Preliminary Design of the Cruise, Entry, Descent, and Landing Mechanical Subsystem for MSL

Pamela Hoffman
Tomasso Rivillini
Eric Slimko
Neilesh Dahya
Anthony Agajanian
Jennifer Knight
Anita Sengupta
Benjamin Thoma
Richard Webster
John Gallon
Michael Gradziel
Pamela.J.Hoffman@jpl.nasa.gov
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract—Mars Science Laboratory is a scientific mission to the surface of Mars that would include a rover with 10 science instruments. In order to accomplish this mission, the rover must be transported from Earth to the Martian surface. The mechanical hardware that transports the rover is developed by the Cruise, Entry, Descent, and Landing (CEDL) Mechanical Subsystem Team. This mechanical hardware includes the Cruise Stage Structure, the Aeroshell Subsystem, the Parachute Deceleration Subsystem, the Descent Stage Structure, the Bridle & Umbilical Device, and the pyro and separation devices that allow for the numerous separation events that occur in the EDL sequence. The key challenges for this system lie in the complex configuration (both geometric and subsystem accommodations), multiple unique load cases, and numerous separation events. This paper will describe the preliminary design and key challenges of each of these mechanical assemblies that comprise the CEDL Mechanical Subsystem. [1][2]

TABLE OF CONTENTS

1.0 INTRODUCTION

Mars Science Laboratory (MSL) is a scientific mission to the surface of Mars that would include an 850 kg rover with 10 science instruments. This planned mission has resulted in a much larger Rover than has been previously placed on the Mars surface. The method of transport from Earth to Mars has remained the same, but once entry into the Martian atmosphere begins, the method of Entry, Descent, and Landing has had to be modified from past missions like Mars Pathfinder (MPF) and Mars Exploration Rover (MER).

In general, the MSL Cruise, Entry, Descent, and Landing (CEDL) system consists of a Cruise Stage, Aeroshell (which includes a backshell and a heatshield), Parachute Deceleration Subsystem (PDS), Descent Stage (DS), Bridle Umbilical Deployment (BUD) Device, and various pyrotechnic and separations devices. See Figure 1-1 for a summary of the various assemblies.

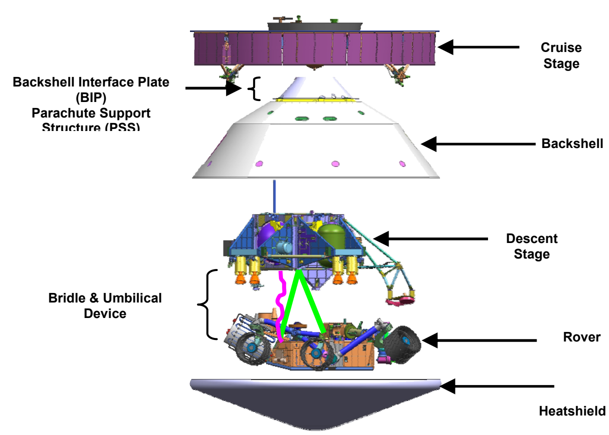

Figure 1-1: MSL Design Concept – Major Assemblies, Exploded View

In addition to the mechanical hardware, the Cruise Stage, which mates the spacecraft to the Launch Vehicle and

[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE
[2] IEEEAC paper #1477, Version 2, Updated January 17, 2007

navigates the spacecraft to Mars, would utilize a simple hydrazine propulsion system, a star scanner, a set of 8 sun sensors, and set of solar arrays for power during the nine to eleven months of cruise. A minimal set of avionics for telemetry and switching is located on the Cruise Stage along with a medium gain antenna which is connected to the telecommunication system on the Descent Stage. See Figure 1-2 for the Launch & Cruise Phase configuration.

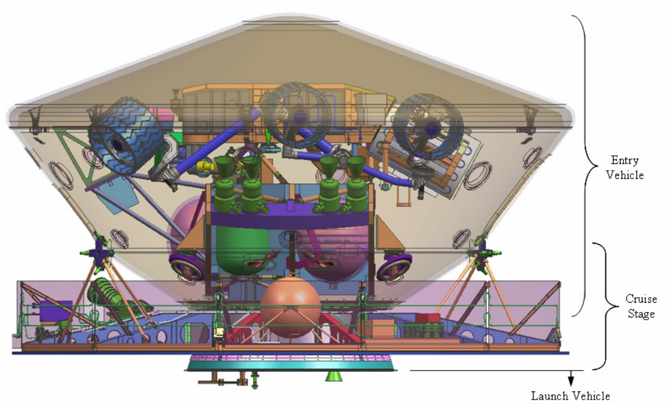

Figure 1-2: MSL Design Concept – Launch & Cruise Configuration

For the Entry, Descent, and Landing, additional critical hardware would include a hydrazine propulsion system, the Descent Inertial Measurement Unit and the Terminal Descent Sensor (a radar system) which sense the environment and provide data to the Descent Avionics (located on the DS) and main computer (located in the Rover) to determine how the Descent Stage Propulsion System must react.

In order to communicate during Cruise and through-out the EDL timeline, the Descent Stage and Aeroshell would be equipped with a complicated telecommunication system consisting of a Small Deep Space Transponder (SDST), a Traveling Wave Tube Amplifier (TWTA), and various X-band and UHF antennas.

The MSL entry would be a lifted entry which means the Entry Vehicle (EV) center of gravity (CG) must be off-set from the Aeroshell center line. However, for the Cruise phase, the spacecraft spins which requires the entry vehicle CG to be located on the Aeroshell center line. Therefore, after Cruise Stage separation but prior to atmospheric entry, the CG of the entry vehicle would need to be moved off-axis to provide a lifting entry. This would be accomplished by ejecting a tungsten mass from the –X side of the backshell. Near the end of the Aeroshell deceleration, a second set of tungsten masses would be ejected from the +X side of the backshell to move the CG back to centerline. This balance mass change would allow the EV angle of attack to migrate from the lifted state to a ballistic state. This ballistic state is highly desired for a robust parachute deployment with minimal dynamic perturbations on the entry vehicle when the parachute fully inflates.

A Disk-Gap-Band (DGB) parachute is deployed once the entry vehicle is in the ballistic state and has slowed down to Mach 2.1. The parachute continues to slow down the entry vehicle until approximately Mach 0.7. During the parachute descent phase, the heatshield is jettisoned.

Once the vehicle reaches a certain altitude, the Powered Descent Vehicle (Descent Stage and Rover), would be released from the backshell and the Mars Lander Engines (MLE's), located on the DS, are started. The now free flying Descent Stage and Rover assembly continues to descend towards the Martian surface using the MLE's, the Descent Inertial Measurement Unit (DIMU), and the Terminal Descent Sensor (TDS) to control the flight path.

When the TDS determines that the vehicle is approximately 20 m above the Martian surface, the Rover would be released from the Descent Stage using the Bridle Umbilical Device (BUD) to lower the Rover to 7 m below the DS. The DS continues to descend at a rate of 1 m/s until the Rover touches down on the surface with its mobility system. See Figure 1-3.

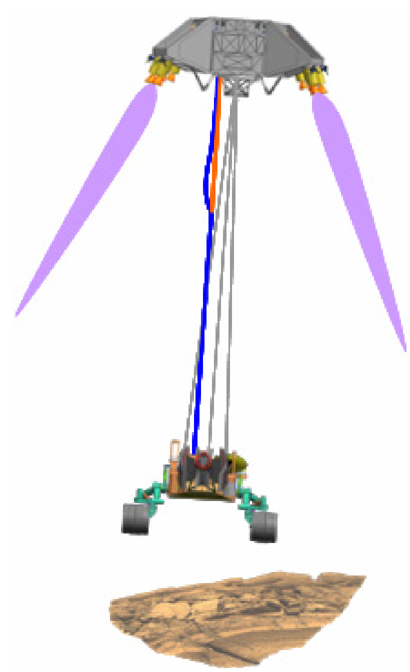

Figure 1-3: MSL Design Concept: Landing Configuration

Once touchdown occurs, the DS senses the large change in suspended mass which initiates the bridle and electrical umbilical between the DS and Rover to be cut at the Rover interface. The DS then flies away on a pre-determined trajectory before impacting on the Martian surface. The Rover now prepares itself to communicate directly with Earth and begin its scientific mission.

A graphical overview of the EDL system is provided in Figure 1-4.

As stated initially, this new EDL system design has several key changes since the past missions of MPF and MER. First, the Entry phase has changed from a spinning ballistic trajectory to a 3-axis stabilized vehicle that uses guided, lifted entry. As such the MSL Aeroshell, which protects the assemblies inside from the high heating of the atmospheric entry, must be designed to take asymmetric forces and heat loads and endure a turbulent environment. Although Viking was a lifted entry, it was smaller in diameter and did not approach the high angle of attack that MSL must use which is driven by the landing trajectory geometery and the overall entry mass. As such, Viking experienced a much lower heating rate and no turbulent environment.

Second, the large mass that would be landed requires a parachute which is larger than any previous deep space parachute (19.7 m). Viking's was the largest parachute previously flown at 16 meters.

Third, to land this large mass on the surface of Mars, a new propulsive assembly, the Descent Stage, is required because the MER and MPF airbag heritage would not be practical for this size of the MSL system. However, the idea is not completely new as the Mars Viking Lander also used a propulsive descent system as will the 2007 Phoenix mission. However, for Viking and Phoenix, the propulsive system with the payload sets itself on the surface as a unit. For MSL, this would trap the rover.

The true uniqueness of MSL becomes apparent in fourth innovation called for in the design: as the vehicle nears the surface, the Descent Stage Assembly of the PDV releases the rover on a 7.5 m bridle system and gently sets the Rover down on the Rover wheels on the surface of Mars. After set down, the bridle system is cut and the Descent Stage flies away, leaving the Rover to roam Mars with its payload of 10 instruments. See Figure 1-4 for the Landing Phase Configuration.

The key challenges for this system lie in the complex configuration, multiple unique load cases, and numerous separation events. This paper will describe the preliminary design and key challenges of each of these mechanical assemblies that comprise the CEDL Mechanical Subsystem.

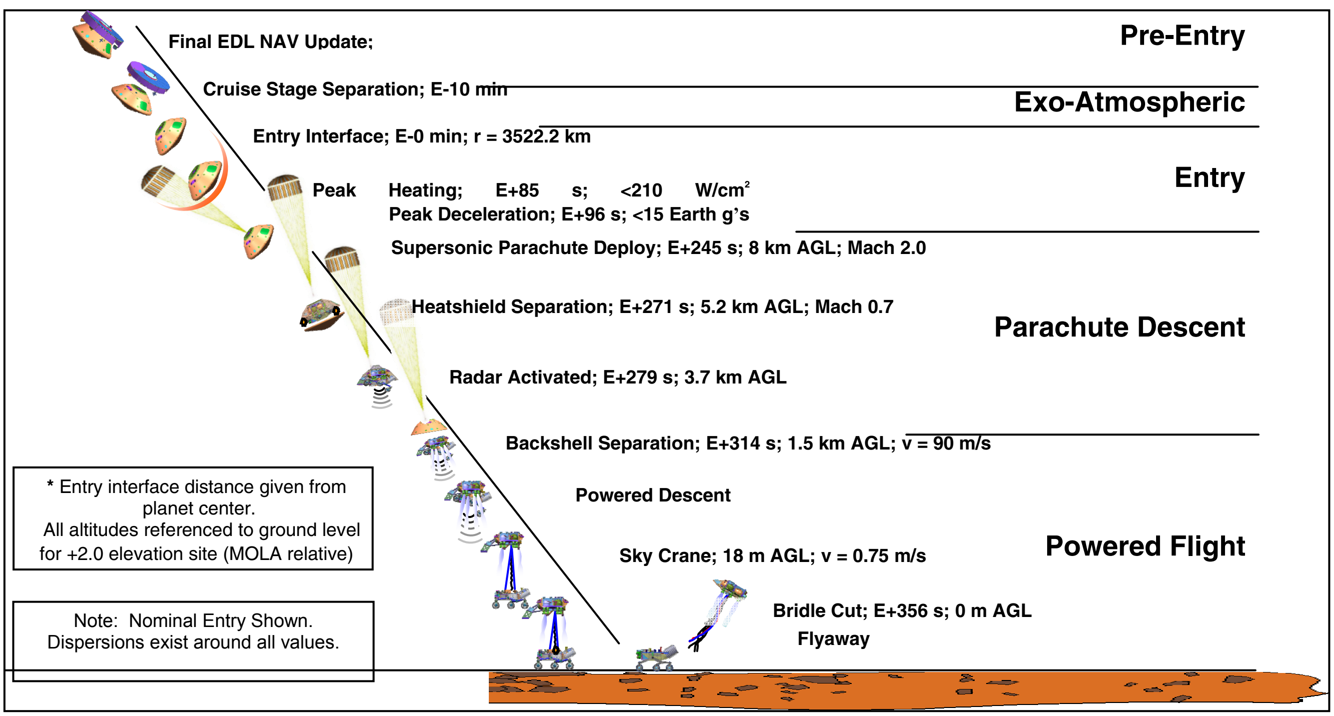

Figure 1-4: EDL Graphical Overview – Design Concept

2.0 CRUISE STAGE

The Cruise Stage (CS) is a major part of the MSL Spacecraft design. During launch, the CS would be the mounting interface to the Launch Vehicle and the structural link to the Entry Vehicle. During the cruise phase of the mission, its primary function is to execute trajectory correction maneuvers and, prior to entering the Martian atmosphere, perform site-adjustment maneuvers. In addition, the CS provides Power, Navigation, Earth Communication and Thermal Control for the spacecraft.

Just before entering the Mars atmosphere, the Entry Vehicle separates from the CS. The CS follows the Entry Vehicle into the Martian atmosphere and burns up during entry.

A summary of the components that the CS structure must accommodate is listed if Figure 2-1 and 2-2.

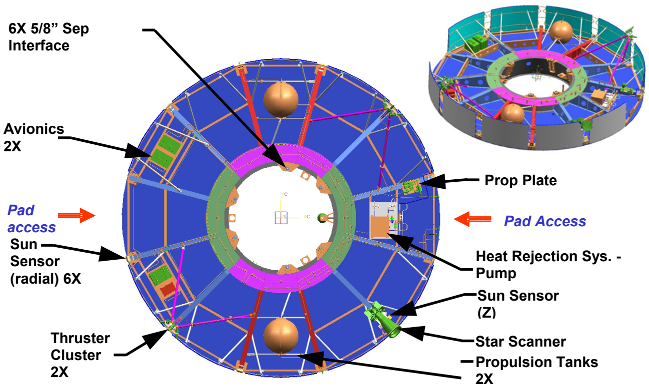

Figure 2-1: Cruise Stage Details (+Z side)

2.2 Structure

As designed, the CS is a disk-shaped structure with a diameter of approximately 4.4 m and an overall height of approximately 1 m. It consists of a primary structure, several secondary structures, and several subsystems.

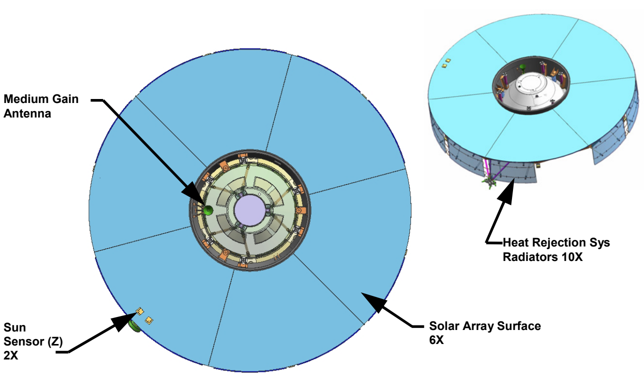

Figure 2-2 Cruise Stage Details (-Z side)

The primary structure consists of the Launch Vehicle Adapter (LVA), twelve ribs that extend radially outward, and intercostals that tie the rib structure together. The LVA interfaces with the Launch Vehicle (LV) and the Entry Vehicle (EV). The secondary structure consists of various support struts and mounting provisions for Subsystem devices. The CS is balanced through selective distribution of subsystem components and counter weights near the outboard end of the ribs. The primary structure is made of aluminum and secondary structure is a combination of aluminum and titanium.

The structure is designed, analyzed, and tested based on the anticipated launch loads and ground-handling loads. As designed, the LVA transfers primary loads between the spacecraft and the LV via a V-band separation clamp. The primary structure (LVA & Ribs) supports the propulsion subsystem, attitude control sensors, the thermal and heat rejection components and the CS electronics boxes. Thrust loads are transmitted to the LVA and through the V-band clamp to the PAF. In addition to launch, the configuration of the flight system requires the CS to design the rib and LVA structure for a ground handling load case that lifts the fully fueled spacecraft in the launch configuration (heat shield up) by the outboard end of all twelve ribs. This particular load case drives the rib cross section sizing.

The key challenge for the CS structural development as designed is the LVA. Entry Vehicle (EV) and Launch Vehicle geometry requires the LVA to be a conical structure with 6 attachment points to the EV and a continuous line attachment (Marmon clamp band) at the LVA side. In order to minimize mass, the transition from the 6 points to the continuous load line is done in less than 0.5 meters. In addition to the need to spread the loads, the radial stability of the LVA must be accomplished external to the adaptor to allow for the EV Parachute Cone to reside in the internal area.

2.3 Structural Verification

Tests performed to verify the MSL Cruise Stage structural design would include a static load test and modal test. The static load test would be performed to verify the primary core spacecraft structure by applying loads to key locations of the system to induce qualification level stresses in the cruise primary structure. Selective load bearing secondary structures would also be verified during static test and by analysis. A modal test would be performed using the flight structure and mass simulators for the various other subsystems. The CS Finite Element Model would be correlated to the modal test results.

3.0 AEROSHELL STRUCTURE

The MSL Aeroshell is the structure which performs the initial aerodynamic deceleration (aero-braking) of the Flight System and protects the Descent Stage and Rover from aero-thermodynamic heating during entry into the Martian atmosphere. As designed, the major components of the aeroshell are: heatshield (HS), backshell (BS), Backshell Interface Plate (BIP), Parachute Support Structure (PSS), and Thermal Protection Systems (TPS). See Figure 3-1 and Figure 3-2 for an overview of the Aeroshell Structure.

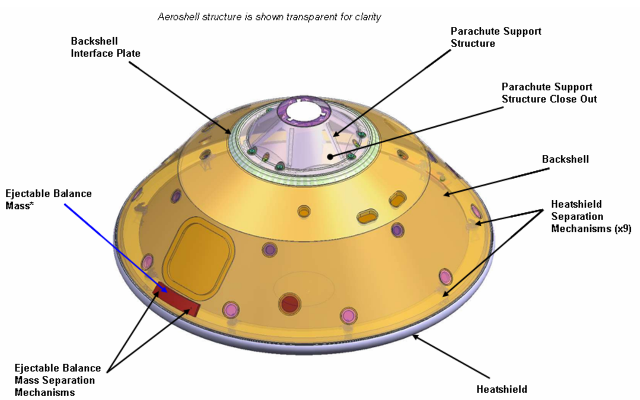

Figure 3-1 Aeroshell Overview

The heatshield and backshell are laminate composite sandwich structures consisting of aluminum honeycomb core with graphite/ polycyanate face sheets bonded to both sides.

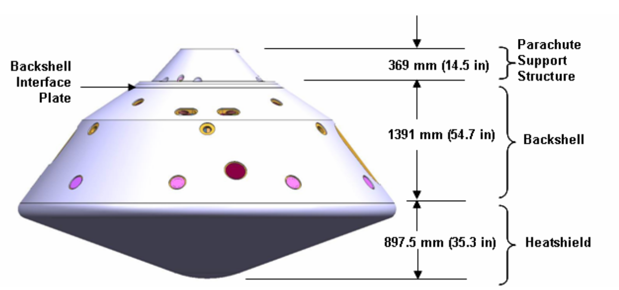

Figure 3-2: Aershell Sub-assemblies

The highest heating rates would occur on the heatsheild and can reach values as high as 225 W/cm^2. Much lower heating rates, 40 W/cm^2 or less, would be seen on the backshell. Both backshell and heatshield heating rates are higher than any previous Mars mission. Both of these structures are covered with a Thermal Protection System (TPS) material. The MPF and MER heritage heatshield TPS material (SLA-561-V) will be used on both the MSL heatshield and backshell. For MPF and MER, heating rates on the backshell were below 10 W/cm^2 and allowed for the use of SLA-561-S. The S material is a sprayable material were as the V material is hand-packed into honeycomb. As such, S material is much simplier to apply to a large surface than V material. Heating rates are higher on the backshell for MSL because of the combination of guided-lifted entry, overall geometry, and RCS thruster wake interaction during atmospheric entry.

3.1 Heatshield

As designed, the heatshield is a 4.5 m diameter by 0.9 m high conical structure with a 70^o half cone angle. This aerodynamic profile is scaled from the Viking lander and uses the MPF/MER cone geometry. The heatshield supports only its external TPS, fixed ballast, and an RF Absorber. Structural loads from the heatshield are transferred to the backshell via the mating surface interface for compressive loads and via the separation nuts for the tension and shear loads.

The key challenges to the heatshield design are structural stiffness and manufacturing. Past Mars missions have used T300 composites for the structure. Because of the large size of MSL and the asymmetric loading, a stiffer design is required in order to minimize local deflections which can impact the lifted entry. Manufacturing of the 4.5 m honeycomb composite structure is also a challenge as many of the materials have time limitations prior to curing. Special equipment is required to handle and manufacture a heatshield of this size as well as tight control of every step of the lay-up process.

3.2 Backshell

As designed, the backshell is a 1.4 m high, bi-conic structure which permanently mounts to the Backshell Interface Plate (BIP) with fasteners around the perimeter of the flange. It supports the structural loads of the heatshield with respect to the spacecraft core structure as well as the ejectable ballast masses on the exterior near the rim on both +X and -X, cabling on the interior surface to the separation nuts, and TPS on the exterior surface.

The backshell design includes a variety of access doors and covers as well as a vent assembly to allow launch depressurization and entry re-pressurization. Access doors include the power source integration door, the DS propulsion access door, and access covers to the heatshield separation nuts (Figure 3-3). As designed, the power source integration door is approximately 0.75 m by 0.75 m and is centered on the –X side. This door will be designed for easy handling and a quick mate to the backshell after that late installation of the power source to the rover at the launch complex.

It is anticipated that the quick mate will be accomplished by using ~¼" fasteners and power tools. The propulsion access door is approximately 0.6 m by 0.5 m and is centered on the +X side. This door is used to access the services valves on the Descent Stage to off-load the propulsion system in an emergency situation at the launch complex. Integration of this door will most likely be the same as the power source integration door.

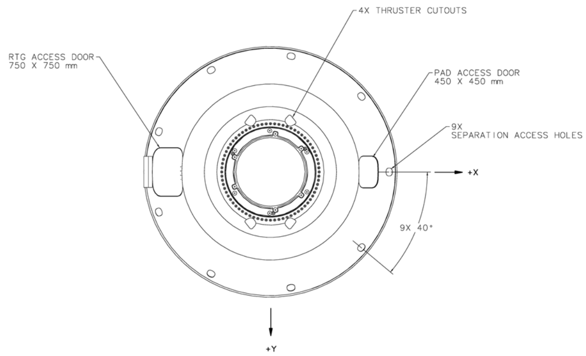

Figure 3-3: Backshell Access Doors

Key challenges for the backshell are similar to the heatshield: stiffness and manufacturing. In addition, the need for access through the backshell to the Rover and Descent Stage at the launch complex creates the challenge of designing doors that are simple and quick to remove and install during this time critical period.

3.3 Backshell Interface Plate

As designed, the Backshell Interface Plate (Figure 3-4) is a machined aluminum ring that is fastened to the backshell cone to become an integral part of the backshell. It is mounted to the Cruise Stage by six bolts. In addition to the backshell, the BIP also supports the Descent Stage using six bolts. The Parachute Support Structure (PSS) hard mounts to the BIP and allows parachute mortar and inflation loads to be carried to the BIP.

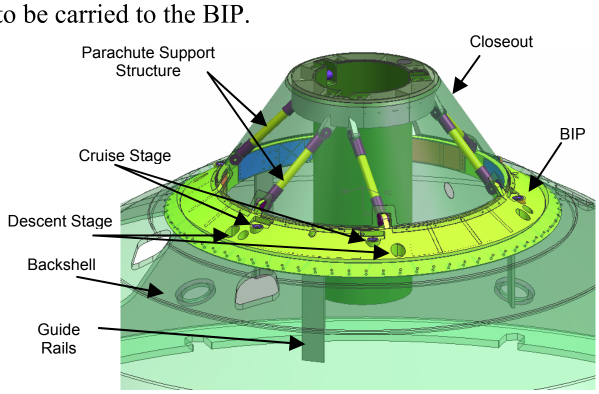

Figure 3-4: BIP & PSS – Iso View

The BIP design also has the guide rails that are used for PDV separation. The three guiderails are hard mounted to the BIP ring with fasteners. During the separation of the PDV from the backshell, these guide rails insure that no contact is made for approximately the first half meter of motion.

The external surface of the BIP is protected thermally from the entry heating environment with Acusil II, a form of TPS (Section 3.5).

The key challenge for designing the BIP is the multitude of complex load cases: launch, entry, mortar firing, parachute inflation, PDV separation. Not only are there many load cases, multiple load paths exist: Cruise Stage interface loads, backshell interface loads, parachute and support structure interface loads, and Descent Stage interface loads.

3.4 Parachute Support Structure (PSS)

As designed, the Parachute Support Structure is an aluminum structure consisting of three bi-pods with a machined ring at the top and a bolt interface to the BIP at the base. A composite cone is placed over the structure that has 8 UHF patch antennas connected together to form an antenna array for communication to a Mars orbiting satellite during EDL.

In addition, two low gain antennas (LGA's) would protrude through this structure. The Parachute LGA (PLGA) is parallel to the Z axis and is used during both Cruise and Entry phases. The Tilted LGA (TLGA) is angled along the angle of attack during entry and allows for communication during just lifted entry.

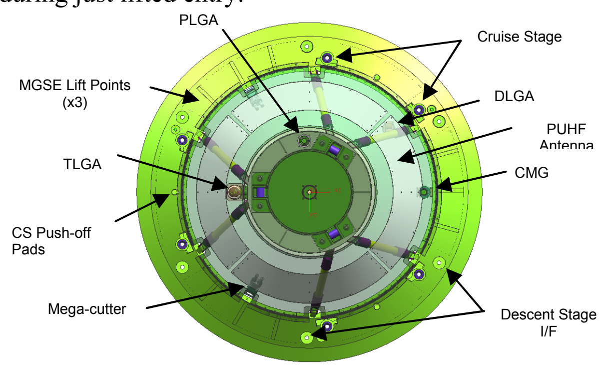

Figure 3-5: BIP & PSS – Top View

The parachute canister is mounted to the top ring of the PSS with 6 bolts. During parachute ejection and inflation, the mortar and parachute loads are transferred to the PSS which results in loading the PSS first in compression and then in tension. To protect the structure and the UHF patch antennas, the surfaces are covered with Acusil II, an RF transparent TPS material that also can withstand heating rates of over 60 W/cm^2.

The key challenge for this hardware is the configuration and accommodation of the various antennas as well as all the co-axial cables and wave guides that must mate to the antennas and cross the various separation planes.

3.5 Thermal Protection System (TPS)

The aero-thermodynamic heating generated by entry into the Martian atmosphere establishes the requirement for a thermal protection system (TPS) to be applied to the external surface of the entry vehicle as insulation. As designed, two different types of TPS are used on the Aeroshell System, see Figure 3-6.

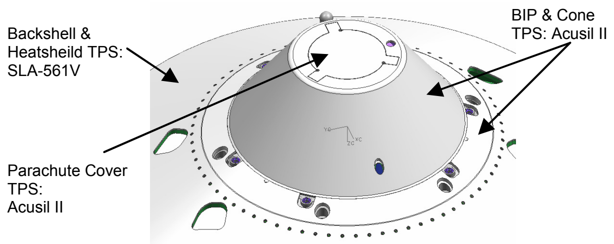

Figure 3-6: TPS Appliciations to Aeroshell

The heatshield TPS is SLA-561-V, a cork based proprietary material with phenolic microballoons in silicone resin binder. The heatshield requires approximately 23 mm of SLA-561-V which is hand packed into a phenolic honeycomb bonded onto the exterior of the heatshield structure. The backshell has approximately 13 mm of SLA-561-V.

A key challenge with the SLA application is the time. The materials involved in the manufacturing process have time limitations for their use. Once the time limitations are exceeded, the properties of the materials significantly degrade and cannot be used. With such a large structure to apply the SLA to, the processing timeline is critical and requires significant planning and personnel training.

The backshell Interface Plate and Parachute Close-out Structure, which hosts the patch UHF antennas, will be covered with Acusil II, a proprietary RF transparent TPS material commonly used to cover antennas on missiles. The SLA-561-V is proprietary to Lockheed Martin; Acusil II is proprietary to ITT.

For both materials, the aerothermal environment that they would be subjected to is significant and pushing the limits of the material performance. The biggest challenge though is the ability to properly test and qualify the material for the full environment including heat rate, total heat load, time pulse of the heating event, static pressure, shear pressure, turbulence.

The NASA Ames Research Center has the test facility that has performed all of the past testing of these materials. For MSL, Ames engineers are looking at how we test in these facilities such that the extremes of the MSL environment can be captured to qualify the TPS system.

3.6 Structural Verification

To verify the structural design, a static test of the heatshield and backshell as well as the BIP and PSS would be performed prior to the TPS installation. Void and gap verification of the TPS will be conducted by visual and radiographic inspection. Functional testing of the heatshield separation from the backshell would be performed using gas and pyro actuated separation nuts. Acoustic, Vibration and Thermal Vacuum testing will be performed on the Flight Unit at the system level.

4.0 PARACHUTE DECELERATOR SUBSYSTEM

During entry into the Martian atmosphere, a mortar-deployed parachute will be used to decelerate the entry vehicle. This establishes a stable vertical trajectory to permit jettisoning of the heatshield. The Parachute Decelerator Subsystem (PDS) delivers the Descent Stage and Rover to a point and flight condition where the Descent Stage Propulsion System can complete the descent and place the Rover on the Martian surface.

The Parachute Decelerator Subsystem (PDS) design consists of two integrated sub-assemblies, namely:

1. The deceleration parachute which includes a payload bridle assembly, link, riser, suspension lines, parachute canopy, and deployment bag. The MSL Parachute is based upon a Viking scaled 19.7 m constructed diameter parachute with attributes from the MER and MPF parachute development

2. The deployment subsystem design consists of a mortar canister and cover, sabot, sabot capture bag, gas generator, and initiators.

The parachute, Figure 4-1 and 4-2, calls for a modified Disk-Gap-Band (DGB) design with a nominal deployed diameter of 19.7 m. Anticipated parachute materials are:

- Lines: braided 1200# Kevlar cord
- Radials: braided 1200# Kevlar cord
- Risers: 6000# Kevlar web
- Band and Disk fabric: Polyester and Nylon

The parachute is conditioned and pressure packed to the required volume and shape. It then undergoes a heat set and sterilization process.

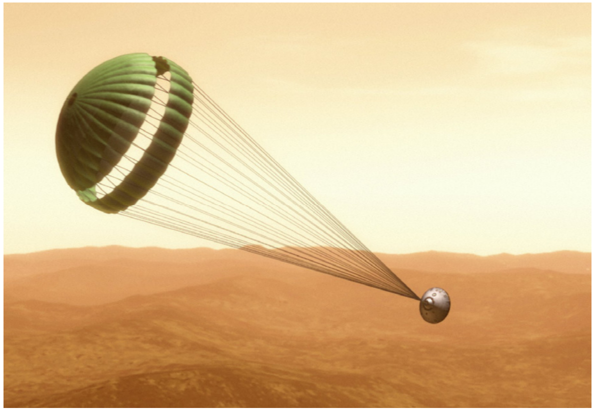

Figure 4-1: MSL Parachute Inflated – Artist's Rendition

4.1 Deployment Subsystem

The Deployment Subsystem provides the means for ejecting the packed deceleration parachute from its stowed configuration. It consists of a mortar / stowage canister and a deployable cover which protects the stowed parachute from external environments.

The cover is jettisoned solely by the impact of the parachute pack which is deployed by the pressure forces induced by the mortar gas generator. The exterior surface of the cover is covered with TPS to protect the mortar and parachute from the entry heating environment.

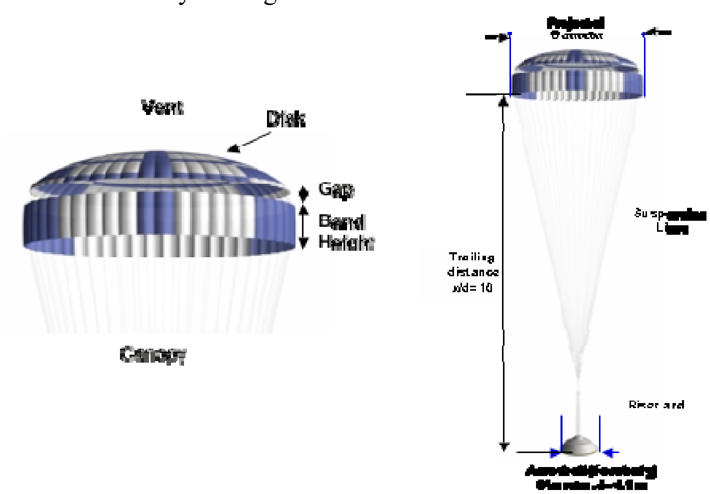

Figure 4-2: MSL Disk-Gap-Band Parachute Configuration

4.2 Parachute Canister

The parachute is packed and inserted into a canister (Figure 4-3) which is mounted to the PSS with 6 bolts. The canister is expected to be made from 7050–T74 aluminum.

The qualification canister will be tested to 1.25 x Peak Operating Pressure at ambient conditions. Provisions are made for installation and removal of the pyrotechnic devices without requiring disassembly of any other components of the PDS. An external electrical connector is provided for connection to the firing circuitry.

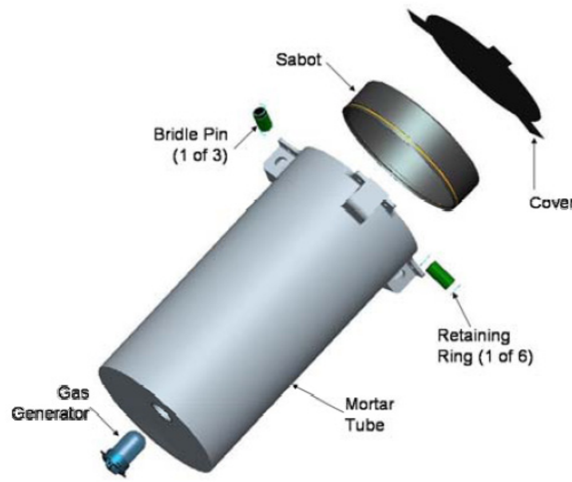

Figure 4-3: Canister and Deployment Configuration

4.3 Structural Verification

The parachute will be tested in a variety of ways. Simple pull tests will be performed on the risers and bridles. A full scale parachute will be deployed in the Ames 80x120 wind tunnel and loaded to the maximum pressure expected. In addition, the parachute will be inflated and deflated in a cyclic manner to insure that the parachute will survive the cyclic dynamic environment it will experience at Mars while decelerating from Mach 2.1 to below 1.5. Below Mach 1.5, the environment becomes steady state like past missions.

For the canister, the shell will be pressurized to 1.25 x Peak Operating Pressure at ambient conditions. In addition to static pressure testing, the mortar will be fired under a variety of environmental conditions and gas generator variations to insure the deployment capability.

5.0 DESCENT STAGE

The Descent Stage (DS) is a major part of the MSL Entry Vehicle (Figure 5-1). For launch and cruise, the descent stage is the structural link between the rover and the Cruise Stage (CS). Upon entry, the DS is the structural link between the rover and the Aeroshell. The DS, along with the rover, is located inside the Aeroshell during launch, cruise, and entry.

The primary purpose of the Descent Stage is two fold during EDL. First, the DS uses its reaction control thrusters during entry to provide control of the entry vehicle. At the end of parachute descent, the DS with the rover is released from the backshell and begins powered descent. Using the Mars Landing Engines (MLE's) and the Guidance & Navigation Control (GNC) Sensors, the Descent Stage descends towards its landing site. As the Martian surface approaches, the rover is released from the Descent Stage on a bridle. Once the rover lands on the surface, the bridle to the DS is cut and the Descent Stage flies away.

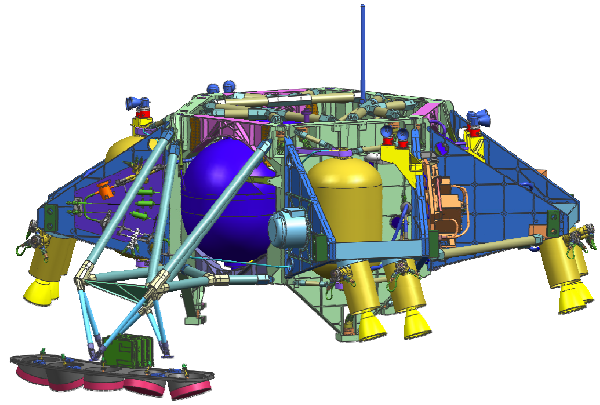

Figure 5-1: Descent Stage –Iso View (+X)

5.1 Descent Stage Overview

The DS provides power, navigation, and communication during EDL. Since the Descent Stage lands on the Martian surface, planetary protection requirements for the DS are similar to those of the rover. Figure 5-2 shows the large number of subsystems and assemblies that the DS structure must accommodate.

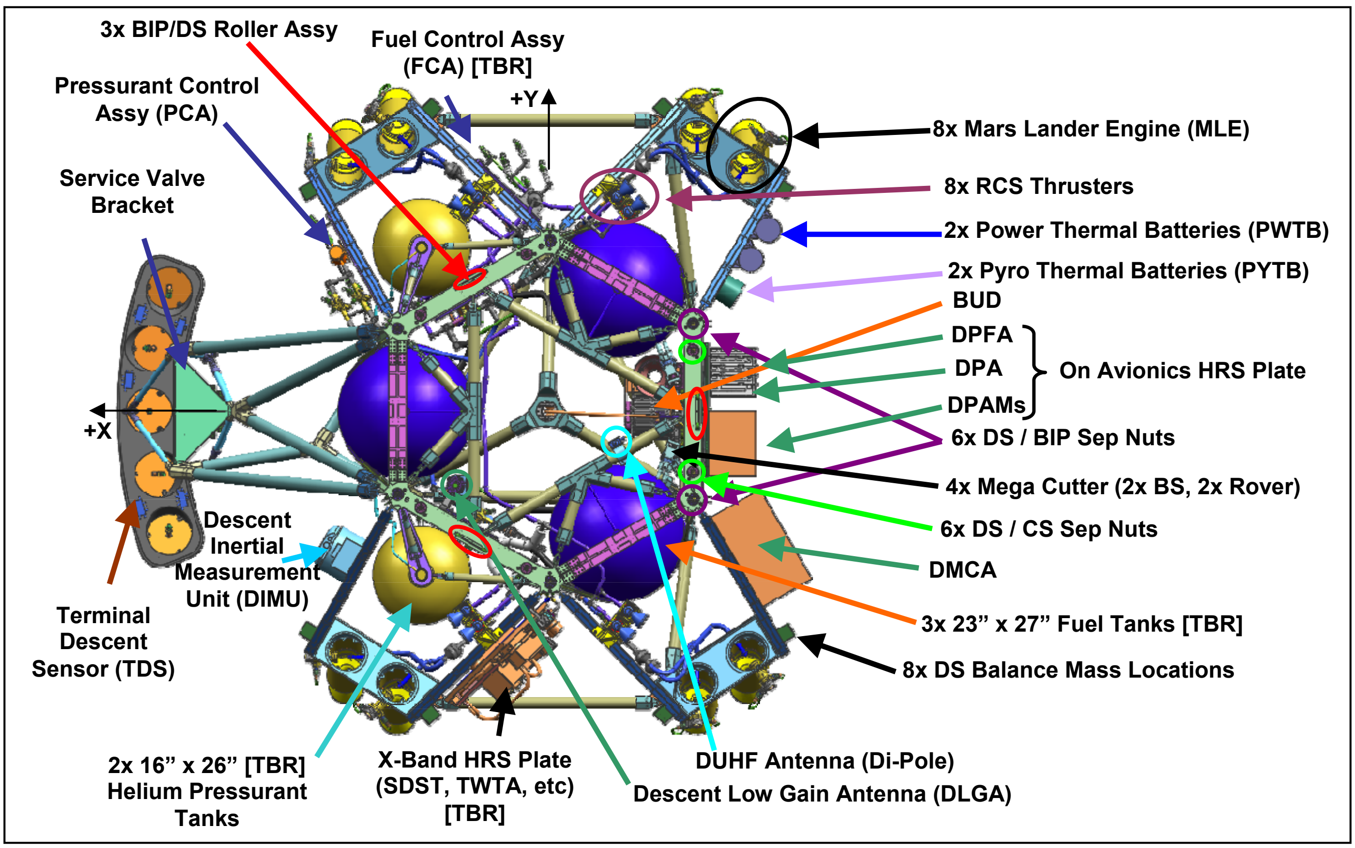

Figure 5-2: Descent Stage Configuration (top view)

5.2 Structure

The DS design consists of a core hexagonal structure that is roughly 1 m high and 1.5 m in diameter. Attached to the core hex are four thruster assembly arms and a truss structure referred to as the proboscis. This integrated set of structure is the primary structure. Miscellaneous pieces of secondary structure are then attached to this primary structure and are used to hold items such as tanks, propellant components, avionics boxes, GNC sensors, and telecommunication components. The fully assembled descent stage structure is approximate 1.5 m high and 3 m in diameter.

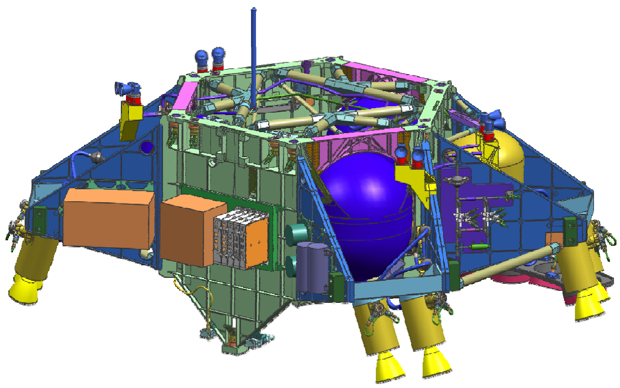

Figure 5-3: Descent Stage – Iso View (-X)

The core hex structure design has provisions for attaching the Descent Stage to the Cruise Stage and to the Aeroshell via two sets of 5/8" separations nuts. The mate of the EV to the CS is with six instrumented 5/8" bolts that are located on the CS and that pass through the Aeroshell's Backshell Interface Plate (BIP) and into the separation nuts in the DS hex. This arrangement allows for the launch loads of the Descent Stage, with the rover, to pass through to the cruise stage and thus to the launch vehicle.

After the CS has separated, a second set of six separation nuts and instrumented bolts maintain the load path from the Descent stage to the Aeroshell during entry. The bolts are located on the BIP with the separation nuts located in the DS hex.

The base of the core hex structure has provisions for attaching the rover to the Descent Stage via a semi-kinematic structure. Again, the separation nuts are located on the DS side of the interface with the instrumented bolts on the rover.

The secondary structure, as designed, is used to hold the many components in place. Each of the propellant tanks use three bi-pods to attach the tanks to the hex structure. The Pressurant tanks use a bi-pod, a pair of mono-pods, and a torsion bracket to attach the tanks to the hex. To the extent practical, propellant components, such as valve, filters, transducers, are collocated on plates which then attach to the primary structure. Three plates are expected and include the Fuel Control Assembly, Pressurant Control Assembly, and a plate that houses Service Valves for loading and off-loading the DS propulsion system.

Other secondary structure includes an HRS plate that houses most of the telecommunications components; brackets for mounting thermal batteries; brackets and stand-offs as needed for HRS fluid lines, propellant lines, and cabling. Other boxes, including avionics and GNC sensors, are expected to be bolted directly to primary structure.

The primary structure is expected to be machined aluminum pieces that bolt and/or rivet together. For secondary structure, parts will be mostly aluminum with the possibly of some titanium and non-metal parts (G-10, Delrin, etc) where local loads or thermal isolation necessitate this need.

The key challenges for the Descent Stage structure are configuration/interface management and the multitude of load cases. As seen in Figure 5-2, the DS is a spacecraft itself with avionics, telecommunications, navigation sensors, propulsion, and thermal control. Locating all the hardware and routing all of the fluid lines, waveguides, and cabling is a continual challenge.

Just as the BIP, the Descent also has a significant number of load cases and load paths. The structure must be designed for launch loads, entry loads, parachute loads, separation loads, powered descent loads, and BUD deployment loads. Each one of these load cases stresses the structure in a different load path.

5.3 Structural Verification

Tests performed to verify the MSL Descent Stage structural design will include a static load test and modal test. The static load test will be performed to verify the primary F/S structure by applying loads to key locations of the system to induce qualification level stresses in the Descent Stage primary structure. Selective load bearing secondary structures will also be verified during static test and by analysis. A modal test will be performed using the flight structure and mass simulators for the various other subsystems. The DS Finite Element Model will be correlated to the modal test results.

6.0 EDL SEPARATION EVENTS AND HARDWARE

In order to perform the various separations of hardware during EDL, various separation devices are used. Pyrotechnic devices are used for each separation with supporting hardware, such as separation springs and guide rails, which insures proper separation during the event. The following list of separtions events occur as part of the EDL sequence:

- Cruise Stage to Entry Vehicle Separation
- Balance mass Separation (Cruise and Entry)
- Heatshield Separation
- Backshell to Power Descent Vehicle (Descent Stage + Rover)
- Descent Stage to Rover Separation
- Bridle and Umbilical Separation from Rover

A description of each separtion event as planned and the associated hardware is described in the next several paragraphs. A system block diagram of the CEDL separations is provided in Figure 6-1 and a pictoral overview of each separation is provided in Figure 6-2.

In general, all of the separation events are accomplished using multiple pyro device firings. For separations that occur during EDL, the dynamic complexity of these events is increased as a result of the atmospheric forces that are applied and the need to analyze both near field and far field trajectories to insure no future contact.

6.1 Cruise Stage to Entry Vehicle

Cruise Stage to Entry Vehicle separation initiates the beginning of the EDL sequence. In order for separation to occur, the six separtion nuts on the Descent Stage are fired in two groupings of 3. The bolt, located on the Cruise Stage, is retracted with a cup and spring. This bolt is retained with the Cruise Stage via a bolt catcher. This bolt catcher is expected to be a honeycomb cover that absorbs the momentum of the retracted bolt.

Between the Cruise Stage and the Entry Vehicle, three separation springs would be used to insure that the two bodies separate at a rate of 5-6 m/s. Just prior to the firing of the separation nuts, several pyro cutters are fired to sever the electrical and fluid lines that cross this separation plane. On the Cruise Stage, retractors for these items insure proper withdrawl of the hardware during separtion. These retractors are still to be designed but are expected to be small spring loaded devices. See Figure 6-3.

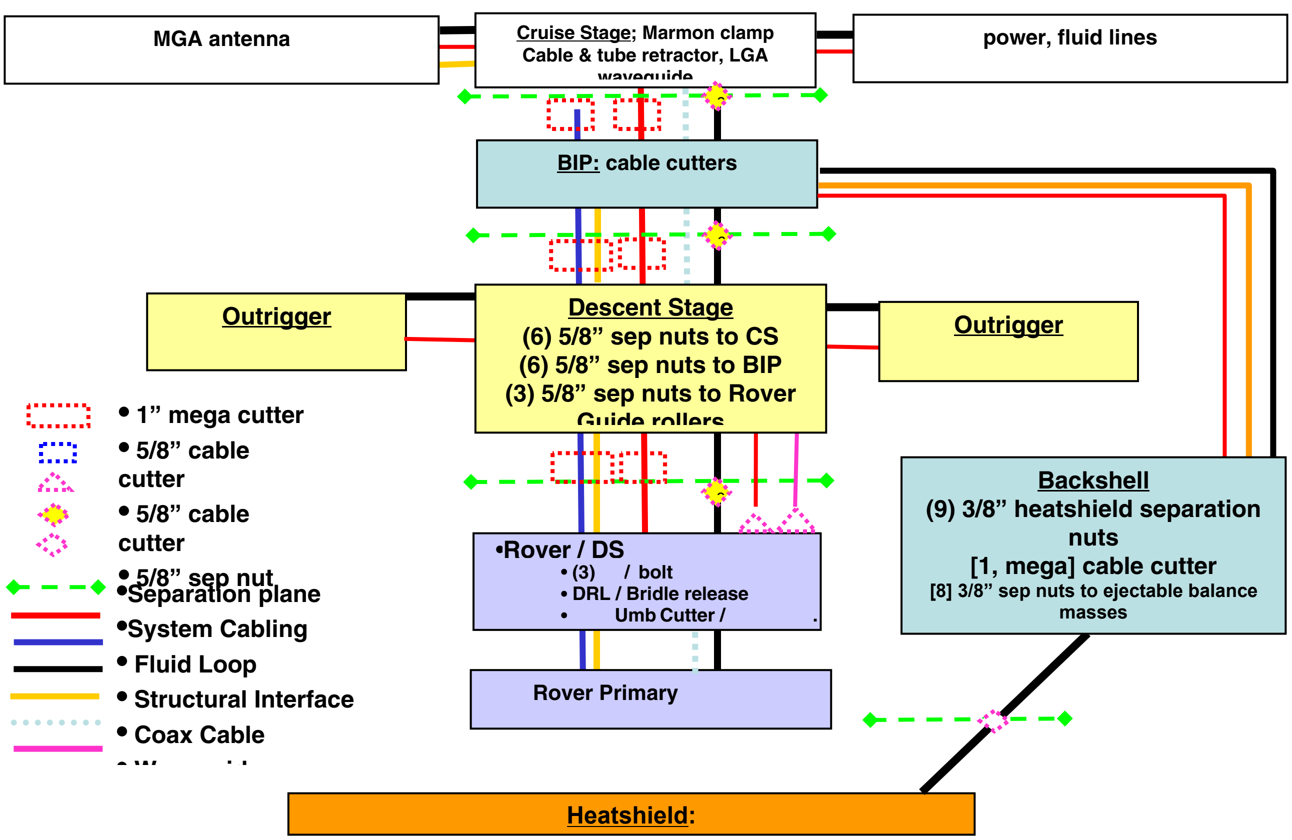

Figure 6-1: EDL Mechanical Separations Block Diagram

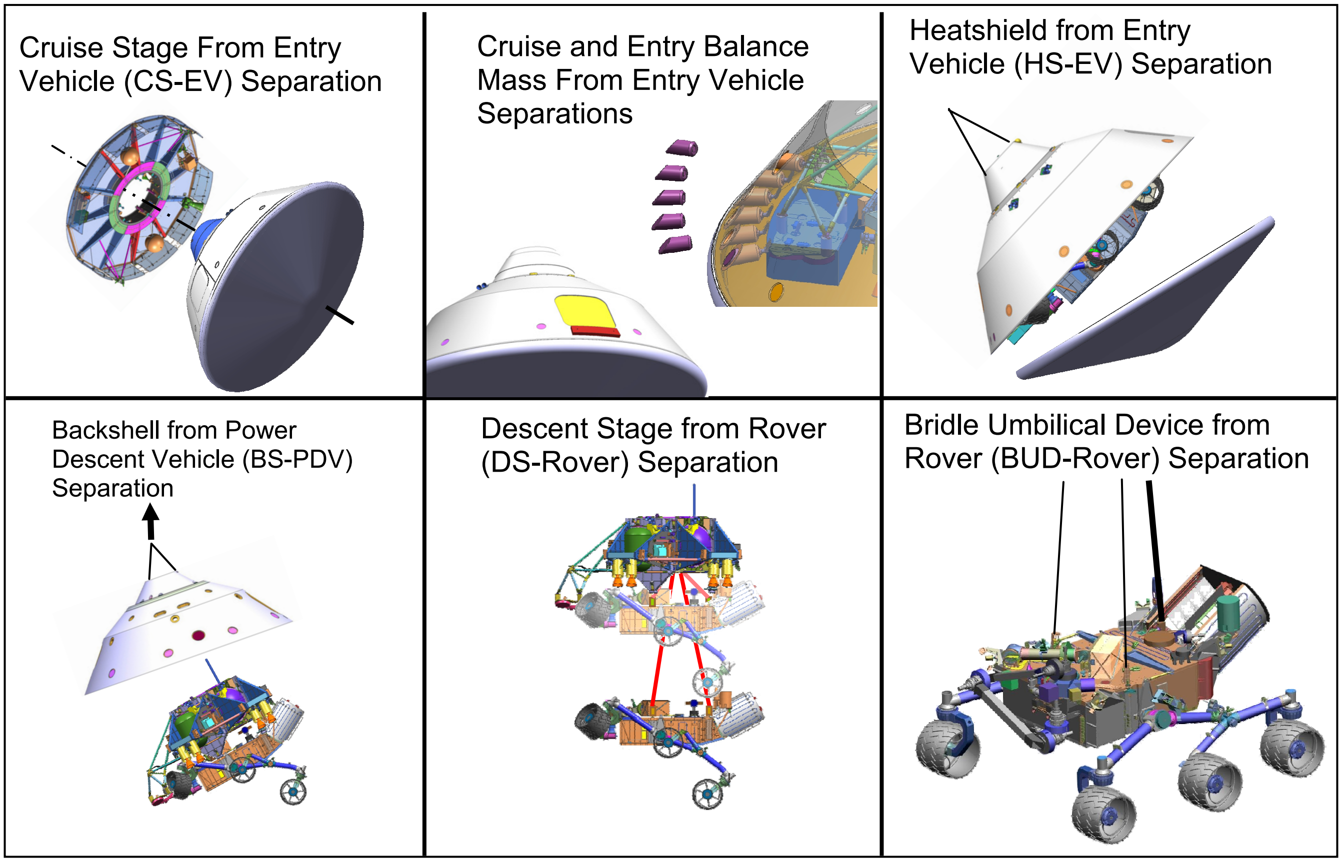

Figure 6-2 Mechanical Separations Design Concept – Pictoral Overview

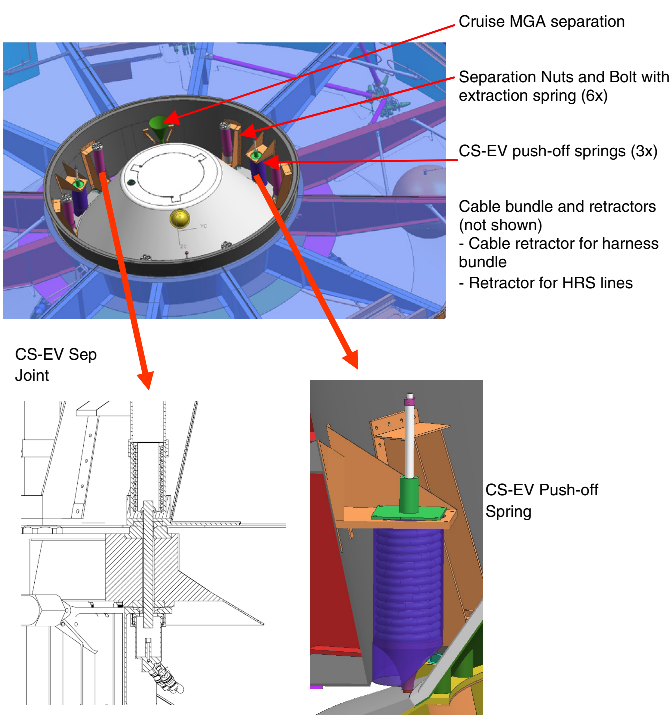

Figure 6-3: Cruise Stage Sep Hardware

6.2 Ejectable Balance Mass Separations – Cruise and Entry

During Cruise, the mass propeties of the system required the CG to be on the Z axis. Upon entry, the CG must be moved off of Z towards +X to achieve lifted entry on the Aeroshell. This CG movement is performed by ejecting a 120 kg piece of tungsten from –X. This tungsten mass is be located on the exterior of the Aeroshell near the Backshell and Heatshield interface. The separation usings two 3/8" separtion nuts. In addition to the separation nuts, some small kick-off springs, such as belleville washers, will be used to insure a separation veleocity.

Near the end of Entry, the parachute is deployed. In order to minimze the dynamics on the entry vehicle and to insure a successful parachute inflation, the entry system strongly desires the CG to be located on the Z-axis which aligns with parachute ejection. In order to achieve this, a similar device to the cruise system can be used. However, we have chosen to increase the quantity from 1 mass ejected to 6 masses with a short delay between each ejection. This allows for the EV to return to a balistic trajectory in a more dynamically controlled method. Because these masses must also survive the heating and aerothermal dynamics of entry with no impact on trajectory control, they must be made conformal to the backshell surface. As such, these devices are designed to be cylinders that are recessed into six fittings in the backshell. Each mass is separated using a 3/8" separation nut and ejection spring located internal to the tungsten mass.

6.3 *Heatshield from Backshell Separation*

The separation of the heatshield from the backshell occurs after 99% of the entry energy has been eliminated. In order for this separation to occur, 9 separation nuts on the backshell are fired in three goupings of 3. At nine locations, nine separation springs are used to insure a separation rate of 2.7 m/s.

6.4 *Descent Stage from Backshell Separation*

The separation of the Power Descent Vehicle from the backshell is initiated just before the system reaches terminal velocity under the parachute. In order for this separation to occur, the six separtion nuts on the Descent Stage are fired in two groupings of 3. The bolt, located on the Backshell Interface Plate, is retracted with a cup and spring. This bolt is retained with the BIP via a bolt catcher. This bolt catcher is expected to be a honeycomb cover or high strength woven fabric that absorbs the momentum of the retracted bolt. Between the backshell and the Descent Stage, three guide rails are used to insure that the two bodies separate without re-contact. No springs are required in this separation since the parachute, attached to the backshell, provides adequate drag relative to the Descent Stage. Just prior to the firing of the separation nuts, several pyro cutters are fired to sever the electrical and fluid lines that cross this separation plane. See Figure 6-6.

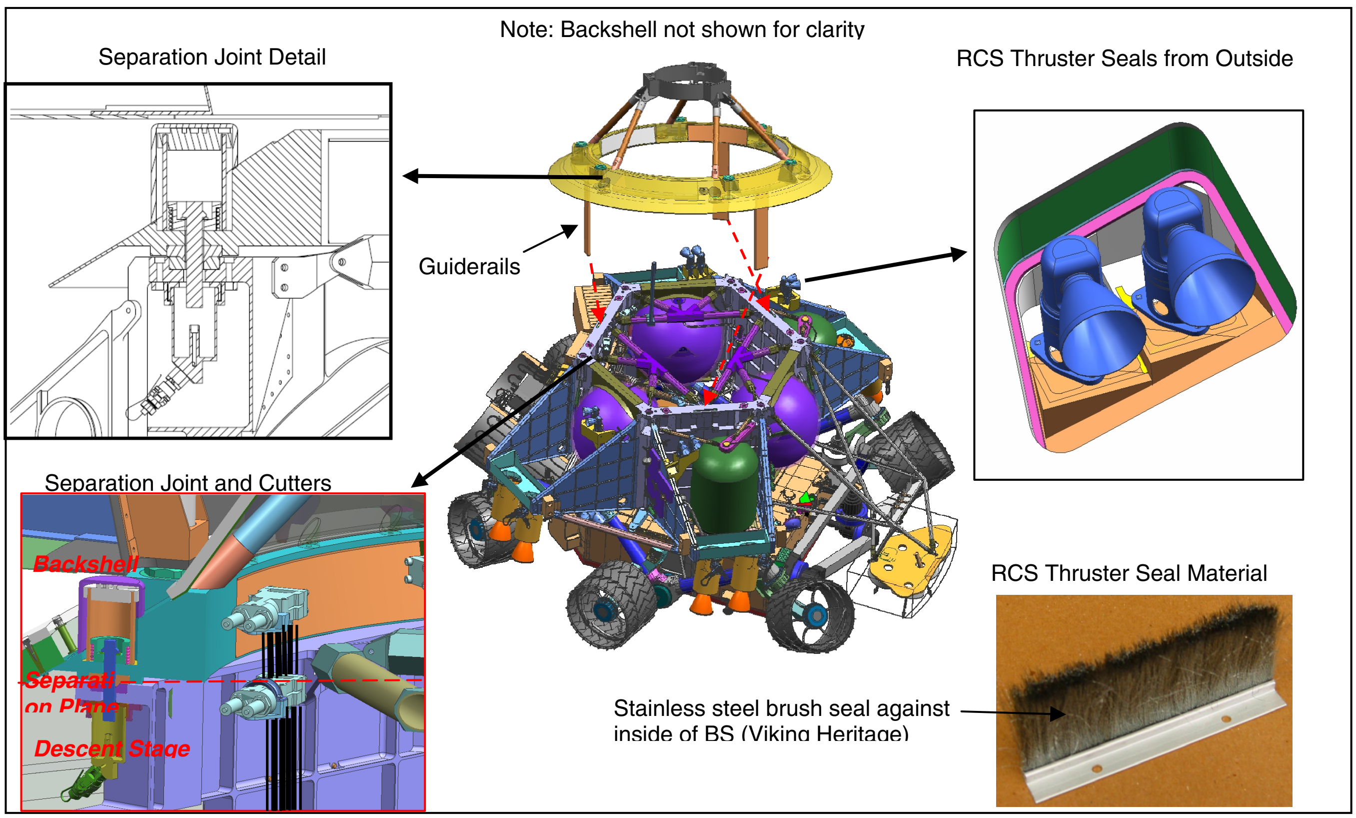

Figure 6-6: Backshell to Descent Stage Separation Design Concept

6.5 Rover from Descent Stage Separation

At approximately 20 m above the Martian surface, the Rover is released from the Descent Stage and lowered approximately 7 m via the Bridle Umbilical Descent-Rate-Limiter (BUD). In order for this separation to occur, the three separtion nuts on the Descent Stage are fired. The bolt, located on the Rover, is retracted with a cup and spring. This bolt is retained with the Rover via a bolt catcher. This bolt catcher is expected to be a honeycomb cover that absorbs the momentum of the retracted bolt. Between the Descent Stage and the Rover, three guide rails are used to insure that the two bodies separate without re-contact. No springs are required in this separation since the Descent Stage propulsion system is providing adequate thrust in the negative gravity vector. Just prior to the firing of the separation nuts, several pyro cutters are fired to sever the electrical and fluid lines that cross this seperation plane. See Figure 6-7.

6.6 Bridle and Umbilical Separation from Rover

During the final seconds of descent, the Descent Stage is attached to the Rover via the three legged bridle and an electrical umbilical. Once the Descent Stage has determined that the Rover has landed on the Martian surface, the bridle and umbilical are separated from the Rover at the top deck of the Rover using pyrotechnic cutters. Once this final set of connections are cut, the Descent Stage flies a pre-programmed path to a safe distance from the Rover. See section 7.0 for further hardware details.

6.7 Separation Verification

For each separation event, two independent dynamic analysis are performed, using Monte Carlo simulations with 3-sigma dispersions. In addition to analysis, each separation is test for first motion in a 1g environment. These tests fire all relevent pyro devices including cutters and separation nuts, simulate all hardware involved in the separation event (cables, fluid tubes, springs, etc.), and include accelerometers and high speed video. Although these tests do not include the full dynamic motion of the two separating bodies as espected in flight, they do confirm that nothing in the mating surfaces or across the interface make unexpected contact or apply an off-nominal force.

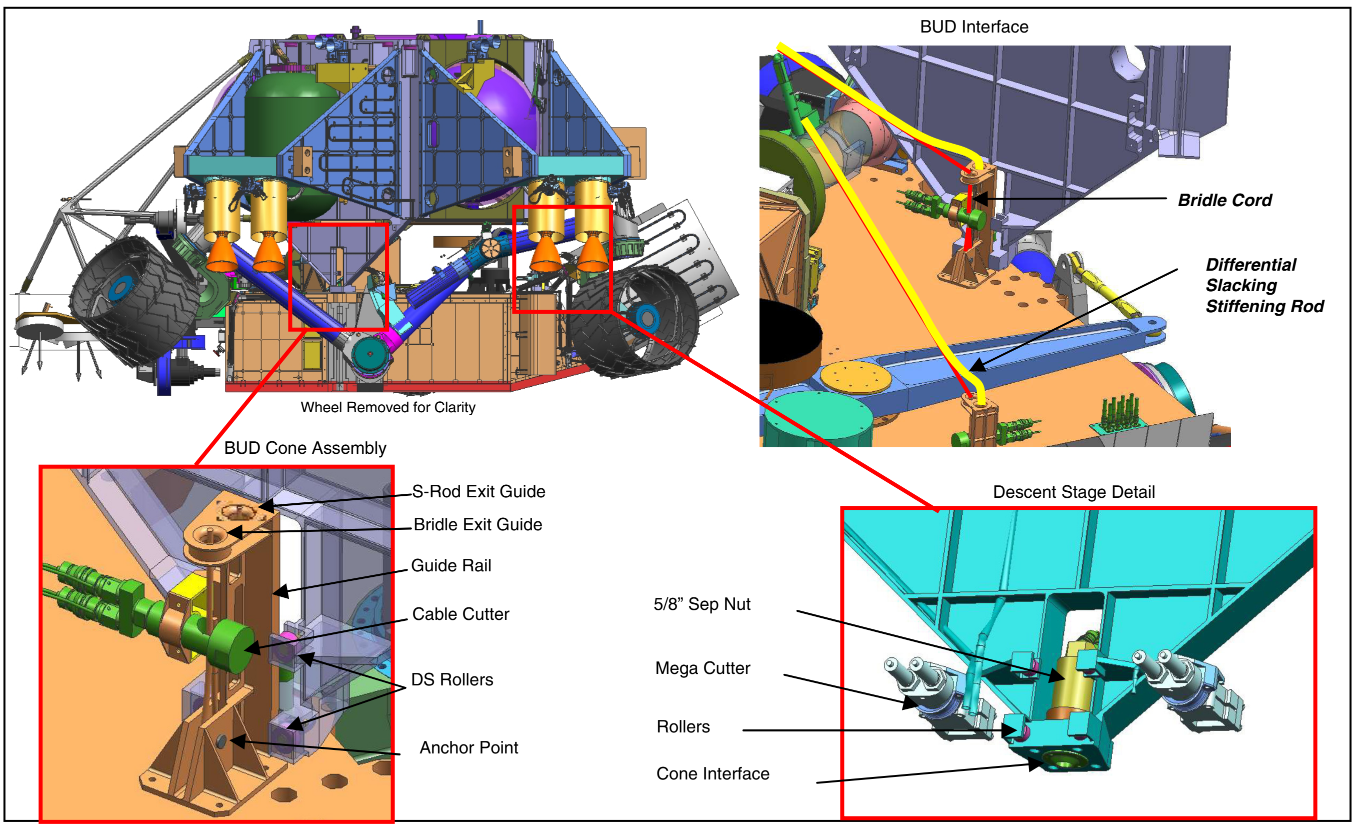

Figure 6-7: Rover – Descent Stage Separation Design Concept

7.0 BRIDLE & UMBILICAL DEVICE

The Bridle Umbilical Device (BUD) will deploy the 850 kg Rover to 7 m below the Descent Stage while maintaining an electrical connection between the Rover and Descent Stage. A key requirement for the BUD is to perform this deployment with an average speed that is higher than the final speed. This key feature of the BUD both minimizes the snatch loads that the Rover and desent stage experience and minimizes the disturbance that the Descent Stage control system must overcome during the Rover deploy event. A picture of the BUD deplyment sequence is shown in Figure 7-1. An overall view of the BUD assembly is provided in Figure 7-2.

The Bridle consists of three pieces of Vectran cord, each 5 mm in diameter. When the Rover is attached to the Descent Stage, the three cords are wrapped around a spool and attached to the spool at one end and to three points on the Rover at the other end. The variable descent speed and braking is accomplished via the output characteristics of the descent brake motor, gearbox, and tapered spool. See Figures 7-2 and 7-3 for a picture of the Bridle and Descent Brake conceptual design. At the time of this paper, the Descent Brake (motor and gearbox) was in the process of a competitive procurement. As such, this area of the BUD is not discussed further.

The electrical connection between the Descent Stage and Rover is made via the umbilical, a wire harness that allows Rover computing elements to communicate with Descent Stage avionics and GNC sensors. The umbilical is inititally wound in two concentric cones. It deploys from the cones under the force applied by the descending Rover and is tensioned and retracted separately from the bridles during touchdown and after cut-away. See Figure 7-4.

The bridles are connected to the Rover in three locations. A portion at the end of each bridle is stiffened to prevent it from catching or tangling on any Rover hardware. Near the Rover chassis attachment point, each bridle cord is routed through a cord guide and pyro cutter. The bridle cords and the umbilical will begin to slack once the Rover wheels make contact with the surface, before the Descent Stage detects touchdown and halts its descent. To prevent cords from contacting hardware on the Rover top deck, springs retract the bridle and umbilical and maintain tension in the cords. This tensioning and retraction feature allows for approximately 1 second of data to be gathered to confirm that the Rover has landed on the Martian surface before the bridles and umbilical are cut. Once the flight system has determined that the Rover has been set down safely, the three bridle pyro cutters and one umbilical cutter are fired and the cords and cables are severed from the Rover. They are rapidly pulled clear of the rover by retraction mechanisms and then fly off with the Descent Stage to a location safely away from the Rover.

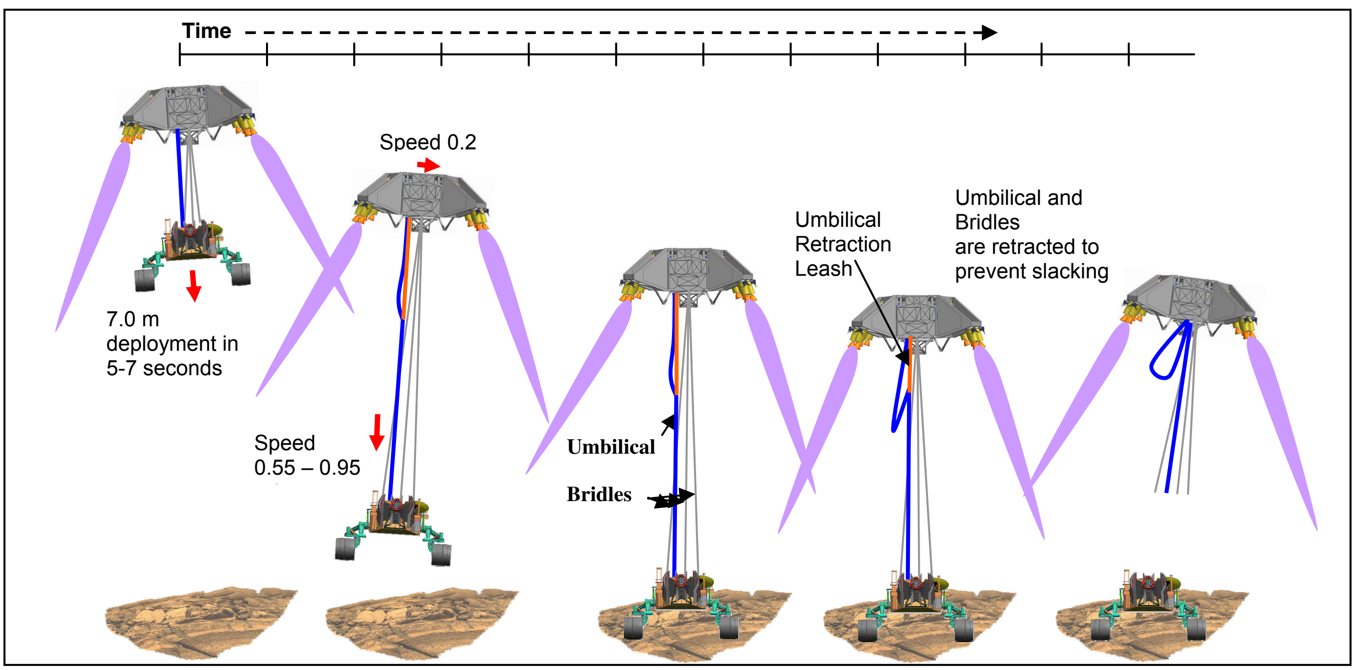

Figure 7-1: BUD Deployment Design Concept

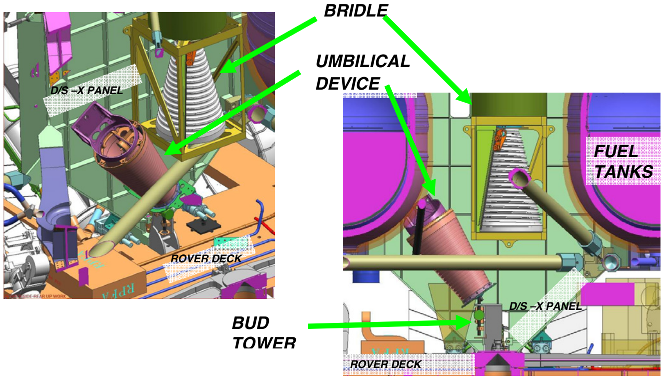

Figure 7-2: BUD Assembly Design

Testing of the BUD device is done in multiple stages and pieces. Initially, a development unit of each device is fabricated and tested to insure that the device will perform as expected. Once all the development pieces have been individually tested, they will be assembled together to run a system test of the overall device. Simple simulators of the DS and Rover will be used in thus full system test. Once the flight hardware is fabricated, one unit will be dedicated to qualification. Limited testing will be repeated at the individual device level and then all the pieces assembled into a full qualification unit. This unit will then be put through a variety of tests including vibration, thermal vacuum, and DS-Rover and BUD-Rover separation tests which will use a flight-like DS Hex structure and a flight-like Rover.

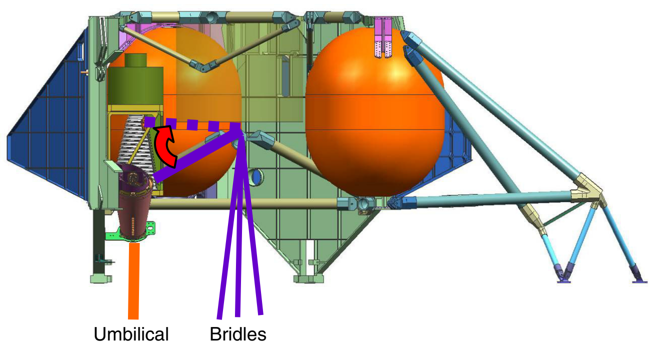

Figure 7-3: Bridle and Umbilical Routing Design

8.0 SUMMARY

In summary, this paper has described the preliminary design of the CEDL mechanical system and the challenges that the team must address. Although there is much heritage to the past Mars missions, the significantly larger payload and Rover has required new design approaches to be implemented for the entry descent and landing portions.

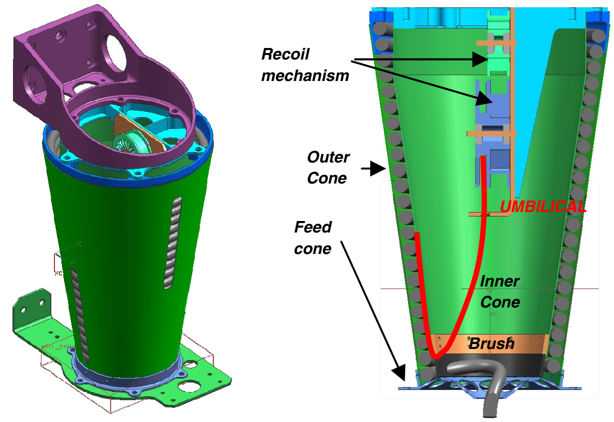

Figure 7-4: Umbilical Design

References

[1] Tom Rivillini, et al., " CEDL Baseline Description Document", October 2006, MSL Docushare Library Collection #4122

[2] Neil Dahya, "Cruise Stage Initial Design Review Package", 19 May 2006, MSL Docushare Library Collection #4235

[3] Tony Agajanian, "Aeroshell Preliminary Design Review Package", 7 May 2006, MSL Docushare Library Collection #27969

[4] Jennifer Knight, "Backshell Interface Plate and Parachute Support Structure Initial Design Review Package",10 August 2006, MSL Docushare Library Collection #28025

[5] Anita Sengupta, "MSL EDL V&V Review: Parachute Decelerator System", 3 May 2006, MSL Docushare Library Collection #4422

[6] Ben Thoma, "Descent Stage Initial Design Review Package", 23 May 2006, MSL Docushare Library Collection #4302

[7] John Gallon, Richard Webster, "Separation and Pyro Initital Design Review Package", 28 July 2006, MSL Docushare Library Collection #4609

[8] Michael Gradziel, Michael Shafer, "Bridle & Umbilical Device: Umbilical Initial Design Review and Bridle Conceptual Design Review", 2 November 2006, MSL Docushare Library Collection #21605

[9] Pam Hoffman, Tom Rivillini, et al., "MSL Mechanical Systems Preliminary Design Review: CEDL Mechanical Subsystem", 12 June 2006, MSL Docushare Library Collection #25607

BIOGRAPHY

Pamela Hoffman *received her B.S degree in Mechanical Engineering from the University of California, Berkeley in 1987 and her M.S. degree in Mechanical Engineering from the California Institute of Technology in 1989. She has been working at NASA's Jet Propulsion Laboratory for the last 19 years developing a variety of deep space missions including Galileo, NSCAT, Cassini, Europa Orbiter, Pluto Kuiper Express, Mars Exploration Rover, and Mars Science Laboratory. Currently, she is the Project Element Manager for the Cruise, Entry, Descent, & Landing Mechanical Subsystem on MSL.*

Tomasso Rivellini *received his Bachelors degree in Aerospace Engineering from Syracuse University in 1989 and his Masters degree in Aerospace Engineering from the University of Texas at Austin in 1991. He has been working at NASA's Jet Propulsion Laboratory for the last 15 years developing innovative landing systems for a variety of planetary landers. Tom co-invented the Mars Pathfinder/MER entry, descent and landing system architecture, and was the lead engineer for the airbag subsystem. Tom was the deputy mechanical systems architect for the Mars Exploration Rover mission. He is currently the mechanical systems engineer responsible for the development of the Mars Science Laboratory's entry, descent and landing hardware elements.*

Eric Slimko *is a Senior Member of the Technical Staff at the Jet Propulsion Laboratory in the Spacecraft Mechanical Engineering Section, specializing in hardware and analyses of entry systems . He has authored and co-authored several papers in the field. He is currently a mechanical system engineer for the Cruise, Entry, Descent, and Landing phase of the Mars Science Laboratory Spacecraft. He received his B. S. in Aerospace Engineering from the University of Michigan and Ph. D. in Computational Neural Systems from the California Institute of Technology.*

Neilesh Dayha *received his Bachelors degree in Mechanical Engineering from University of Delaware in 1995. He has been working in the Aerospace industry for the past 12 years at a multitude of Aerospace companies and Nasa Centers. Neil has supported the CAPL 3 Shuttle Experiment, the MAP mission at NASA Goddard, the GALEX program at Orbital Sciences, and CEV proposal work at Northrop Grumman. Neil is currently the MSL Cruise Stage Cognizant Engineer.*

Anthony Agajanian *received his Bachelors degree in Electrical Engineering from the California Polytechnic Institute - Pomona in 1990. Recently returning to NASAs Jet Propulsion Laboratory, Anthony has assumed the role of Contract Technical Manager for the MSL Aeroshell Subsystem. Anthony also brings a diversified experience base to the MSL team as he has worked on a variety of Government and commercial space programs including Mars Pathfinder, ICO, Cassini and Spaceway™.*

Jennifer Knight *received her B.S. in Aerospace Engineering from the California State Polytechnic University, Pomona in 1999 and her M.S. in Mechanical Engineering from the University of Southern California in 2003. She has been at the Jet Propulsion Laboratory since 1998 in the structures area, and has worked several missions including the Mars Exploration Rovers (MER) and the Active Mirror Telescope (AMT). She is currently the Cognizant Engineer for the Mars Science Laboratory (MSL) Backshell Interface Plate (BIP) and Parachute Support Structure (PSS).*

Anita Sengupta *received her PhD and MS in Aerospace Engineering from the University of Southern California and BS in Aerospace Engineering from Boston University. 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 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.*

Benjamin Thoma *received his B.S. in Mechanical Engineering from the University of Wisconsin in 1999 and his M.S. in Mechanical Engineering from the University of California, Berkeley, in 2000. He has been working at the Jet Propulsion Laboratory since 1998 in the structures area and has supported several missions including Mars Exploration Rover (MER). He is currently the Cognizant Engineer for the Mars Science Laboratory (MSL) Descent Stage.*

Richard Webster *has over 35 years experience in electro-mechanical design engineering with 25+ years in the field of pyromechanical design and development. Prior to JPL, he worked at Hi-Shear Technology Corporation, supporting diverse NASA and JPL projects such as Galileo, Magellan, COBE, TOPEX-Poseidon and Pathfinder. He has been at Jet Propulsion Laboratory since 2000 as the lead pyro engineer and has supported several missions including Mars Exploration Rover (MER), Deep Impact, Phoenix and Aquarius. He is currently the Cognizant Engineer for the Mars Science Laboratory (MSL) Pyro Devices.*

John Gallon *received his B.S. in Mechanical Engineering from the University of Kansas in 2000. Before coming to JPL in 2005, he worked five years with the Department of Defense at the Naval Air Warfare Center Weapons Division at China Lake, CA, supporting various military and NASA programs including Mars Exploration Rover (MER). In 2005, he came to work at JPL in support of the Mars Scince Laboratory Project and is currently the Cognizant Engineer for Separations.*

Michael Gradziel *received his Bachelors degree in Mechanical Engineering from Rensselaer Polytechnic Institute in 2003. He has been working at NASA's Jet Propulsion Laboratory since 2001 primarily on the Mars Exploration Rover and Mars Science Laboratory projects.*