The Mars Exploration Rovers Entry Descent and Landing and the Use of Aerodynamic Decelerators

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Abstract

The Mars Exploration Rovers (MER) project, the next United States mission to the surface of Mars, uses extensive aerodynamic deceleration in during its entry, descent and landing (EDL) phase. These two identical missions (MER-A and MER-B), which deliver NASA's largest mobile science suite to date to the surface of Mars, employ hypersonic ablative energy dissipation, a supersonic/subsonic disk-gap-band parachute and an airbag landing system within EDL. This paper gives an overview of the MER EDL system and speaks to some of the challenges faced by the aerodynamic decelerators.

Introduction

The MER-A and MER-B missions will deliver the identical rovers to the surface using an EDL scenario based on Mars Pathfinder heritage.[1] The overall challenge of the EDL phase to MER is quite great. MER is exploiting very similar EDL architecture to that of MPF but is delivering ~80% more payload mass (445 kg vs. 250 kg). This increased delivery performance of the EDL system has required extensive redesign of the aerodynamic decelerators used in the system.

The vehicles are headed to the equatorial region of Mars with MER-A targeted to land at the in the Gusev crater and MER-B scheduled for landing in the Meridiani plains. They are to be launched in June and July of 2003. Each lander will carry a rover that will explore the surface of Mars making in-situ measurements. However, unlike the Mars Pathfinder Sojourner rover, these rovers are larger (approximately 1.5 m by 1 m) and more capable accommodating an increased suite of science instruments. In addition, the rovers will be able to traverse greater distances (approximately 1 km) during surface operations.

The landers will decelerate with the aid of an aeroshell, a supersonic parachute, solid propellant retrorockets, and air bags for safely landing on the surface. Fortuitous hyperbolic approach conditions in the 2003 opportunity enable the use of the MPF architecture for EDL. An overview of the EDL hardware is shown in Figure 1.

Unlike MPF, however, there is no base station on the MER landers. The more capable MER rovers carry all equipment (e.g., science instruments, communications, etc.) necessary for surface operations. Hence, once the rovers drive off the landers after landing, they are self-sufficient (Fig. 2). The MER

landers act functionally as "pallets" that only delivery a payload (the rovers) to the surface.

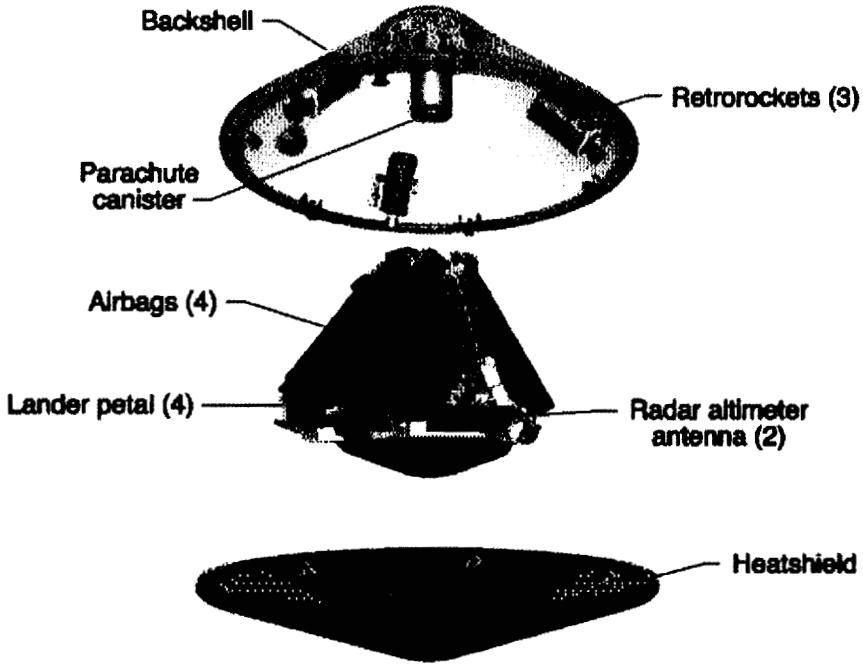


Figure 1. EDL Hardware Overiew

Figure 2. Mars Exploration Rover On Surface

The MER mission relies on Mars Pathfinder "heritage". However, to meet the increased surface payload requirements, the EDL performance needs have driven some significant changes to the MPF EDL design. First, the parachute has been increased in size by 40% in area and its construction has been extensively modified to deliver higher strength to weight. Additional sets of steering rockets and additional sensing capacity has been added to the vehicle to counter the threat of increased wind shear brought about in part by a requirement to land during the daylight hours. Finally, extensive redesign of the airbag subsystem was required to meet the final impact requirements.

Entry Conditions

The MER landers will arrive at Mars in January and February 2004. There are a number of differences between the MER and MPF entry conditions. In particular, the entry mass, entry local time, and landing site altitude are different. All of which drive changes to the EDL design from that of MPF. The entry conditions for MER and MPF are summarized in Table 1.

Table 1

COMPARISON OF MER AND MPF ENTRY CONDITIONS

Parameter	MER-A	MER-B	MPF
Arrival Date	4 Jan 2004	8 Feb 2004	4 Jul 1997
Arrival Season	Mid Winter	Late Winter	Summer
Entry Velocity	5.7 km/s	5.8 km/s	7.26 km/s
Entry Direction	Posigrade	Posigrade	Retrograde
Local Landing Time	Afternoon	Noon	Pre Dawn
Entry mass	845 kg	845 kg	585 kg
Landed mass	550 kg	550 kg	310 kg
Landing site altitude	−1.3 km	−1.3 km	−2.6 km
Landing Latitude	5° N to 15° S	10° N to 10° S	19° N

The MER entry mass of 845 kg is much higher than the 585 kg of MPF. The local entry time is in the middle of the afternoon, leading to a less dense atmosphere profile than the pre-dawn entry of MPF. In addition, there is a requirement to be capable of reaching a higher landing site altitude than MPF. These three differences produce a higher terminal velocity and less time for performing all the EDL events due to the reduced deceleration during the entry. Therefore, the EDL systems are being modified to accommodate these issues. An overview describing the specific changes to each EDL flight subsystem is presented in the following sections.

EDL Sequence

Both MER landers will entry the Mars atmosphere directly from their interplanetary transfer trajectories. The MER EDL sequence is illustrated in Fig 3. Upon Mars arrival, the landers will be separated from their respective cruise stages 30 minutes prior to atmospheric entry. After approximately 240 s from entry interface, the parachute is deployed (altitude of ~8.9 km), followed by heatshield release 20 s later. The lander descent along its bridle is initiated 10 s later. At an altitude of 2.4 km above ground level (AGL), the radar altimeter acquires the ground. Altimeter data is used by the on-board flight software to

determine the times for airbag inflation, retrorocket motor ignition, and bridle cut. Nominally, airbag inflation will occur 4 s prior to retrorocket motor ignition (~160 m AGL). At an altitude of ~15 m AGL, the bridle will be cut, and the inflated airbag/lander configuration freefalls to the surface. Sufficient impulse remains in the retrorocket motors to carry the backshell and parachute to a safe distance away from the lander.

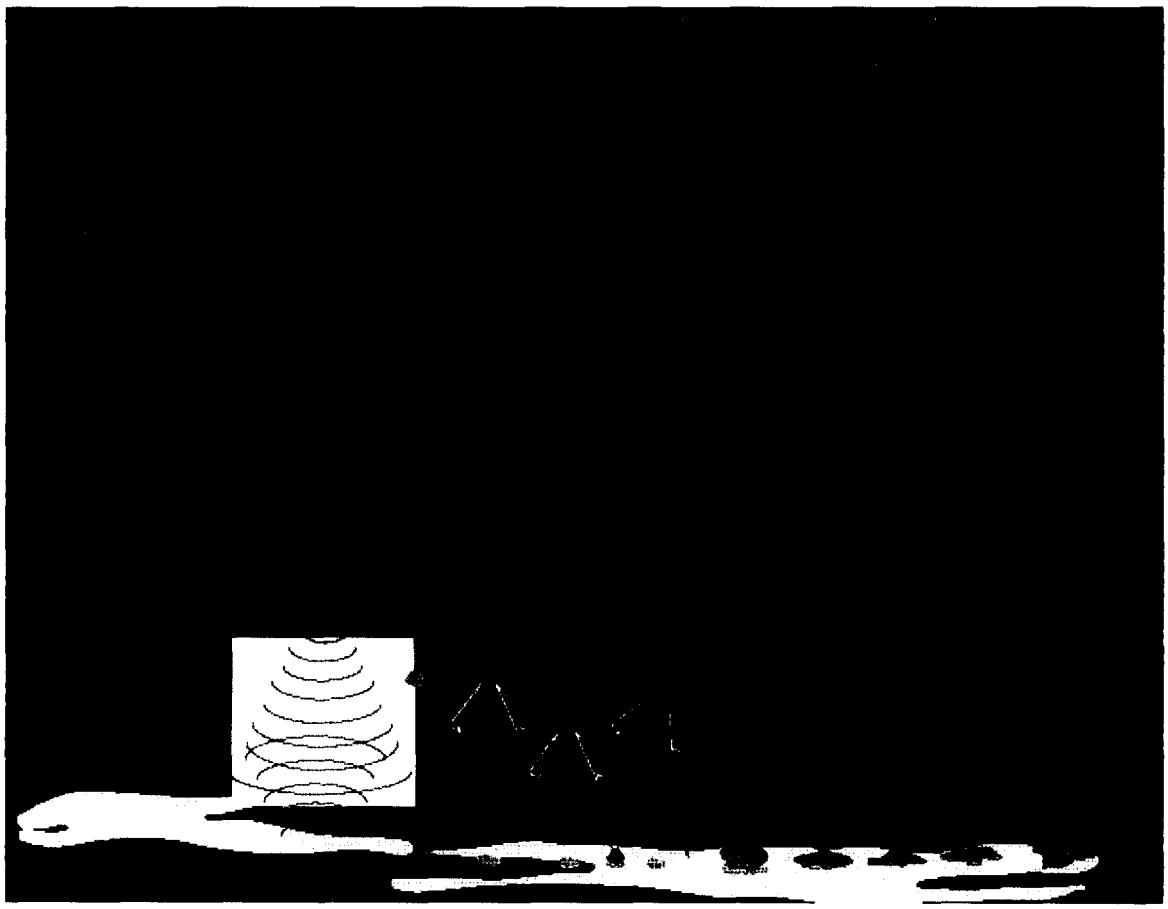


Figure 3. MER EDL Sequence of Events

Entry

The maximum inertial entry velocity (across MER-A and MER-B) of 5.8 km/s is 20% less than that of MPF. This slower entry velocity coupled with utilizing a shallower entry flight-path angle allows the accommodation of the higher MER mass of 775 kg during the entry. The nominal entry flight-path angle selected for MER is −11.5 deg. For comparison, the MPF entry flight-path angle was steeper having a value of −14.2 deg. The MER entry angle was chosen to be as shallow as possible to accommodate the entry mass, while still satisfying the requirement of maintaining a 1.0 deg margin between skip-out and the 3-σ shallow entry. The navigation uncertainty on the entry flight-path angle is ±0.5 deg for MER-A and ±0.7 deg for MER-B. This navigation capability may

require the execution of a trajectory correction maneuver as late as 12 hours prior to entry. For comparison, MPF planned for a late maneuver, but its execution was not necessary due to fortuitous navigation. The uncertainties listed are for arrival to Northern Latitude landing sites. As the landing sites shift towards Southern Latitudes, these uncertainties decrease approximately by half.

Hypersonic deceleration is accomplished utilizing an aeroshell. The MER aeroshell is based on the MPF design with only minor changes to increase inside volume[2]. Figure 4 shows the MER aeroshell dimensions. The aeroshell consists of a forebody heatshield and an aftbody backshell. The forebody shape is a Viking heritage 70 deg half-angle sphere cone. The forebody material is a lightweight ablator (SLA-561), while the backshell is protected with a spray-on version of the SLA-561 material. The heatshield is also based on MPF heritage with a minor change to the thermal protection system (TPS) thickness. The MER heatshield is sized to 1.63 cm instead of the 1.91 cm of MPF. Despite the heavier entry mass, the combination of a slower entry velocity and shallower entry flight-path angle produces a less severe entry environment as compared to MPF. The resulting performance margin allows for a reduction in the TPS thickness. The entry environment is described in Table 2.

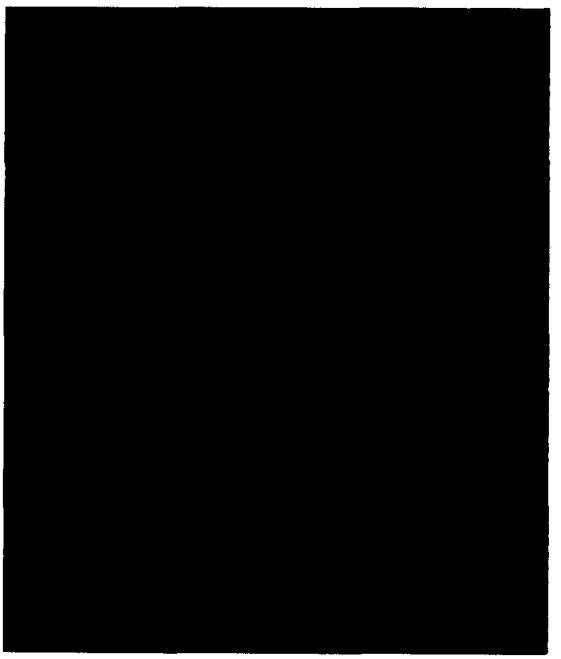


Figure 4. MER Aeroshell Configuration

(from Desai and Lee 2002, with permission of authors)

Table 2

COMPARISON OF MER AND MPF ENTRY ENVIRONMENTS

Metric	MER	Design Limit	MPF
Peak heating, W/cm^2	41	50	105
Total heat load, J/cm^2	2900	3400	3900
Peak deceleration, Earth g	8	10	20
Peak stagnation pressure, kN/m^2	12.2	25	24

Initial Descent

Due to the higher entry mass, less dense atmosphere, and higher landing site altitude, the time from parachute deployment to retrorocket initiation is reduced as compared to MPF. In order to provide sufficient time for performing all EDL

events during descent, a combination of modifications is made to the MER entry. The altitude at parachute deployment is raised, the parachute deployment algorithm is modified, and the size of the parachute is increased from that of MPF.

The parachute system/deployment process is modified in three ways to provide sufficient time for descent. First, the parachute deployment altitude is raised by setting the deployment dynamic pressure for MER to a mean value of 650 N/m^2, slightly higher than the 600 N/m^2 used by MPF. This condition corresponds to an altitude of approximately 8.9 km. Second, a more accurate parachute deployment algorithm is implemented based on dynamic pressure rather than a deceleration value which was used on MPF. A dynamic pressure trigger minimizes the variation in the deployment dynamic pressure resulting from off-nominal conditions. The maximum dynamic pressure observed in approximately 730 N/m^2, which is a little higher than 703 N/m^2 expected by MPF. Overpressure tests conducted during MPF indicate feasibility of exceeding 730 N/m^2.

Lastly, in order to accommodate the higher entry mass, the MER parachute area is increased by 40% (as compared to the MPF design). The larger area provides greater deceleration, thereby increasing the descent time. The MER parachute is based on the MPF design, which was a modified Viking heritage disk-gap-band design. However, the MER parachute maintains the same disk-gap-band ratios as MPF. Additionally, the parachute trailing distance of 9.4 body diameters is identical to MPF, which avoids wake interference issues. This increase in chute size coupled with the changes to parachute deployment, allow for sufficient time for performing all EDL events.

Terminal Descent

After deploying the parachute, the vehicle will take approximately 120 s to descend to the surface. However, simulations indicate that the statistical variations in atmospheric density and parachute drag performance predictions may result in descent times as short as 65 s. The predicted upper-bound terminal velocity of 85 m/s is 32% greater than that experienced by MPF. Table 3 lists the major contributions to the differences in terminal velocity between MER and MPF.

Table 3

CONTRIBUTION OF ENTRY CONDITIONS ON TERMINAL VELOCITY

	MER	MPF	Terminal Velocity Change
Heaver Descent Mass (kg)	752	530	+20%
Less Dense Atmosphere	Mid-afternoon	Pre-dawn	+21%
Higher Landing Site Altitude (km)	−1.3	−2.6	+3%
Larger Chute Drag Area (m^2)	57	50	-7%

The higher velocity results in the need for larger retrorockets with 70% more impulse than those used on MPF. These solid rockets are arranged in a symmetric cluster of three along the inside surface of the backshell (see Fig. 1), and will provide a total system impulse of up to 95,000 N-s. During the descent, the flight-computer will utilize radar altimeter data to ignite the retrorockets at

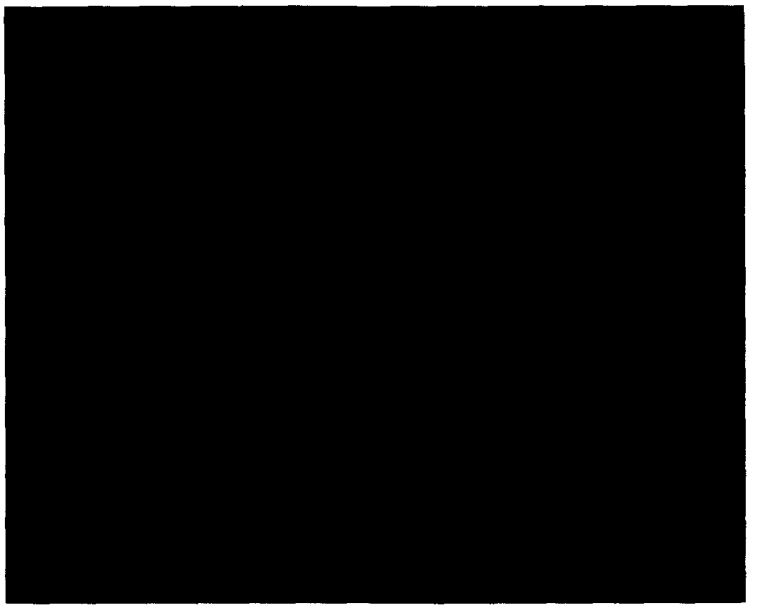
an altitude of approximately 160 m. The goal is to zero the vertical velocity 13 m above the ground. At that time, the parachute and backshell will be released by severing the bridle, after which the lander freefalls to the ground.

Monte Carlo analysis of the terminal descent performance indicates a non-trivial (~10%) number of cases with impact velocities in the 20 m/s to 30 m/s range which reduces the margin on airbag capability described below. These cases result when the vehicle is hit with wind shears near the time of retrorocket ignition. The shears cause pendulum motion in the terminal descent configuration. This causes the backshell to swing off vertical at angles of up to 20 deg, resulting in a self-induced horizontal velocity component from firing the retrorockets with a net off-vertical thrust vector. In order to improve the performance reliability of the EDL system, the three small "steering" rockets (1200 N-s each) were added. These rockets can be fired at the time of retrorocket ignition to steer the net rocket impulse vector to a more verticle position.

Landing

Impact with the Martian surface will be cushioned by a set of airbags similar in outward appearance but significantly changed in design to those used on MPF. The airbag system actually consists of four separate interconnected airbags arranged in a tetrahedron shaped structure. Each of the bags consists of six spherical-shaped lobes and is made from the material Vectran. The significant modification in the airbag design comes from the use of a double bladder system. The MPF airbags had single bladders and four layers of "abrasion protection" in the form of 100 denier vectran cut with ~6% fullness and attached atop the bladder. Testing has shown that a double bladder system in which the inner gas sealing membrain is cut with fullness, removes the gas membrain from the pressure vessel induced stresses (PR/t stresses). This keeps a gas seal in cases where the Pressure related stresses locally overwhelm the material strength. Recent drop tests performed at the NASA Glenn Research Center, Plum Brook Station facility, indicate an impact velocity absorption capability of at least 26 m/s with a MER landed mass of 550 kg. For comparison, the airbags were qualified to 26 m/s with a landed mass of 410 kg during the MPF testing campaign.

The performance of the EDL system during the landing event is a function of not only the impact velocity state and the surface features with which the airbag landing system is interacting (rocks and slopes). A prediction of the maximum size for the landing footprint for the arrival opportunity is determined by assuming a Northern Latitude landing (corresponding to largest navigation uncertainties). The resulting landing footprints for MER-A and MER-B are approximately 215 km by 15 km and 330 km by 20 km, respectively. The landing ellipses are shown in Fig. 5. As the landing site moves further south, the size of the landing footprint decreases. For comparison, the predicted landing footprint for MPF was 300 km by 50 km.



MER-A Landing Footprint

MER-B Landing Footprint

Figure 5. MER-A and MER-B Landing Footprints

SUMMARY

This paper gives an overview of the Mars Exploration Rover (MER) mission entry, descent, and landing (EDL) system design. This mission relies on Mars Pathfinder heritage. However, the entry, descent, and landing conditions and environments are different from that of Mars Pathfinder. The entry mass will be higher. In addition, the local time of entry is later in the day (early afternoon) which will result in a less dense atmospheric profile. Furthermore, the landing

site altitude is higher. These differences result in a higher terminal velocity and less time for performing all the EDL events as compared to Mars Pathfinder. As a result of these differences, modifications are made to a number of the EDL systems. The parachute size has been increased and its deployment algorithm has been changed to improve deployment accuracy. In addition, the size of the retrorocket motors is increased to provide greater impulse. These modifications are made to safely deliver the rovers to the surface of Mars. The EDL system will continue to evolve as the mission approaches the launch date.

NOTATION

AGL	Above Ground Level
EDL	Entry, Descent, and Landing
MER	Mars Exploration Rover
MPF	Mars Pathfinder
TPS	Thermal Protection System
A	Area
C_D	Drag Coefficient

ACKNOWLEGDEMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology (under a contract with NASA) and the NASA Langley Research Center. The authors would like to extend their appreciation to all the members of the MER EDL design team for their contributions.

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