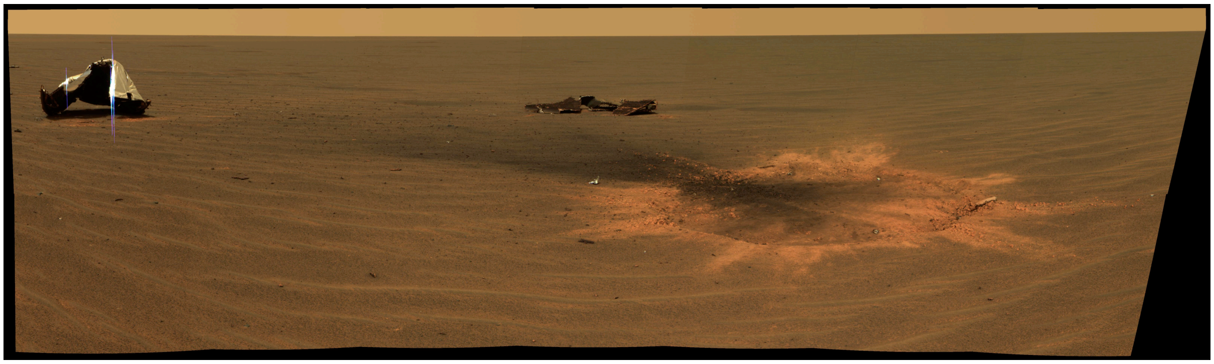

Figure 8: Main heatshield, “flank piece”, and impact divot

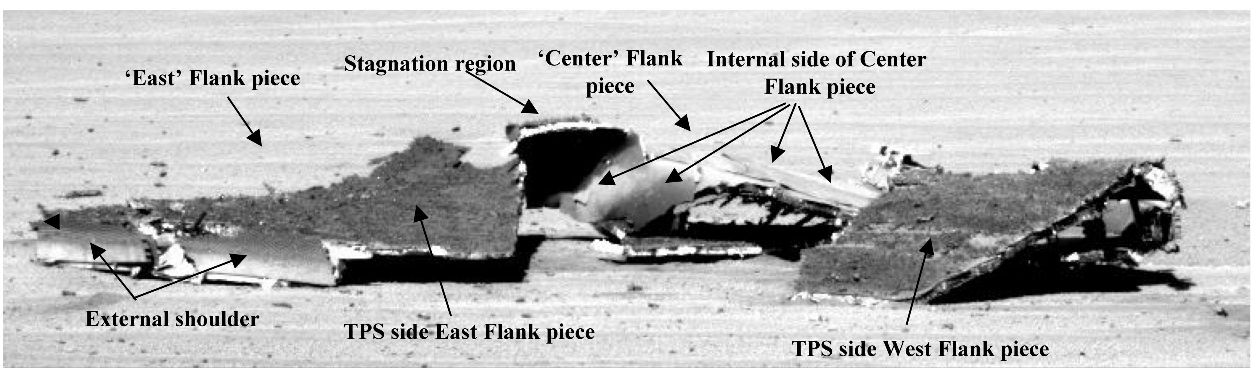

Figure 9: Identification of the “flank” pieces

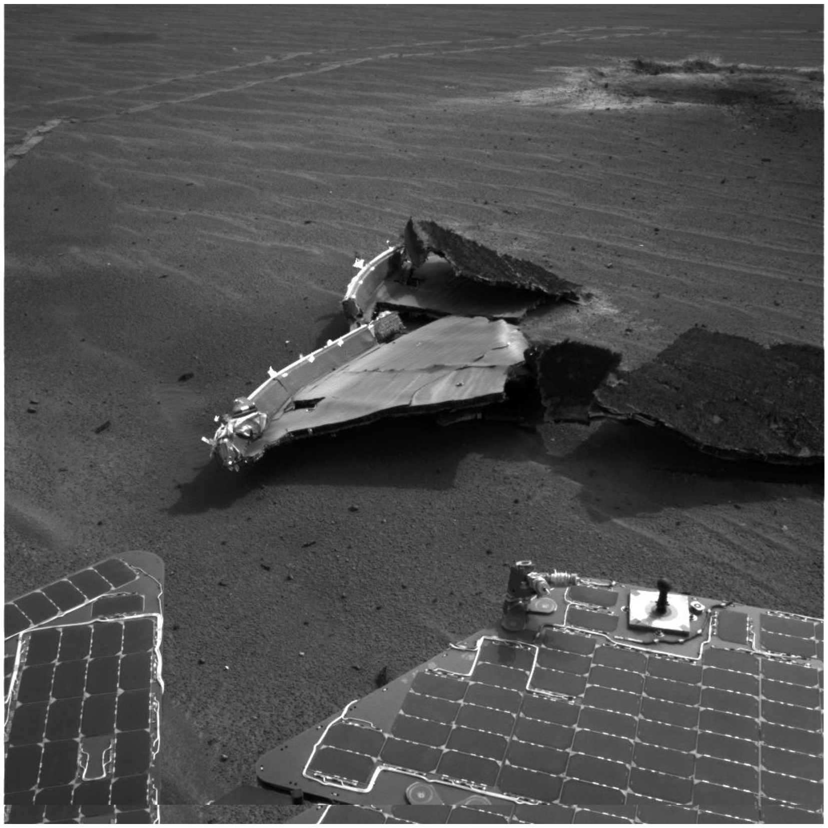

Figure 10: Sol 331 image of “flank” piece from the South (the rover’s solar panels can be seen in the foreground)

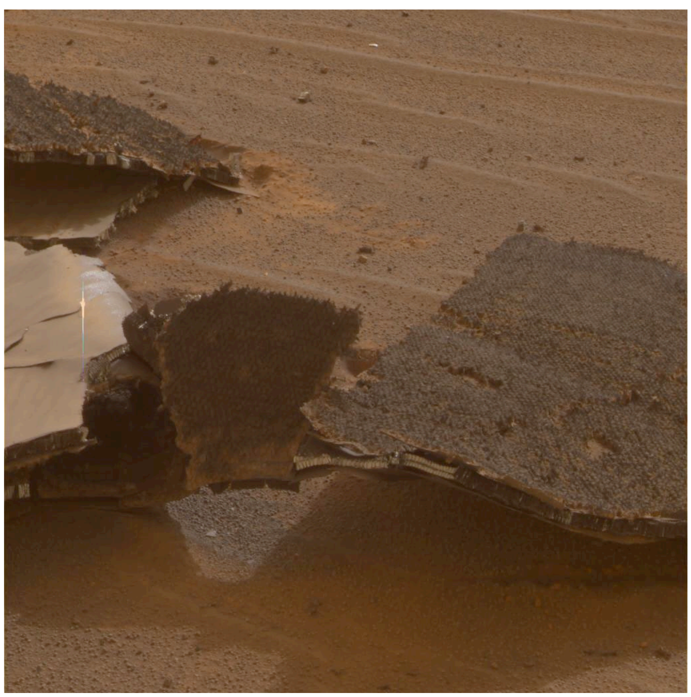

Figure 11: Color PanCam Image of the heatshield stagnation area

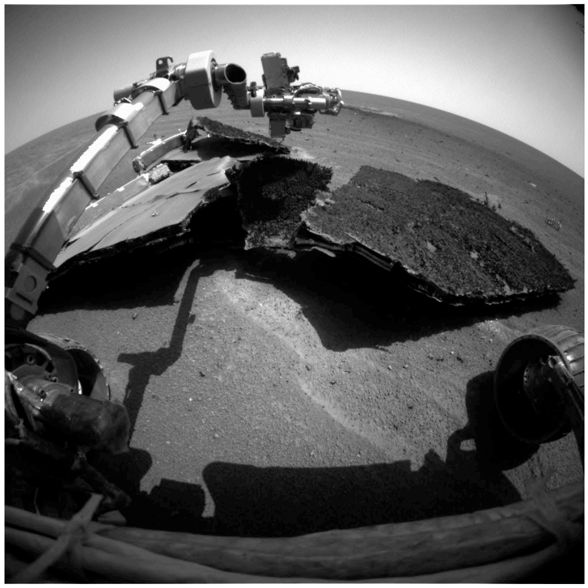

Figure 12: *Opportunity*'s Instrument Deployment Device positioning the MI for close-up images

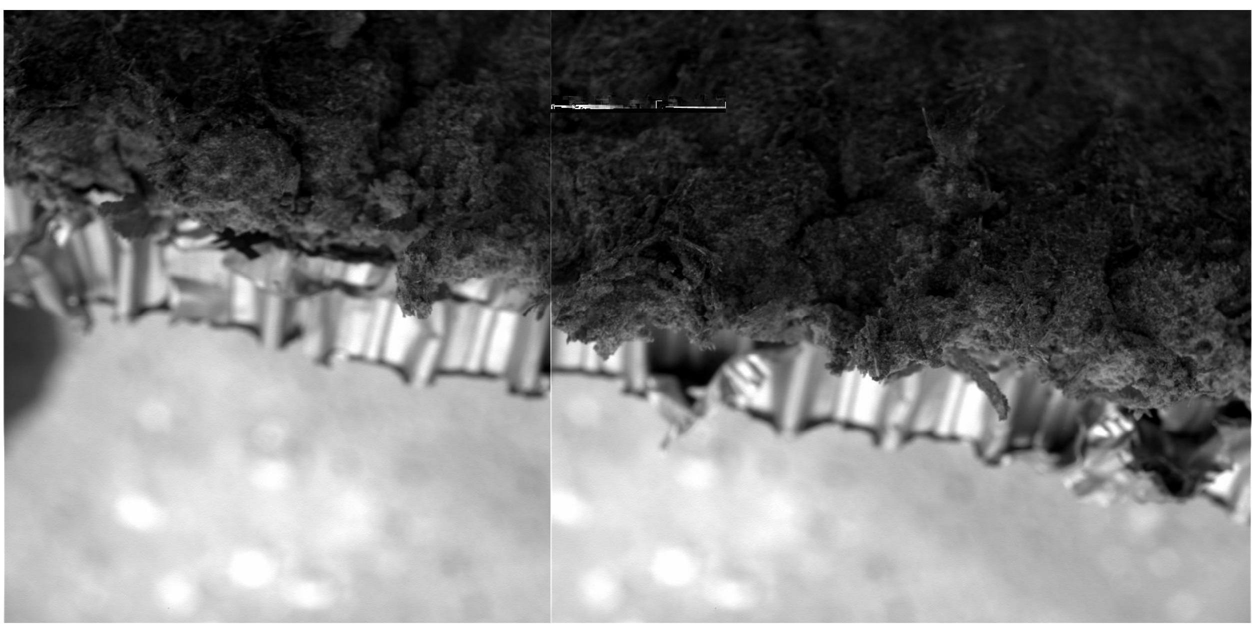

Figure 13: MI images of the "flank" piece stagnation area

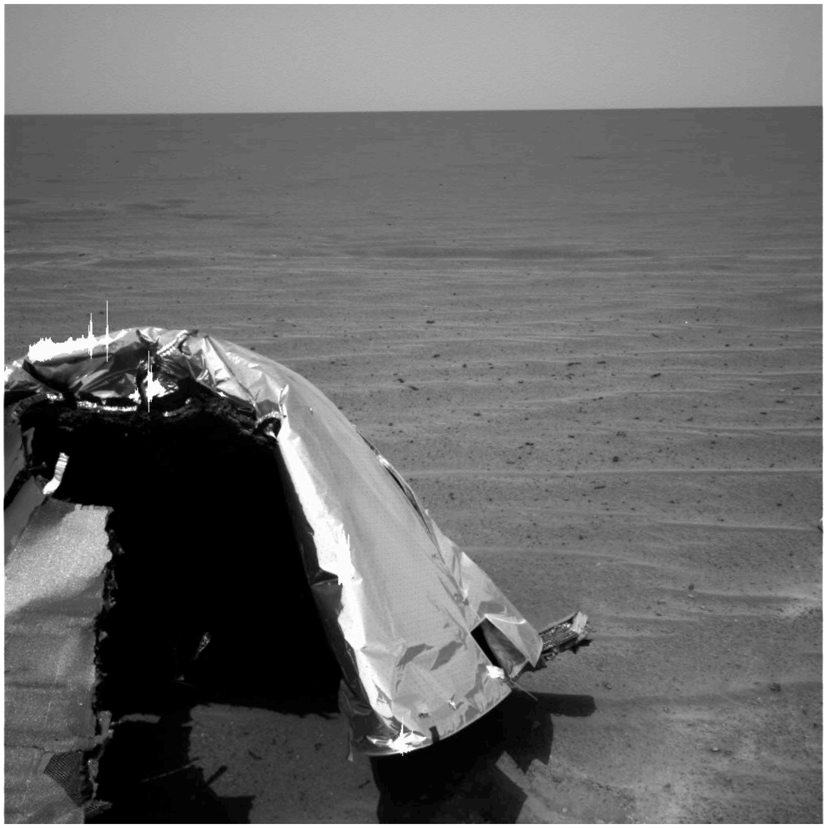

Figure 14: Main heatshield image in the attempt to view TPS surface characteristics

Figure 15: Sol 329 image of the main heatshield from the west

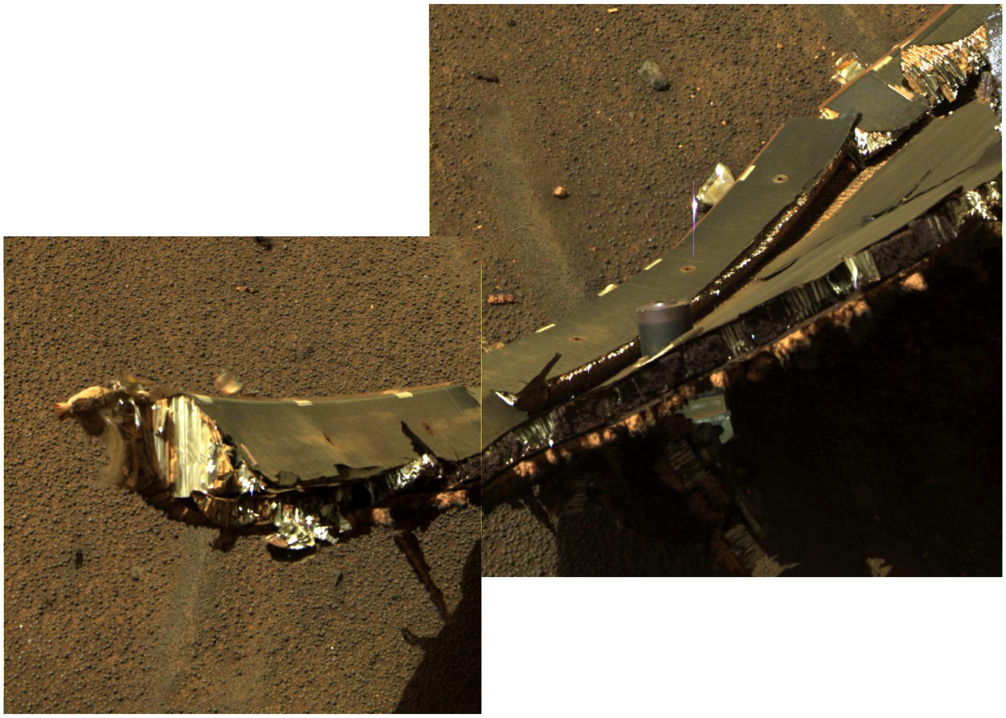

Figure 16: Mosaic close-up image of the heatshield shoulder

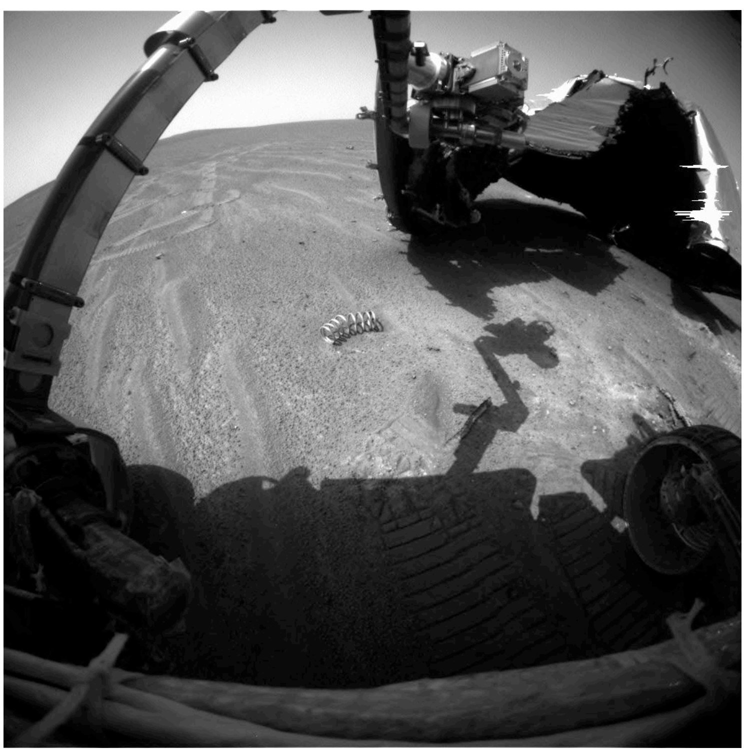

Figure 17: Rover IDD placement of MI on heatshield shoulder target (heatshield separation spring can be seen in foreground)

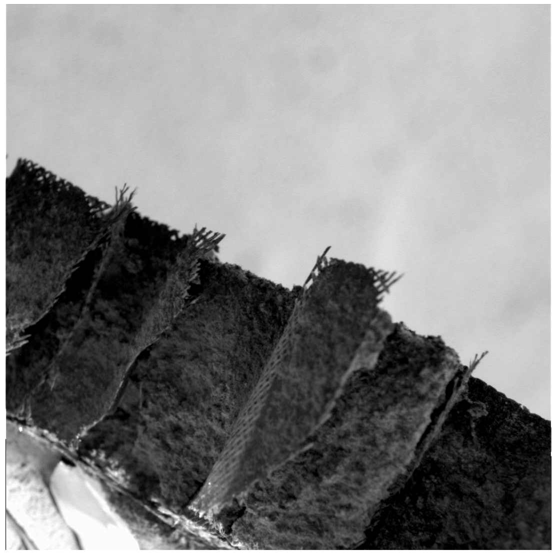

Figure 18: MI image of heatshield shoulder cross-section

Figure 19: Color image of heatshield shoulder

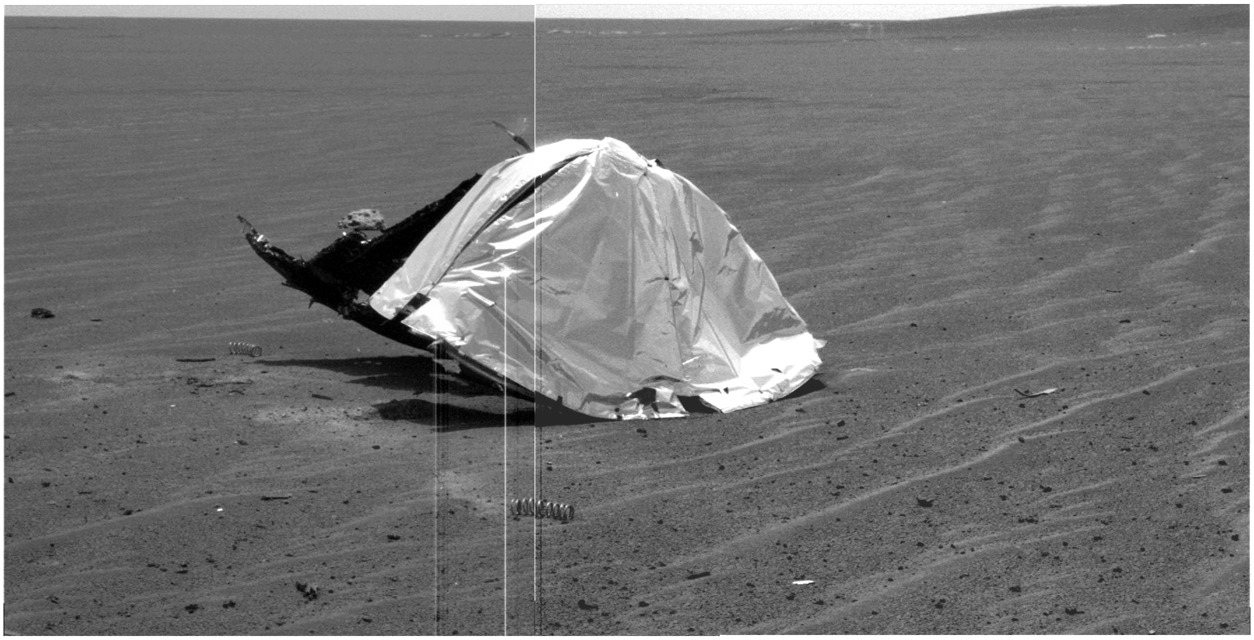

Figure 20: Sol 335 image of the heatshield ("heatshield rock" can be seen just behind the heatshield)

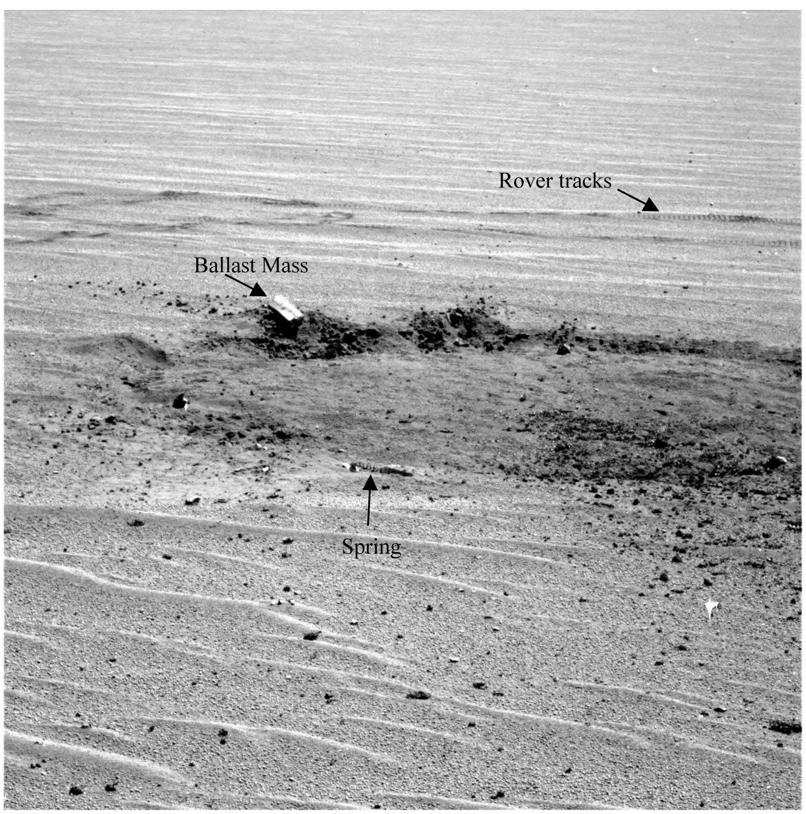

Figure 21: The impact divot and various heatshield hardware

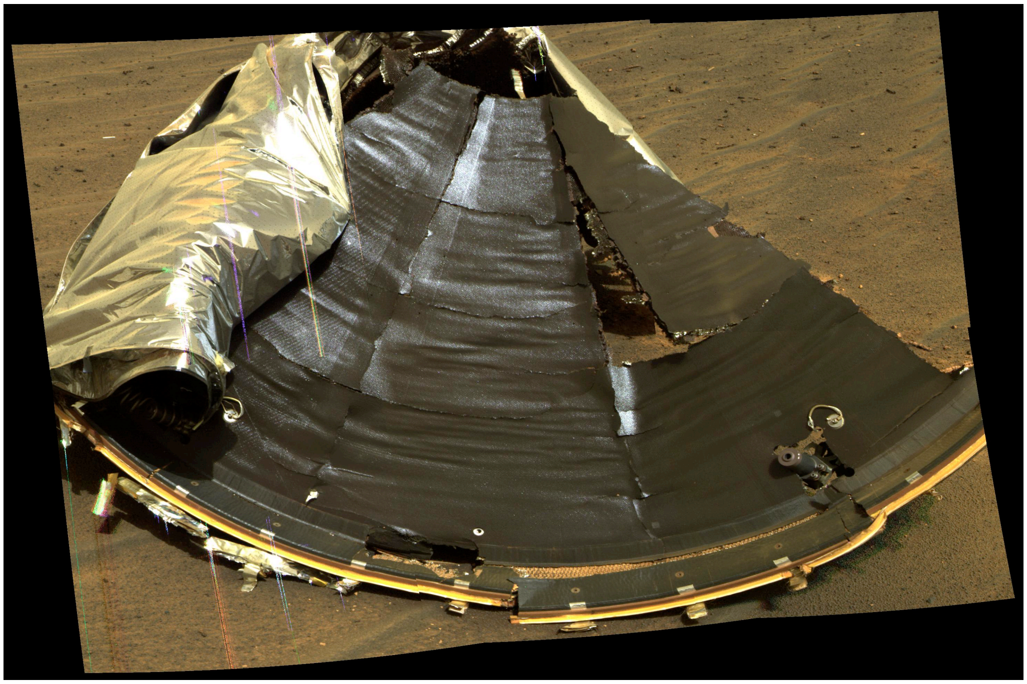

Figure 22: Heatshield structure and main seal

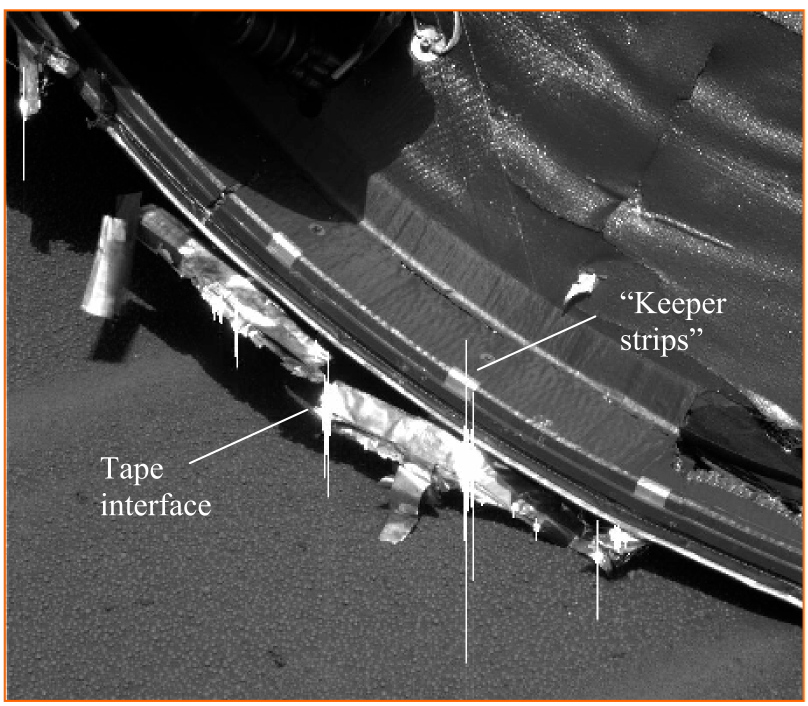

Figure 23: Thermal blanket "keeper strips" and tape interface for external thermal blanket remnants

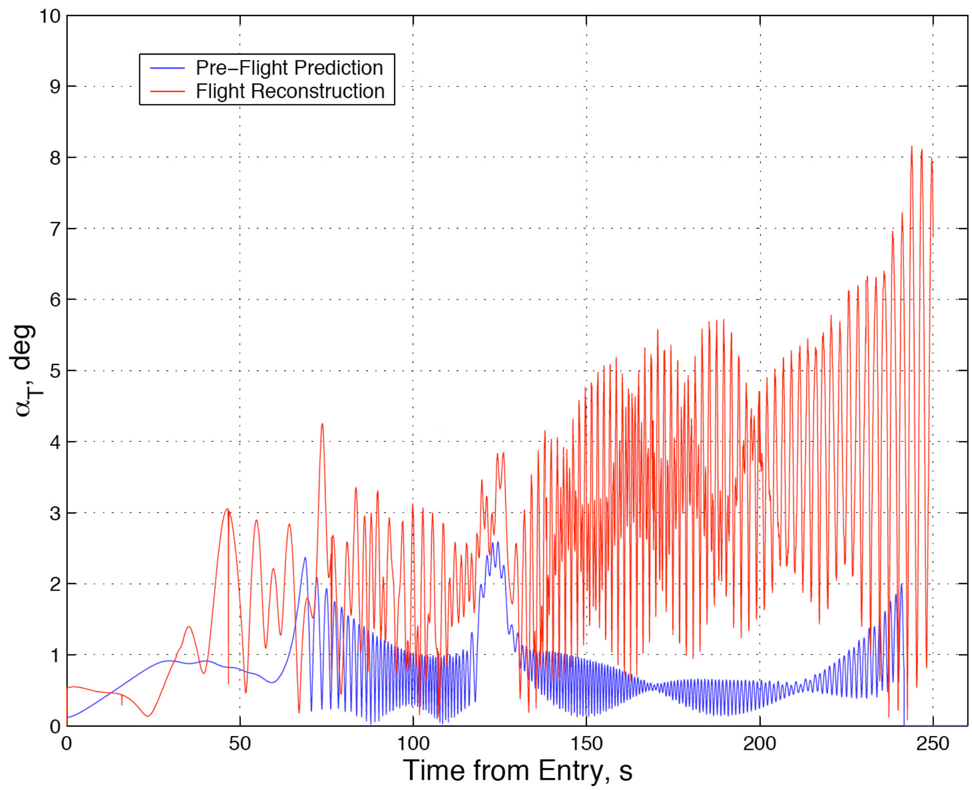

Figure 24: *Opportunity* entry attitude reconstruction (NASA Langley Research Center)

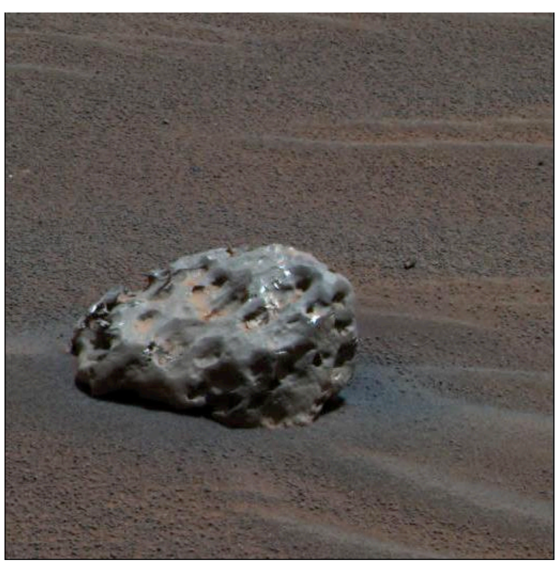

Figure 25: “Heatshield Rock”; the first ever meteorite identified on another planet