An Overview of the Mars Science Laboratory Parachute Decelerator System

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Abstract—In 2010 the Mars Science Laboratory (MSL) mission will deliver NASA's largest and most capable rover to the surface of Mars. MSL will explore previously unattainable landing sites due to the implementation of a high precision Entry, Descent, and Landing (EDL) system. The Parachute Decelerator System (PDS) is an integral part of the EDL system, providing a mass and volume efficient source of aerodynamic drag to decelerate the entry vehicle from Mach 2 to subsonic speeds, prior to final propulsive descent to the surface. The PDS for MSL is a mortar-deployed 19.7m Viking type Disk-Gap-Band (DGB) parachute, chosen to meet the EDL timeline requirements and to utilize the heritage parachute systems from Viking, Mars Pathfinder, Mars Exploration Rover, and Phoenix NASA Mars Lander Programs. The preliminary design of the parachute soft goods, including materials selection, stress analysis, fabrication approach and development testing, will be discussed. The preliminary design of the mortar deployment system, including mortar system sizing and performance predictions, gas generator design, and development mortar testing, will also be presented. [1 2]

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[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE.
[2] IEEEAC paper #1432, Version 2, Updated December 25, 2006

1. INTRODUCTION

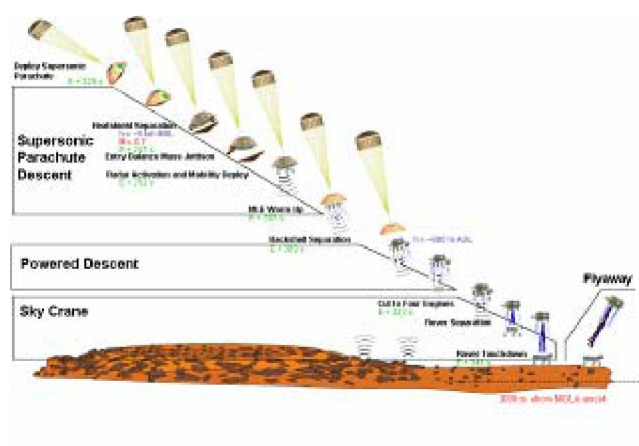

Figure 1. EDL Timeline

The Mars Science Laboratory (MSL) is NASA's next rover mission to Mars, scheduled to reach the red planet in 2010. Its goal is to determine if microbial life can and/or did exist on the planet's surface. MSL will deliver the largest and most capable rover ever developed by NASA, enabling in-situ analysis of Martian rocks and soil. The Entry, Descent and Landing (EDL) system of MSL will enable access to previously unattainable landing sites up to 2 km above the gravitational equipotential reference surface, up to 60 degrees from the equator, and with a precision of 10 km from the designated surface target [1]. To enable this landing site capability, MSL will expand upon the previous EDL technologies flown by Viking, Mars Pathfinder and Mars Exploration Rover, in addition to pioneering new technologies and architectures, such as the sky crane maneuver used to lower the rover to the surface. The Parachute Decelerator System (PDS) is an integral part of the EDL system, as it provides aerodynamic drag to decelerate the entry vehicle from supersonic to subsonic speeds, provides the required difference in ballistic coefficient for the heat shield separation event, and places the rover in the appropriate initial state for starting powered descent. Derived from Viking heritage, the PDS consists of a mortar-deployed, 19.7 m Disk-Gap-Band (DGB) parachute. This will be the largest parachute to be deployed on Mars. A 19.7m parachute was chosen to provide a closer match to Viking heritage-scaling and trajectory characteristics. Specifically, a 19.7m parachute limits the time above Mach 1.5, maintains the Viking capsule-to-parachute diameter relationship, decreases the on-chute ballistic coefficient, and provides the required timeline and altitude margins to complete the EDL sequence.

The MSL parachute system will deploy at Mach 2.2 at a dynamic pressure of 650 Pa [1]. Its supersonic trajectory is similar to that of Viking Balloon Launched Drop Test (BLDT) AV1 and AV4, enabling direct comparison of BLDT flight tests for the determination of drag and peak inflation load. The parachute spends approximately 5 seconds above Mach 1.5, a flow regime observed in previous flight tests to induce significant parachute fabric dynamics, including collapse and re-inflation of the canopy. This will be discussed further in section 5.

2. PARACHUTE SYSTEM

Parameter	Value
Nominal Diameter (D_o)	19.7 m
Disk Diameter	$0.72D_o$
Reference Area (S_o)	$\frac{1}{4} \pi D_o^2$
Geometric Porosity (Area)	12.5%
Vent Diameter	$0.07\ D_o$
Band Height	$0.121\ D_o$
Gap Height	$0.042\ D_o$
x/d	10
Suspension Line Length	$1.7\ D_o$

Table 1. Parachute Dimensions [2]

The MSL parachute is a 19.7 m nominal diameter Disk-Gap-Band parachute. The key design drivers for the MSL parachute are a peak inflation load of 286 kN, the ability to withstand repeated loading (10 cycles) associated with supersonic parachute dynamics, and a multi bridle that can withstand the full inflation load in each leg. The geometric scaling of the parachute is identical to that of the Viking parachute system and is shown in table 1. This differs from the Mars Exploration Rover (MER) and Mars Pathfinder (MPF) parachutes which increased the band length from the Viking standard scaling for mission specific stability requirements [4]. The MSL capsule scaling parameters are also very similar to the Viking configuration and were selected to create a similar level of capsule wake interaction with the parachute flow field. The non-dimensional trailing distance (x/d), as defined from the band leading edge to entry vehicle (capsule) maximum diameter, is 10, as compared to 8.5 for the Viking parachute. Similarly, the capsule diameter to nominal diameter ratio (d/D_o) is 0.228, versus 0.223 for Viking. The MSL parachute uses the same geometric scaling as the Viking configuration in order to utilize the existing supersonic wind tunnel and high altitude earth drop test data for its qualification.

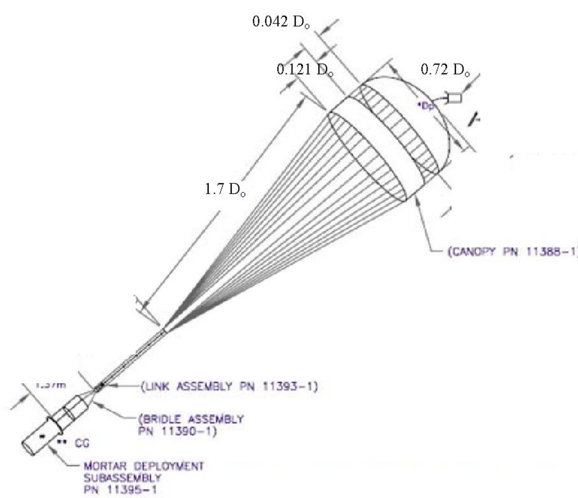

Figure 2. MSL Canopy Schematic

The MSL parachute design is an 80 gore canopy with nylon broadloom fabric and a Kevlar™ structural grid. The gore count was chosen to reduce fabric stress allowing the use of light weight fabric, to provide an efficient division of lines for the riser leg interface, and to provide additional robustness for repeated loading observed during supersonic operation. V-tabs are placed at every suspension line to hem interface in order to maintain load path stability and to preclude premature separation of the joints. The structural grid utilizes a continuous line construction technique similar to the MER and Phoenix parachutes, to reduce the number of joints and increase overall structural capacity and stability.

A low mass and profile titanium link, similar to the MER design, attaches the suspension line riser leg interface to the multi bridle. The multi bridle consists of three legs of 8 ply Kevlar™ webbing designed to withstand the peak inflation load in a single leg. The multi bridle connects to the parachute support structure ring (Figure 3) providing an efficient load transfer to the spacecraft and decoupling the peak inflation load from the mortar canister.

The sabot capture bag assembly is similar to that developed during the MER and Phoenix programs. Its primary function is to capture the sabot after mortar fire, to prevent it from damaging the canopy. It is also used to retain the parachute pack during exposure to launch loads. The assembly differs from those previously developed in that it is not integrated to the multi bridle. It is directly connected to the mortar canister with a three pin interface at the top of the canister.

3. MORTAR DEPLOYMENT SYSTEM

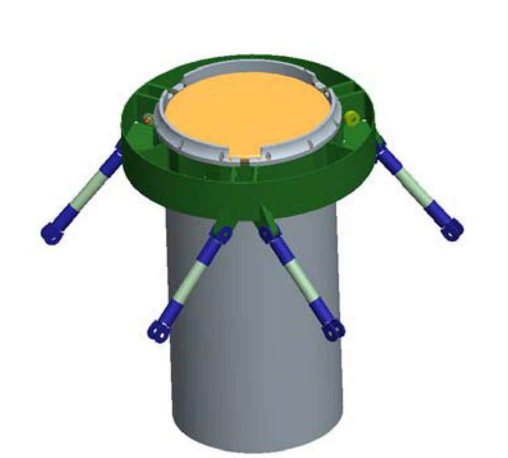

Figure 3. Mortar Canister in Parachute Support Structure Ring

The purpose of the Mortar Deployment Subsystem (MDS) is to eject the parachute pack at a specific ejection velocity range in order to enable successful bag strip and line stretch without line tangling or damage to the parachute pack. The mortar reaction load, a compressive load, must also be within a range acceptable to interfacing spacecraft structure. The MSL MDS is similar in design and function to that developed for MPF, MER, and Phoenix Mars programs [4]. The mortar is a blow down device, with no active flow rate control and most of the propellant burned within the gas generator prior to release into the mortar. A blow down system was chosen for its consistent performance over a wide range of temperatures, simplicity of design and testing, and heritage use on MPF, MER, and Phoenix.

The MDS consists of the mortar canister, gas generator, sabot and cover. The mortar canister is a 0.5 m by 1 m three-piece aluminum weldment with a machined flange at the top to connect to the parachute support structure ring, and opening at the bottom to connect the Gas Generator (GG). The parachute pack rests inside the mortar canister on top of the sabot. The triple bridle is not connected to the canister, as in previous Mars programs, enabling a low mass and simple design. The parachute pack is pressure-packed inside a Teflon™-lined, aluminized Kevlar™ deployment bag. The GG consists of a two-piece, stainless steel, hermetically-sealed pressure vessel. A propellant cartridge housed within the GG is ignited by two NASA standard initiators at the base. The GG utilizes WC 231 ball powder propellant in order to meet the ejection velocity and space heritage requirements. The propellant exits the gas generator via four constant area orifices. Prior to mortar fire, the orifices are covered by brazed on burst disks to create a hermetic seal. At mortar fire these disks are ruptured.

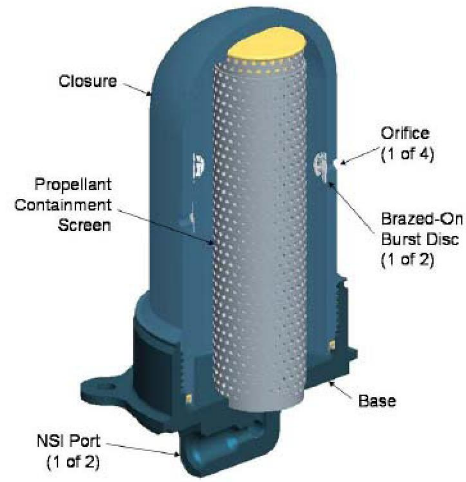

Figure 4. Gas Generator

4. QUALIFICATION PROGRAM

As deployment conditions on Mars are characterized by low atmospheric pressure at supersonic speeds, traditional low altitude, end to end drop testing cannot be used to qualify a parachute system for Mars deployment. The prohibitive cost of high-altitude testing therefore requires the use of heritage or low altitude and ground based tests programs to simulate the different aspects of the parachute. It is convenient to subdivide the qualification of parachute systems into distinct areas that can be individually verified by test, analysis and/or heritage [5]. The five areas of qualification used to subdivide the MSL parachute qualification program are as follows:

1. Deployment
2. Initial Inflation
3. Inflation Strength
4. Supersonic Performance
5. Subsonic Performance

Each of these areas will be addressed as they pertain to the MSL qualification program below.

Deployment

The criteria for mortar deployment is to successfully eject the parachute pack in the required ejection velocity range over the range of environmental conditions expected at deployment and below the allowable reaction load limit for the spacecraft interface. The sabot shall be captured and successful bag strip, parachute unpacking and line stretch shall occur without line tangling or damage to the parachute.

The MSL approach for deployment qualification is three-fold. Functional deployment tests with a pneumatic mortar are performed to demonstrate the orderly deployment process from bag strip to line stretch. Ground based static fire tests of the MDS with a flight like packed parachute are used to demonstrate the GG performance, ejection velocity range, pack ejection, reaction load range, structural integrity of MDS, and sabot capture. The mortar static firings are done under nitrogen purge and over the temperature range expected at deployment on Mars. Full scale wind tunnel testing is used to provide an end to end test of the parachute system from mortar fire to parachute inflation.

A similar approach was used on the MPF and MER programs which were successfully deployed on Mars. The risks due to deviation from actual Mars deployment include gravitational and external atmospheric density differences, but these have negligible effect on mortar performance

Initial Inflation

Initial inflation is defined as the time period from line stretch to full open. The criteria for initial inflation qualification is to fully inflate the parachute without damage to it. As inflation is highly dependent on aerodynamics during deployment (due to capsule wake, dynamics and atmospheric properties) it is not possible to demonstrate initial inflation without a high altitude supersonic test. As this is prohibitively expensive, the MSL approach is to utilize the extensive database of supersonic low density inflations for Viking scale DGB parachutes tested during in high altitude test program in the Viking and pre-Viking era. During the course of the PEPP (Planetary Entry Parachute Program), SPED (Supersonic Parachute Experiment Development) and Viking BLDT testing programs, DGB parachutes of nominal diameters from 9.1 to 19.7 m were demonstrated from Mach 1.1 to Mach 2.6 and from 500 to 750 Pa dynamic pressure at deployment. The successful deployments of Viking Lander, MPF, MERa, and MERb also add to the existing database of successful supersonic DGB parachute inflations. In addition, comparison of the PEPP 19.7 m DGB inflation at Mach 1.56 resembles that of the 16.1 m Viking BLDT at Mach 2.1. This suggests that supersonic inflation at the Mach and size of the MSL deployment is not parachute scale dependent. The primary concern associated with initial inflation is, of course, failure to open. But no Viking-scaled DGB has ever failed to open for demonstrated deployments from Mach 1.1 to 3.0. In

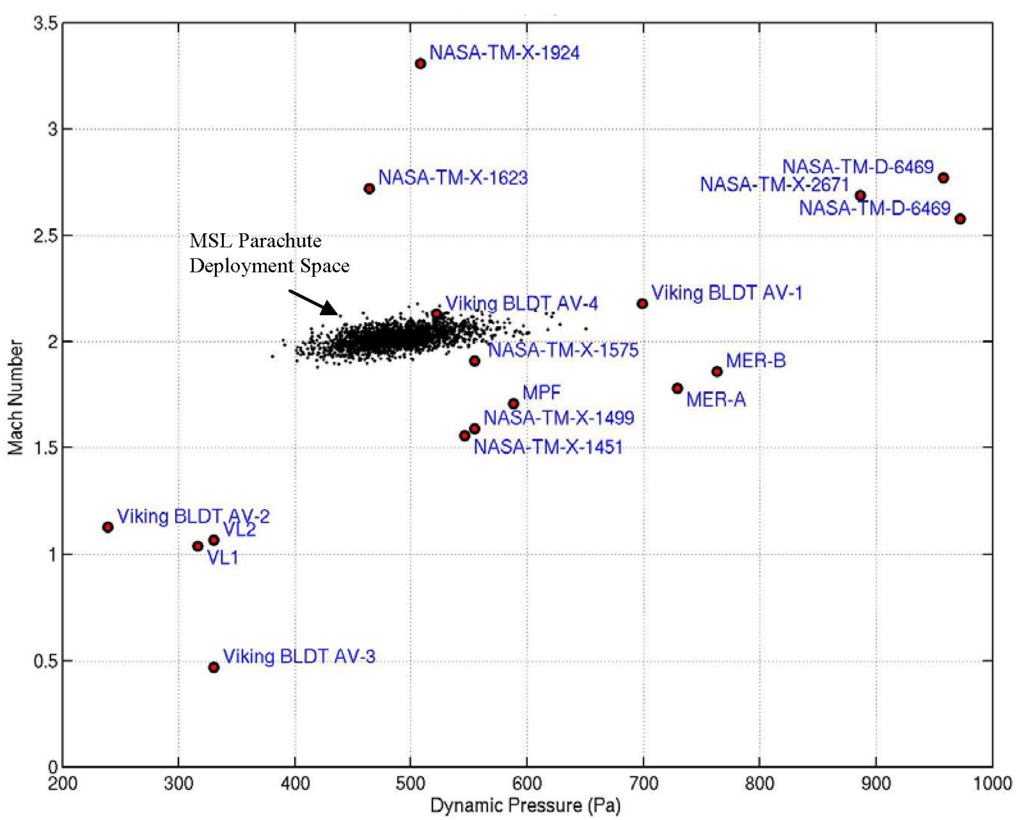

Figure 5. Heritage Viking DGB Deployments

terms of a test program, the MSL parachute will be inflated in the National Full Scale Aerodynamics Complex (NFAC) 80x120 wind tunnel and during low altitude drop tests, but the subsonic environment and inflation time will be dramatically different.

Inflation Strength

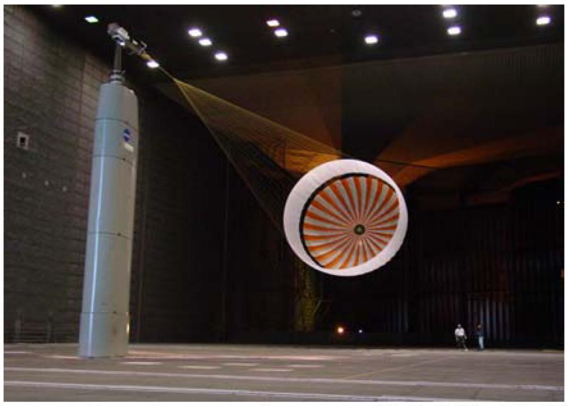

Figure 6. Parachute Testing at the NFAC 80x120 Wind Tunnel

The criterion for inflation strength qualification is to withstand the expected initial peak inflation load with margin and subsequent loading due to supersonic parachute dynamics (area oscillations). The MSL approach for the initial inflation strength qualification is full scale subsonic strength testing at the NFAC 80x120 wind tunnel, as a wind tunnel is able to simulate the infinite mass inflation environment. This test subjects the canopy to a controlled load at the fully inflated condition. This test approach was successfully used for the MER parachute program. Although the MSL parachute is relatively large, compared to the size of the test section, CFD simulations of the parachute test indicate that the rectangular test section does not induce an asymmetrical pressure distribution on the canopy. The MSL approach for repeated loading strength qualification is to subject the canopy to repeated loading in the NFAC test facility. The parachute will have a reefing line installed, enabling it to be reefed between cycles to generate a controlled exposure in the subsequent cycle. The parachute will be subjected to 10 cycles at the peak inflation load. This reefing approach was successfully used on MER in the 80x120 wind tunnel during development testing of the parachute system.

The primary limitation associated with using a subsonic test for strength qualification is the inability to replicate canopy-canopy or canopy-line interactions not recreated in subsonic conditions. Inspection of video data from the Viking BLDT and PEPP suggest that this is not issue compared to the primary inflation loading. Significant margin is built into the design and test load to address all unknowns, a design practice which has proven to be successful on all previous Mars deployments.

Supersonic Performance

The criteria for supersonic performance qualification is to provide predictable drag performance and stability over MSL supersonic trajectory. The MSL approach for qualification is to rely on the existing heritage data set. Drag as a function of Mach number for the Viking scaled DGB has been defined in numerous supersonic subscale wind tunnels tests [6] and the Viking BLDT test program [2][3]. These drag coefficient measurements are compiled into a database and used in Monte Carlo MSL trajectory simulations to ensure that the parachute provides the required drag performance for the EDL timeline [7].

Subsonic Performance

Similar to supersonic performance, the success criteria for subsonic performance qualification are to provide the required drag and stability over the MSL subsonic trajectory. Drag as a function of Mach number has been well defined in subscale wind tunnel test programs and Viking test data. The drag coefficients as a function of Mach number are also used in the MSL Monte Carlo trajectory simulations. The Mach efficiency factor (MEF) curve used for MSL is shown in Figure 7.

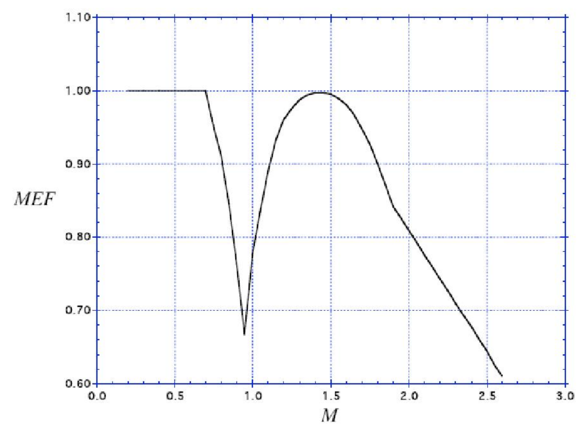

Figure 7. MSL Parachute MEF

5. SUPERSONIC DELTA QUALIFICATION

A 19.7m DGB was chosen as it meets the MSL EDL timeline requirements and also provides the closest geometric scale, aerodynamic and trajectory similarity to the existing Viking BLDT qualification program. The BLDT program qualified a 16.1m Viking DGB parachute system over a range of supersonic deployment conditions up to and including the deployment conditions of the MSL PDS. All previous NASA Mars missions since Viking have deployed DGB parachutes smaller than 16.1 m and have utilized a heritage by similarity to Viking BLDT for their respective supersonic qualification. The MSL parachute will deploy at the upper Mach limit demonstrated by the BLDT, for a longer period of time, and is 22% larger. In addition, a canopy breathing phenomenon (area oscillations) exhibited by DGB parachutes of all sizes, at or above Mach 1.5 operation, has been shown to effect drag performance and canopy loading. To reduce risk to the PDS, MSL has embarked on a multi-phase delta qualification by analysis and subscale supersonic wind tunnel test program to address the fundamental physics of the supersonic operation of DGB parachutes as a function of Mach number, parachute size, and capsule wake interaction. The first phase is Computational Fluid Dynamics (CFD) of a 2% scale rigid parachute canopy and capsule validated by a 2% scale wind tunnel test of the rigid configuration over the MSL Mach and Reynolds (Re) number deployment range in the AMES 9x7 ft Unitary tunnel. Phase two is Fluid Structure Interaction (FSI) analysis of a flexible canopy with capsule validated by 5% scale wind tunnel tests over the MSL deployment Mach and Re range in the GRC 10x10 ft Unitary tunnel. The final phase is the application of the validated FSI tools to the prediction of the full scale parachute performance in Mars type deployment conditions, providing predictions of supersonic drag performance, stability and canopy loading. These will be discussed in more detail below.

CFD and FSI Analyses

Several computational efforts are being undertaken in order to enable a physical understanding of the flow field and parachute dynamics response. In the first phase, computational fluid dynamics simulations, utilizing the US3D code by Dr. Graham Candler at the University of Minnesota, modeled the flow field around a full scale rigid representation of the MSL parachute with capsule. Although rigid bodies cannot be deformed by the variations in pressure as a flexible parachute can, the simulations did predict a highly unsteady but cyclical flow field (Figure 8). The simulations indicate that the cyclic nature of the flow is due to the unsteady subsonic flow from the capsule wake, inducing oscillations of the parachute's bow shock. This resulted in highly variable pressure distribution within the parachute canopy and periodic pressure reversals in the band region. Pressure reversals are representative of potential canopy in-folds if the body were flexible or a fabric. Although these initial results are encouraging and aerodynamically sound, they need to be validated quantitatively by experiment before they can be used as a predictive tool for the MSL parachute. Therefore, an experiment of a 2.7% scale rigid MSL parachute with capsule is underway to obtain time and spatially resolved measurements of velocity in the capsule wake and parachute bow shock region, as well as pressure distributions and drag inside the canopy.

The second phase of the computational effort is fluid structure interaction analysis by the University of Minnesota (Dr. Graham Candler) and University of Illinois Urban Champagne (Dr. Carlos Pantano) where the CFD solver will be coupled to a structural model of the parachute. As with the CFD code, this too will need to be validated and a 5% scale test program with flexible parachutes is planned for the summer of 2007 in the NASA GRC 10x10 Unitary tunnel.

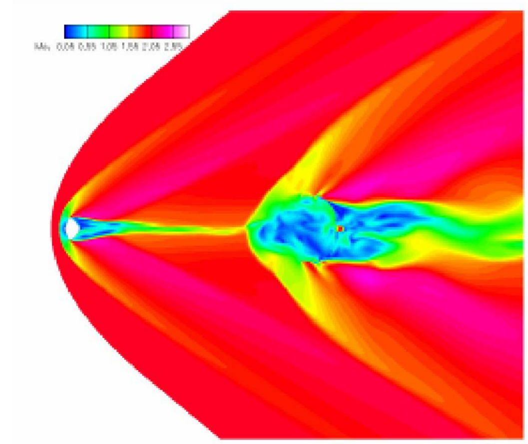

Figure 8. Rigid Parachute with Capsule Flow Field at Mach 2.0

Wind Tunnel Test Programs

Two wind tunnel test programs are underway to validate the CFD and then FSI codes being developed for MSL. Test conditions are chosen to match the Reynold's number and Mach number of the Mars deployment conditions. Geometry scaling of the test articles is chosen to match the flight configuration.

The first test program is a 2.7% scale rigid parachute with aeroshell test being conducted in the NASA AMES 9x7 Unitary tunnel, which is capable of variable pressure operation. The intent of the test program is to provide quantitative data of the aerodynamics of the parachute with capsule flow field as a function of Mach number and trailing distance in the range of Mach 1.5 to 2.5 and x/d from 10 to 14. The test will explore three configurations: capsule only, canopy only, and capsule with canopy. This will render a piecewise understanding of the flow field. Rigid Body CFD simulations of the test have been used to: ensure that the configuration will replicate the physics of interest, minimize test article mounting arrangement interference with the flow field, and size the test configuration such that all shocks reflect downstream of the canopy. The data to be collected from the test includes:

1. Particle Image Velocimetry (PIV)

    a. time and spatially resolved measurements of three components of velocity in the capsule wake to compare to simulations of the turbulent wake expansion and unsteadiness.

b. Time and spatially resolved measurements of three component velocity of the parachute bow shock region to compare to simulations of the rigid parachute with and without capsule.

2. Force balance - time resolved measurements of drag on the rigid canopy to compare to predicted drag.

3. High speed pressure transducers – the rigid canopy is equipped with multiple high speed pressure transducers to measure the internal and external pressure in/on the canopy at discrete spatial locations. These time resolved measurements will be compared to predictions for pressure in these same locations.

4. Schlieren – Interferometric video of the parachute bow shock oscillation frequency and standoff distance to compare to CFD simulations of the experiment.

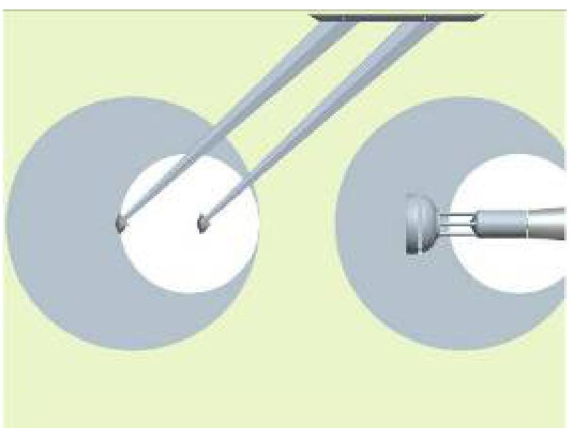

Figure 9. AMES 9x7 Test Configuration

The second test program is a 5% scale flexible parachute with MSL capsule in the NASA GRC 10x10 variable pressure Unitary tunnel to validate the FSI codes under development. As with the 9x7 test, test conditions are set to match the Mach and Reynolds number of the anticipated Mars deployment conditions. The parachute will be tested in laterally constrained and unconstrained configurations. Parachute constraint will be accomplished via a bushing through the apex of the canopy and increasing vent area to account for bushing blockage, similar to the approach used during the MER TDT tests [8]. This test will use PIV and Schlieren to measure the parachute bow shock oscillation and standoff distance, as well as load cell measurements of time resolved drag. The test will also use 3D photgrammetry to provide a quantitative measure of the parachute fabric motion in space and time allowing determination of fabric stress.

6. CONCLUSIONS

The Mars Science laboratory Parachute Decelerator System is a key component of the EDL system. It will be the largest extraterrestrial parachute ever flown and is to be deployed at a Mach number in excess of any previous Mars Lander. The parachute development effort will also expand upon the existing design and construction techniques developed for MER and Phoenix parachute programs. The qualification program will develop and validate new computational design tools that will improve upon the understanding of parachutes in supersonic flight and aid in the qualification MSL and future parachute systems for planetary exploration.

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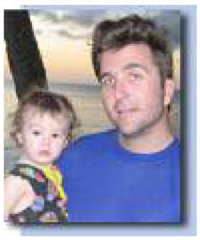
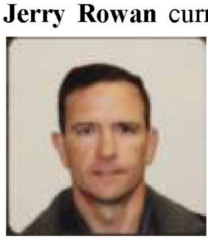
BIOGRAPHY

Dr. Anita Sengupta currently holds the position of the Parachute Decelerator System Contract Technical Manager and Cognizant Engineer for the Mars Science Laboratory Mission at NASA's Jet Propulsion Laboratory. Previously she held the position of risk reduction lead on the Prometheus 1 Ion Thruster System and project manager for the VHITAL Hall Thruster and NEXIS Ion Thruster programs. She received her PhD and MS in Aerospace Engineering from the University of Southern California and BS in Aerospace Engineering from Boston University



Dr. Adam Steltzner currently holds the position of the Mars Science Laboratory Entry Descent and Landing Development Manager at NASA's Jet Propulsion Laboratory. He previously held the position of lead mechanical systems engineer on the Mars Exploration Rover Mission where he worked extensively on the development of the parachute system. He received his PhD in Engineering Physics from the University of Wisconsin Madison, MS in Applied Mechanical Engineering from the California Institute of Technology, and BS is Mechanical Engineering from University of California Davis.

Al Witkowski currently holds the positions of Chief Engineer and Principal Engineer of Space and Special Projects at Pioneer Aerospace Corporation in South Windsor, CT. He has been fortunate to be the person responsible for the parachute systems for every successful landing on the surface of Mars since, and including, Mars Pathfinder in 1997. He was the Test Director for the Mars Pathfinder (MPF) Parachute Decelerator Subsystem (PDS) and Program Manager for Mars Polar Lander, Mars Surveyor 2001, and Mars Exploration Rovers PDS programs. He is currently the Program Manager for the Mars 2007 Phoenix PDS and Mars Science Laboratory PDS. He has a BSAE from Embry-Riddle Aeronautical University and has been working on parachute development programs for over 18 years.



Jerry Rowan currently holds the position of Engineering Manager at Pioneer Aerospace in South Windsor, CT. He has been responsible for the development of the Genesis Drogue Mortar Deployment Subsystem (MDS). He is currently the program manager for the Mars 2007 Phoenix MDS, as well as the Mars Science Laboratory Parachute Decelerator System Deputy Program Manager. He has an MSME from Rensselaer Polytechnic Institute and has been working on parachute development programs for over 10 years.