Mars Exploration Rover Parachute Decelerator System Program Overview

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Abstract

In the Mars Exploration Rover (MER) Mission, NASA returns to the red planet, following the extremely successful Mars Pathfinder in 1997The mission will send two lander-rovers to the surface of Mars with separate launches in May and June, 2003. This paper describes the Parachute Decelerator System for the entry vehicle. A Disk-Gap-Band parachute will be deployed at approximately 10 km altitude and Mach 2. Key considerations leading to the selection and design of the parachute and Mortar Deployment Subsystem are described. The paper also includes brief descriptions of developed hardware and significant testing conducted to validate and qualify the system. References to other papers that describe various aspects in more detail are provided. Major technical challenges were overcome and are briefly described.

Mission Description

In 2003, two spacecraft will be launched to send two rovers to separate landing sites on the surface of Mars. The two rovers are identical, each capable of traveling up to 100 meters each Martian day (sol) with an expected life of at least 90 sols. Each rover contains a suite of instruments to search for evidence to determine if liquid water existed in the past.

The Entry, Descent, and Landing (EDL) system for MER is based on the Mars Pathfinder EDL system, but it's capability has been extended to accommodate the MER payload. The entry and landing sequence is shown in Figure 1. Although the original MER system baselined a MPF parachute with the same configuration and a 12.7 m reference diameter, the final chute is now a 14.1 m diameter chute with a slightly shorter band. These changes have been made to maximize the drag area of the chute while maintaining Pathfinder-like stability. Two reasons drove the need for increased drag area: 1) the MER payload mass increased from 650 kg to 840 kg and 2) the previous estimate of the drag coefficient for the MPF parachute was found to be low. These differences meant additional drag area was needed from the parachute to meet requirements for heatshield separation and the descent timeline.[1,2,3]

System Description

Disk Gap Band Main Parachute

The main parachute for the MER mission is a 14.1 meter diameter Disk Gap Band (DGB) (Figure 2). The configuration of the parachute is similar to that used for the Mars Pathfinder Mission (MPF), with slight alteration. If one considers the DGB qualified for the Viking missions of the 1970's as a "standard," then the MPF DGB band is approximately 1.9 times the length of the "standard." The DGB used for the MER mission has a band length that is 1.8 times the "standard." Both the MPF and MER parachutes used the extended band design to optimize the aerodynamic moment coefficient, thereby reducing parachute oscillation and improving system descent stability. Nearly all other features of the MER DGB, such as line length, weave orientation, etc., followed the design criteria of the MPF and Viking "standard."

The MER DGB construction has 48 gores, a disk diameter of 8.9 meters, a band length of 3.0 meters, a gap of 0.54 meters and suspension lines 24.0 meters in length. In addition, there is a 12-leg riser extension designed similar to the MPF riser that will accept up to 12 rotations of the forebody relative to the parachute before imparting any significant torque force to the suspension lines. This design eliminated the need for a swivel. A titanium link was developed to attach the riser to the bridle. The link is low mass (~380 grams) and very strong (over 213.5 kN strength). Due to pressure packing volume constraints, the link was also designed to have a low profile (~ 27 mm thick) and smooth, rounded edges. The Bridle Assembly is a three-leg bridle with integrated sabot capture bag. Each leg is made from two-ply 15,000 pound 1 inch Kevlar™ web. The integral bag was developed during the MPF program and serves to restrain the mortar sabot from

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becoming a damaging projectile. The resultant deployed system is approximately 10 forebody diameters aft of the spacecraft, thereby avoiding most wake disturbances. The deployment bag, used to contain the packed parachute in the mortar, is designed to remain attached to the vent band of the canopy via a 2500 lb Kevlar™ web loop. The attached bag is similar to previous applications and should prevent re-contact damage. The deployment bag is lined with Teflon™ fabric to prevent friction damage during deployment, especially at non-zero angles of attack.

The canopy is a hybrid fabric construction, with the disk made from nylon and the band made from polyester. The polyester fabric is the same as was used for the MPF and Mars Polar Lander (MPL) missions. The nylon is a standard, lightweight canopy material, Mil-C-7020 Type I. The vent band material is Kevlar™ 1 inch, 4000 pound web. The disk skirt and band upper and lower hems are reinforced with Kevlar™ 1 inch, 2500 pound web. The suspension lines are constructed of braided, 1200 pound Kevlar™ cord. The suspension lines are a continuous design, running from riser confluence, through the band seam, across the gap, through the disk seam, across the vent and back to an opposing riser leg confluence. The continuous line design eliminates many joints and reduces the overall weight of the canopy. Suspension line reinforcements (v-tabs) are included at the disk skirt and band skirt to improve load distribution during deployment and inflation dynamics.

Mortar Deployment Subsystem

The Mortar Deployment Subsystem (MDS) was manufactured by General Dynamics Ordnance and Tactical Systems (GD-OTS) in Redmond, WA. The MDS is similar to that used for the MPF mission with some significant changes. Both MPF and MER mortars are classified as "blow down" systems, with most of the propellant burned in the gas generator prior to release into the mortar. This type of system was chosen for its fairly consistent response over a large range of temperatures. The diameter of the MER mortar was increased to accommodate the larger parachute and the design was altered in order to produce the lowest feasible mass. In addition, rail bosses were added at three locations to provide a guide for the lander during the separation event (Figures 3 and 4). The volume constraints of the spacecraft require that the MDS protrude into the lander during cruise to Mars. During EDL, the lander separates from the backshell while the system descends under canopy. Lander and spacecraft relative movement during separation could generate damage to the lander if not controlled by these rails.

MDS mass reduction efforts resulted in a mass of approximately 7.4 (I think this is closer to 7.1)kilograms, which compared well with the smaller-sized MPF MDS at a mass of 7.6 kilograms. The mortar was machined from a solid, hand forged, aluminum billet. The rail bosses are integral to the tube and provide fastener holes for the JPL-provided rails. The top of the mortar is similar to MPF, with three titanium bridle attachment pins and locations for backshell interface (attachment to the spacecraft). The base of the mortar provides for attachment of the Gas Generator power device.

The stainless steel Gas Generator (GG) provides the high-pressure gas used to propel the packed parachute from the spacecraft in a velocity range between 30.5 and 42.7 meters per second. The GG is ignited by two NASA Standard Initiators (NSI), but is qualified to operate with one 80% output NSI. Vasas[4] provides further information on the Mortar, Gas Generator, other components, and development of the system.

Cover

The cover provides protection for the packed parachute from launch and Martian atmospheric entry damage. JPL-supplied SIRCA is bonded to the outside surface of the cover to provide insulation from Mars entry aerodynamic heating. The cover is not retained and was designed to have the lowest ballistic coefficient possible in order to preclude re-contact with the decelerating parachute/spacecraft combination. Unlike MPF, the cover for the MER mission is constructed of composite, carbon-fiber material. This cover is extremely lightweight and separates from the MDS via tear-out at three small fastener locations.

Program Chronology

The MER PDS Program spanned 31 months and required significant effort by an integrated product development team. For discussion purposes, the program can be divided into three phases: Study Effort, Development, and Qualification. Each Phase is described in the following paragraphs.

Study Effort

The PDS portion of the MER Mission began in August of 2000 with a presentation to JPL on the capabilities of Pioneer and the history of experience from MPF, MPL, and the terminated Mars 2001 PDS. A study effort contract was awarded to research additional information on the above referenced programs and conduct analyses on the

performance of an MPF "build-to-print" system for the MER mission. Data from this effort, combined with a JPL-conducted "Tiger Team" review, led to the conclusion that the MPF "build-to-print" system was inadequate.

The drag coefficient estimate for the MPF DGB parachute was reported to range from 0.40 to 0.45 during the MPF program. Early examination of the flight data collected during the MPF mission suggested that the range was closer to 0.35 to 0.46. Taking the low estimate into account along with the higher mass of the MER suspended system, it became clear that a build to print MPF parachute did not meet the requirements for heatshield separation and had insufficient margin on terminal descent velocity for the RAD impulse. The MER system needed a parachute with increased drag area and with comparable stability.. In addition, a decision was made to explore intermediate configurations between MPF and Viking to determine whether an increase in drag could be obtained while still meeting the stability requirements.

The study effort was increased to conduct design trade analyses and additional testing to obtain quantitative data necessary to conduct more detailed performance analyses. This additional data included tested values for drag and moment coefficients. Coincident with this effort, NASA Langley conducted a more extensive analysis of the flight data from MPF in order to ascertain the "true" Martian canopy drag performance.[5] Because Mars flight experience is a critical consideration, all design trades were based on disk-gap-band variants. Variations included alteration of gap height, band length, tapered band, and others.

Four designs were chosen for a simple aerial test program intended to rate relative performance. The test program is described in Taeger.[6] Results from this program corroborated earlier trades analyses and resulted in the selection of two canopies for further wind tunnel testing (Figure 5): MPF and a variant with band length approximately 1.6 times the Viking standard. A third wind tunnel model design, based on the Viking standard, was constructed in order to compare this wind tunnel test data to that conducted during the Viking program. Considerable effort was made to generate the most accurate scaled models feasible. An unfortunate side effect of this scaling was that the models were subject to significant wear during the test process and had limited test life. Cruz[7] provides details for this wind tunnel test program.

Simultaneous with the aerial and wind tunnel efforts was an optimization analysis to reduce the overall weight of the parachute system. Zylon™ material was considered and cord/web specifications were generated for joint efficiency study. During the course of the study and early development efforts, it was determined that Zylon™ material exhibited significant joint degradation during pressure packing/heatset and that not enough use history existed for it to be included in the MER PDS program.

Weight reduction efforts for the MDS resulted in the decision to machine the mortar from a single billet and the use of a titanium GG. Development testing indicated that the titanium GG was unsuitable for this application. Excessive erosion of the gas orifices and design alterations to meet stress requirements resulted in a titanium GG that was not mass efficient. Further design and test activity led to the stainless steel GG described earlier.[4]

Opening loads analysis for the parachute design was completed by trajectory simulation using the range of predicted entry conditions for the MER spacecraft. The trajectory simulation was developed from a multi-degree of freedom numerical model of the spacecraft and parachute combination. Simulation inputs included spacecraft and parachute geometric, inertial, elastic, and aerodynamic parameters. The initial simulation was a variant of the same computer code used for MPF.[8] During the Preliminary Design Review, the Mach efficiency curve, originally developed in the MPF program,was found to have errors.. This curve relates the relative drag performance of the canopy during transition through the expected Mach number regime. The error in the MPF curve resulted in a low estimate of the parachute inflation loads which drives the parachute strength requirements. The PAC, JPL, and LaRC team conducted an extensive review of the development of the MPF Mach efficiency curve and generated a corrected curve for MER. The resulting opening loads analysis was used to develop the parachute material properties and mortar mechanical interface constraints. Additional analyses were conducted by NASA Langley, Sandia National Laboratories, ASI, and Irvin and verified that the Pioneer analysis provided a conservative and accurate result. Further verification also included confirmation of the Viking and MPF mission performance analysis match. Cruz[9] provides additional information on the analyses and their relation to the MER structural test programs.

At the conclusion of the study effort in the summer of 2001, a 15.1 meter diameter, MPF-style DGB (~1.9 x standard band) was chosen. This configuration provided the maximum drag area

allowed by volume/mass constraints with the required stability demonstrated by the MPF design.

Development Effort

The development effort began with the construction of test articles. Initial prototypes of the canopy were produced to ascertain and refine manufacturing documentation. In an effort to advance the schedule, Pioneer conducted two programmer-deploy structural tests with the prototype canopies. Both tests resulted in canopy failures attributed to test set-up. Analysis of the failure modes did provide some information regarding the performance of the canopy fabric and structure. As a result of the test failure analyses, four designs were chosen for planned structural testing. The designs differed in selection of fabric materials in both the disk and the band.

Significant effort was expended in the design and instrumentation of the test vehicles intended for structural testing as described in Taeger[6] and Way.[10] It was expected that the testing would encompass both the requirement for structural load and deployment of the system at maximum forebody angle of attack.. Structural testing began in May of 2002 and was halted after the first two tests resulted in generated forces significantly below the designed inflation loading. It was immediately evident that the vehicle mass was insufficient to develop the "infinite mass" profile necessary for this type testing. The vehicles were redesigned and testing resumed in June.

Testing with the revised vehicle mass resulted in structural overloads due to the omission of entrained air inertial effects in pre-test predictions. Subsequent testing resulted in the development of the desired loads, but continued canopy structural failure. These results led to the change to stronger hem reinforcements, three canopy configurations, and increased fidelity stress analyses. Historical research and failure analyses confirmed that the highest stress region of this canopy type is located at the lower band. The three configurations differed in size and band length in order to maintain the desired mortar ejected mass and minimum drag area. Each configuration contained alternate strength fabrics in the disk and band regions.

Although the aerial drop tests are capable of generating the conditions necessary to evaluate the parachute strength, the uncertainty in initial conditions and the natural variation in parachute inflation make it difficult to reliably obtain the desired loads to meet the test requirements. Because of this the number of drop tests planned to obtain the required data needed to take into account no-tests where the test objectives are not met. Since the redesign to strengthen the parachute led to schedule and resource concerns a more reliable method of conducting the strength test was investigated. Discussions with JPL indicated that the National Full-Scale Aerodynamics Complex at NASA Ames might be available for use as an alternative to aerial drop testing. Engineering assessment of the suitability of NASA Ames began in mid September and resulted in the selection of the wind tunnel over aerial testing. Structural testing re-started in the 80 by 120 foot wind tunnel and concluded in the month of October (Figure 6). A description of this test program and advantages of this method over aerial testing can be found in Zell.[11] The canopy configuration used in the last test was chosen as the flight baseline described earlier.

Mortar development continued in parallel with the above described efforts. A "workhorse" mortar and gas generator were manufactured to test and refine the expected designs. During the course of development and initial flight-like mortar manufacture, it was found that the mass-saving design was more difficult to manufacture than anticipated. Significant manufacturing and machining process development was required to produce the final design. The additional machining and stress-relief cycles resulted in an approximate 22% success rate for the final design. Additional information can be found in Vasas.[4]

Qualification Effort

Because of the schedule delay created by three separate parachute structural test programs, production of the canopies for the actual mission occurred much later in the program than anticipated. This required the division of the qualification of the flight system. The MDS would be qualified separately from the canopies, using mass simulators. With this division, the canopies could be manufactured at the same time as the qualification of the MDS. Qualification testing was limited to static firing at ambient and cold temperatures, after exposure to vibration and thermal cycling. The flight lot canopies were qualified by an additional wind tunnel test. This test used one flight lot canopy at the same conditions as the last development Ames test. Canopy qualification resulted in the desired peak inflation load sustained with zero canopy damage. The last development test generated 112,540 newtons (25,300 lbf) versus the qualification test 112,095 newtons (25,200 lbf) (estimated peak Mars inflation ~78,290 newtons (17,600 lbf)). This result confirmed that the design was robust and that the testing was repeatable.

The MDS was qualified in February, 2003, with two static firings.

Conclusion

The parachute for the MER PDS utilized the heritage of the Viking and Mars Pathfinder programs to the maximum extent possible. During the course of the program, advances in the technology used to analyze, test, and measure performance were discovered and applied to optimize the MER parachute and mortar design. For comparison, the Viking DGB weighed approximately 47 kg and was designed to withstand nearly identical Mars inflation loads as the MER DGB, which weighs approximately 15.4 kg.

The MER PDS Team produced what is believed to be a very robust and well-tested design. The early (NASA Langley) wind tunnel and aerial efforts served to provide significantly more quantitative data on the performance characteristics of all of the designs tested. The later (NASA Ames) wind tunnel efforts highlighted the usefulness of that test facility for the application of structural qualification of parachute designs. The aerial structural testing, and its subsequent analysis, highlighted the fact that the maximum fabric stress in this design is located in the lower band region.

The hardware for this system included several design challenges. Although titanium ordnance devices are not new, the application of this material proved unsuitable for this program. The efforts to reduce the mass of the mortar produced a design that yielded a very low machining success rate. Additionally, Zylon™ materials appear to exhibit significant degradation due to pressure packing/heat sterilization.

The authors wish to acknowledge the contribution of all of the people at Pioneer, JPL, NASA Langley, NASA Ames, Sandia, and private contractors for their hard work and long hours on a most challenging parachute program.

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EDL Process

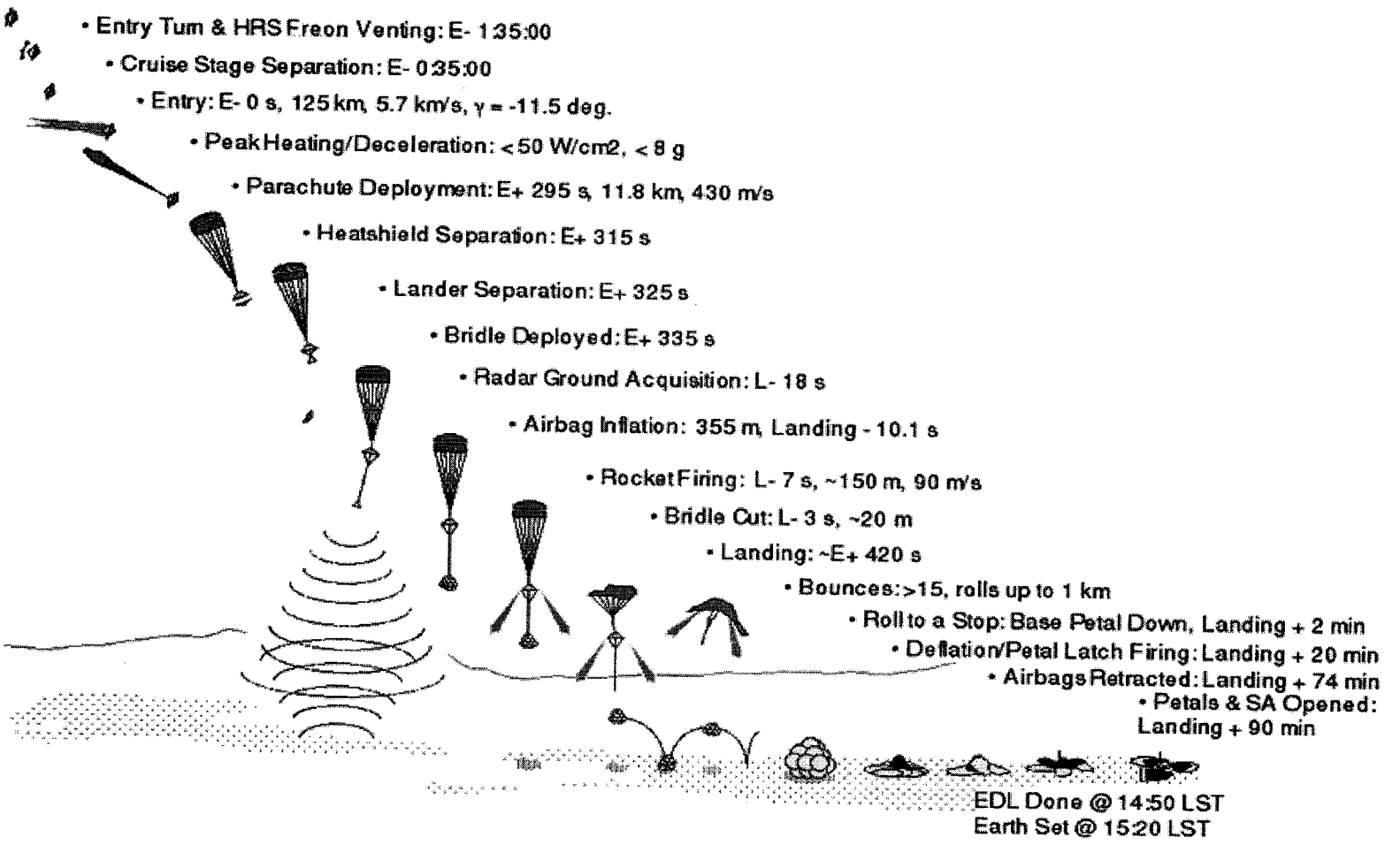

Figure 1 EDL Sequence
(Image courtesy of NASA)

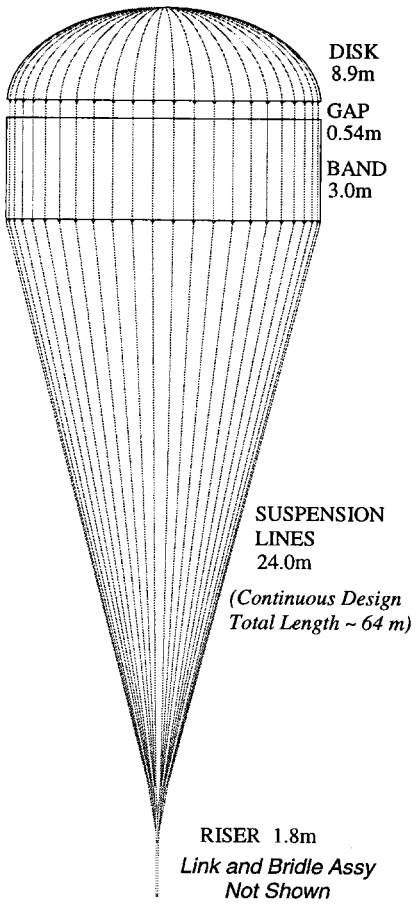

Figure 2 MER PDS Parachute Sketch (Shown with elements approximately to scale)

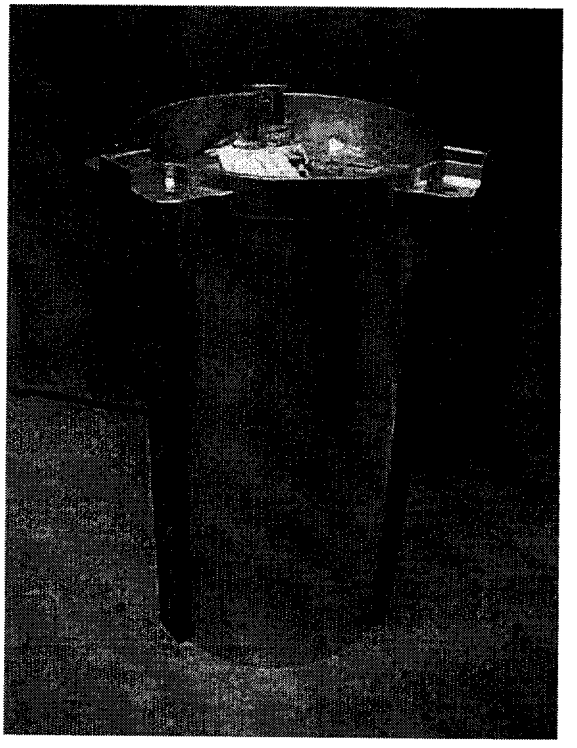

Figure 3 MER Mortar Deployment Subsystem (with pack, cover not shown)

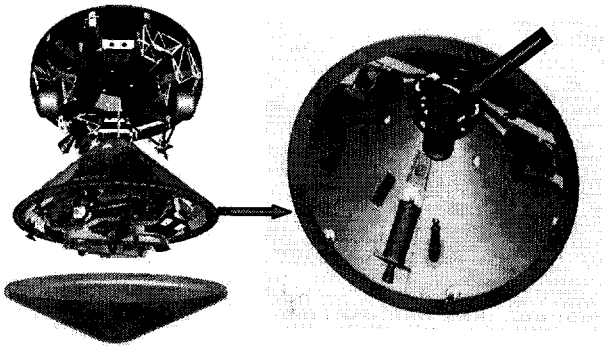

Figure 4 MER PDS Installed in Spacecraft Backshell (Arrow at upper right indicates canister) (Courtesy NASA)

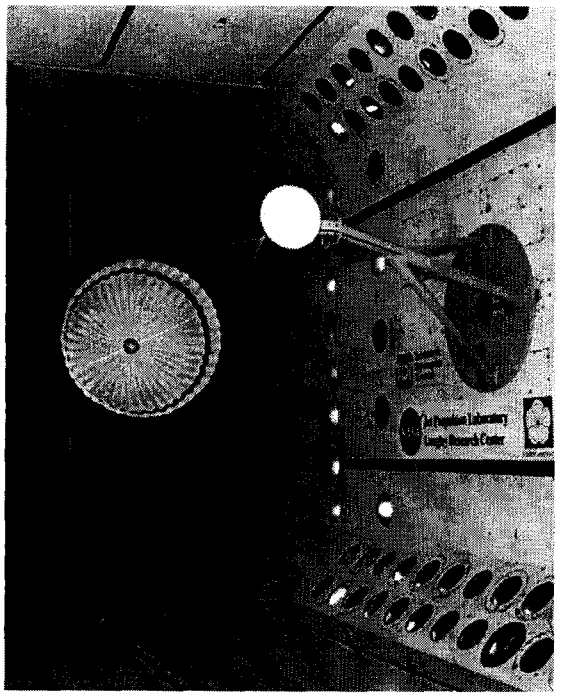

Figure 5 **Scale Model Wind Tunnel Testing at NASA Langley**
(Courtesy NASA)

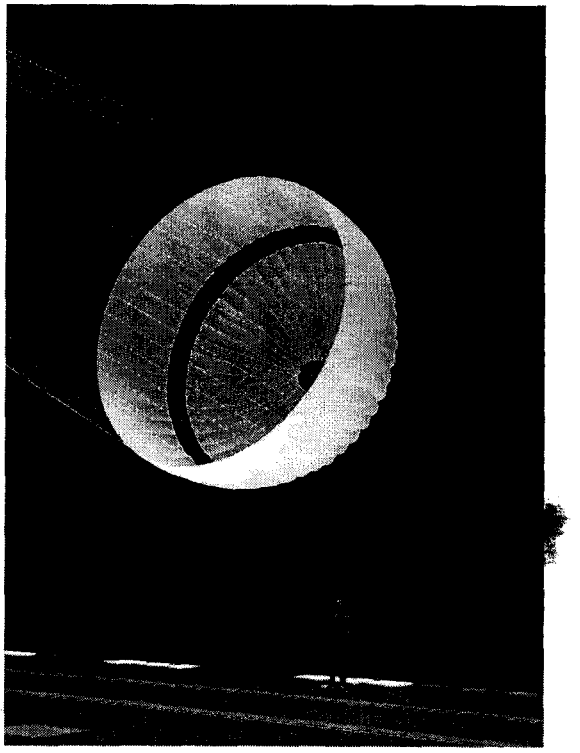

Figure 6 **Full Scale Structural Wind Tunnel Testing at NASA Ames**
(Courtesy NASA)