

Landing on Mars

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Abstract

There have been five fully successful robotic landings on Mars. The systems used to deliver these robots to the surface have shown large design diversity and continue to evolve. How will future Mars landing systems evolve to eventually deliver precious human cargo? We do not yet know the answers, but current trends tell us an interesting and daunting tale.

Nomenclature

Q	Dynamic Pressure, Pa or N/m^2
β	Ballistic coefficient, kg/m^2
EDL	Entry Descent and Landing
MT	Metric Ton
MSL	Mars Science Laboratory
MER	Mars Exploration Rover

Introduction

The foremost challenge in the design of Entry, Descent, and Landing (EDL) systems for Mars landers is energy removal. The need to precisely remove between 99.9995% and 99.99999% of the initial energy with respect to the surface is obvious. A landing event with a residual energy dissipation error of great than 3 ppb may spell disaster for some landers. Designers are further challenged by the need to position the final landing point within 10s of km (or less) of a target for satisfying mission objectives and for targeting safe territory.

Unlike EDL at Earth where the viscous drag of our thick atmosphere focuses descent trajectories toward acceptably low (1 – 20 m/s) vertical descent velocities for aerodynamic vehicles (like winged Shuttles or capsules with parachutes), Mars' rarefied atmosphere (less than 1/100th of Earth's) demands propulsion or very high impact velocity touchdown systems for safe landing. The bulk of the residual energy from hyperbolic or orbital entry (>99%) is dissipated 10 – 50 km above the ground in the hypersonic domain (Mach >5), by the time that the velocity is low enough to deploy supersonic and subsonic decelerators (including

propulsive ones), the vehicle may well be very near the ground with insufficient time to prepare for landing. EDL on Mars is further exacerbated by the bi-modal (hypsometric) surface elevation where fully half of the surface of Mars may be out of reach of aerodynamically decelerated landers due to insufficient atmosphere (see Fig. 1). So far, all of the US Mars EDL systems flown to Mars have been under 0.6 MT at landing and have been limited to landing at elevations less than -1.3 km (see Fig. 2). The Mars Science Laboratory mission, planned for landing in 2010 is attempting to target its highest landing elevation capability near +2 km so that a reasonable fraction of the Ancient Highlands can be accessed.

These limitations are primarily due to the velocity reduction limitations inherent in the entry and descent systems inherent in these Viking-derived entry and descent systems. These limitations pose a challenge to designers of future EDL systems that need to deliver larger robotic payloads to the surface of Mars. For even larger landed payloads intended for piloted missions, the challenge is even greater. Before human-scale missions to the surface of Mars can be taken seriously, the development of new EDL systems and technologies must commence.

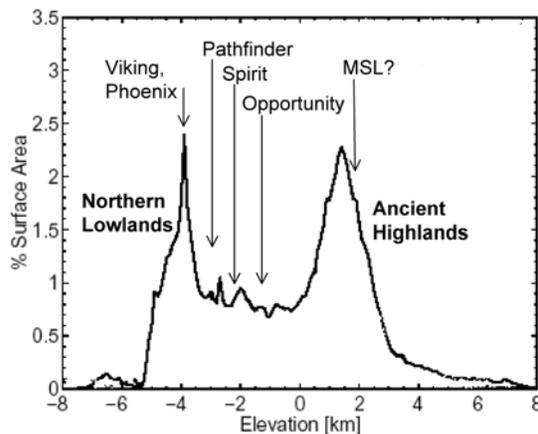


Figure 1. Mars elevation area distribution and various elevation capabilities of past and current missions.

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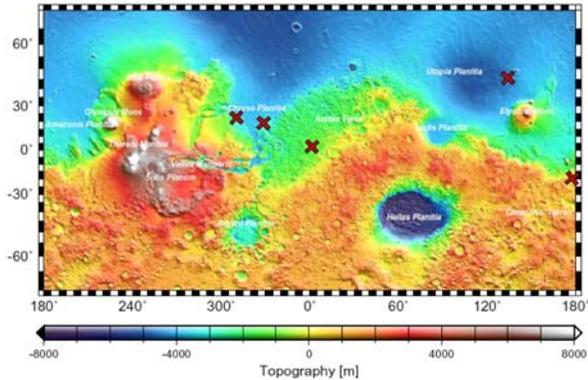


Figure 2. Past five US landing sites (all below -1.3 km).

History

The first Mars landing attempt (Mars 2) in late 1971 by the USSR resulted in failure, however the second attempt later in that year (Mars 3) resulted in a partially successful landing and 20 seconds of transmission from the surface before permanently falling silent. The EDL

architectures employed by these early missions were later adopted successfully in 1997.

The five successful US landing attempts began in 1976 with the dual landing of Viking 1 and 2. The Viking mission and the EDL technology that was developed for it, has become the backbone for all US missions since. More than 20 years later in 1997, Mars Pathfinder (MPF) lander, containing Sojourner Rover, adapted entry and descent technology from Viking and merged it with the deceptively simple terminal descent and landing architecture also employed by the Soviets. Most recently, the Mars Exploration Rover (MER) EDL system that landed Spirit and Opportunity Rover in early 2004 was an “improved” spin-off from the Mars Pathfinder EDL design. In the coming years, the Phoenix lander (2007), and MSL (Mars Science Laboratory) will apply new variations on these designs. Key entry, descent and landing parameters for past missions and for upcoming Mars missions are summarized in Table 1.

Landing Year:	1976	1976	1997	2004	2004	2008	2010
Mission:	Viking 1	Viking 2	MPF	MER-A (Spirit)	MER-B (Opportunity)	Phoenix (planned)	MSL (planned)
Entry From	Orbit	Orbit	Direct	Direct	Direct	Direct	Direct
Entry Velocity (km/s)	4.7	4.7	7.26	5.4	5.5	5.67	7.47
Orbital Direction	Posigrade	Posigrade	Retrograde	Posigrade	Posigrade	Posigrade	TBD
Entry Flight Path Angle (deg)	-17	-17	-14.06	-11.49	-11.47	-12.5	-14.6
Ballistic Coefficient (kg/m ²)	64	64	63	94	94	70	100
Entry Mass (kg)	992	992	584	827	832	600	2700
Entry Attitude Control	3-axis RCS	3-axis RCS	2 RPM passive	2 RPM passive	2 RPM passive	3-axis RCS	3-axis RCS
Entry Lift Control	C.M. offset	C.M. offset	no offset	no offset	no offset	C.M. offset	C.M. offset
Entry Guidance	Unguided	Unguided	Unguided	Unguided	Unguided	Unguided	Apollo guidance
Lift to Drag Ratio	0.18	0.18	0	0	0	0.06	0.22
Aeroshell (Heatshield) Diameter (m)	3.5	3.5	2.65	2.65	2.65	2.65	4.6
Heat Shield Geometry	70 deg cone	70 deg cone	70 deg cone	70 deg cone	70 deg cone	70 deg cone	70 deg cone
Heat Shield TPS	SLA-561	SLA-561	SLA-561	SLA-561	SLA-561	SLA-561	SLA-561
Peak Heating Rate (W/cm ²)	26	26	80-100	50	50	50	140?
Parachute Diameter (m)	16	16	12.5	14	14	12.4	19.7
Drag Coefficient (approx.)	0.6	0.6	0.4	0.4	0.4	0.6	0.6
Parachute Deploy Mach No.	1.1	1.1	1.57	1.77	1.77	1.6	2
Parachute Deploy Dyn. Pressure (Pa)	350	350	585	725	750	420	750
Parachute Deploy Altitude (km)	5.79	5.79	9.4	7.4	7.4	9	6.5
Altitude Sensing	RADAR Altimetry	RADAR Altimetry	RADAR Altimetry	RADAR Altimetry	RADAR Altimetry	RADAR Altimetry	RADAR Altimetry
Altitude Sensing Range (km)	137	137	1.6	2.4	2.4	1.6	6
Horizontal Velocity Sensing	Doppler RADAR	Doppler RADAR	none	Imaging/IMU	Imaging/IMU	Side-looking RADAR	Doppler RADAR
Terminal Descent Decelerator	Throttled Bi-prop	Throttled Bi-prop	Solid Rockets	Solid Rockets	Solid Rockets	Pulsed Bi-prop	Throttled Bi-prop
Horizontal Velocity Control	Throttled Bi-prop	Throttled Bi-prop	passive	lateral SRMs	lateral SRMs	Pulsed Bi-prop	Throttled Bi-prop
Touchdown Vertical Velocity (m/s)	2.4	2.4	12.5	8	5.5	2.4	<1
Touchdown Horizontal Velocity (m/s)	1	1	20 (design)	11.5	9	<1	<0.5
Touchdown Attenuator	3 legs	3 legs	4-pi Airbag	4-pi Airbag	4-pi Airbag	3 legs	6 wheels
Touchdown Rock Height Capab. (cm)	20	20	50	50	50	20?	100
Touchdown Sensor	Leg crush motion	Leg crush motion	none	none	none	Leg crush motion	Off Load
Landed Ellipse Major axis (km)	280	280	200	80	80	260	20
Landed Ellipse Minor axis (km)	100	100	100	12	12	30	20
Landing Site Elevation (km MOLA)	-3.5	-3.5	-2.5	-1.9	-1.4	-3.5	2

Table 1. Past and Future Mars Lander Summary.

Entry Vehicles

The initial conditions for Mars entry are typically established at an altitude about 125 km above the surface and well above the atmosphere. Specifically this entry point is defined by convention to be 3522.2 km from the center of Mars. The atmosphere-relative velocity of entry ranges from 5.5 – 7.5 km/s for direct entry systems to 3.3 – 5 km/s for entry from Mars orbit.

The objective of entry is to deliver the vehicle into the Mach number and dynamic pressure range of the supersonic decelerators (e.g. parachutes) at an altitude above the ground such that there is sufficient time to further decelerate and perform terminal propulsive descent. For the Viking-derived entry systems, this target is typically 6 – 11 km above the ground at Mach 2.1 or less. The entry and descent altitude (referenced to MOLA altitude) vs. velocity phase plot for these missions are shown in Fig. 4. The inflection point in the trajectories in the lower left corner of Fig. 4 indicates where the parachute is deployed.

As can be inferred from the Table, while there is considerable variability in the terminal descent systems, the design of these entry vehicles are all based directly on Viking's blunt 70 deg sphere-cone heatshield and the Silica Lightweight Ablator (SLA-561) thermal protection subsystem material (TPS) design. Despite its axial symmetry (see Fig. 3), this shape is stable even if an angle of attack is induced (e.g. a center of mass offset). This allows for a lift-to-drag ratio as high as 0.24.

While modest, studies based on Apollo-like (Earth return) hypersonic guidance algorithms have shown that this small lift-to-drag ratio (or even smaller) in combination with inertial sensing can result in nearly a 10x reduction in the size of the dispersed a-priori landing ellipse. Studies being performed for MSL and previous missions indicate that 7 – 10 km semi-major axis landing precision (3-sigma) is attainable at the point of parachute deployment. Compare with the >40 km semi-major axis for MER, MPF and Viking. However, for hypersonic guidance control margin, only about 0.18 is useful for "average lift to drag ratio" that may be utilized to maximize elevation at landing. To maximize the use of this lift in reduction of energy, generally the lift is applied in the downward direction (forcing the trajectory downward) while the vehicle's

velocity is above the orbital velocity of Mars (around 3.4 km/s) and is upward for slower velocities.

The Viking heatshield forms the backbone of all of the Mars EDL systems in Table 1. While many other hypersonic decelerator architectures (shapes and TPS) for Mars have been considered, the Viking system has proven itself to be the most cost effective so far: the aero-database, including the lift characteristics for that shape are well characterized and the SLA TPS has been well-tested and flight-proven.

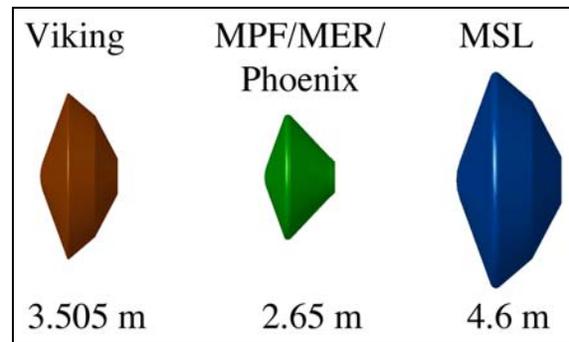


Figure 3. Viking-heritage aeroshells and diameters.

In the era of frequent low cost missions, the Viking entry heritage has obvious advantages, but it has its limitations as well. The delivered (landed) mass that has been flown to date has been less than 0.6 MT. Even the much larger MSL rover will weigh in at only 0.7 MT. Mission design analysis for (small) robotic sample return missions suggest that landed and entry mass capability twice that of MSL may be required. For human-scale missions, the delivered mass may need to go up by nearly two orders of magnitude. What constraints limit growth of the heritage Viking entry system?

One very important constraint is the aeroshell diameter. In order to maximize drag area and thus ensure sufficient deceleration, the diameter must be sized such that the entry mass to drag area (also called ballistic coefficient or β) is maintained sufficiently low such that the parachute deployment conditions can be attained before running out of altitude. However the diameter is limited by the interior diameter of the Earth launch vehicle fairings (see Fig. 7). These range from less than 3 m (Boeing Delta II) to 5 m (ATLAS V).

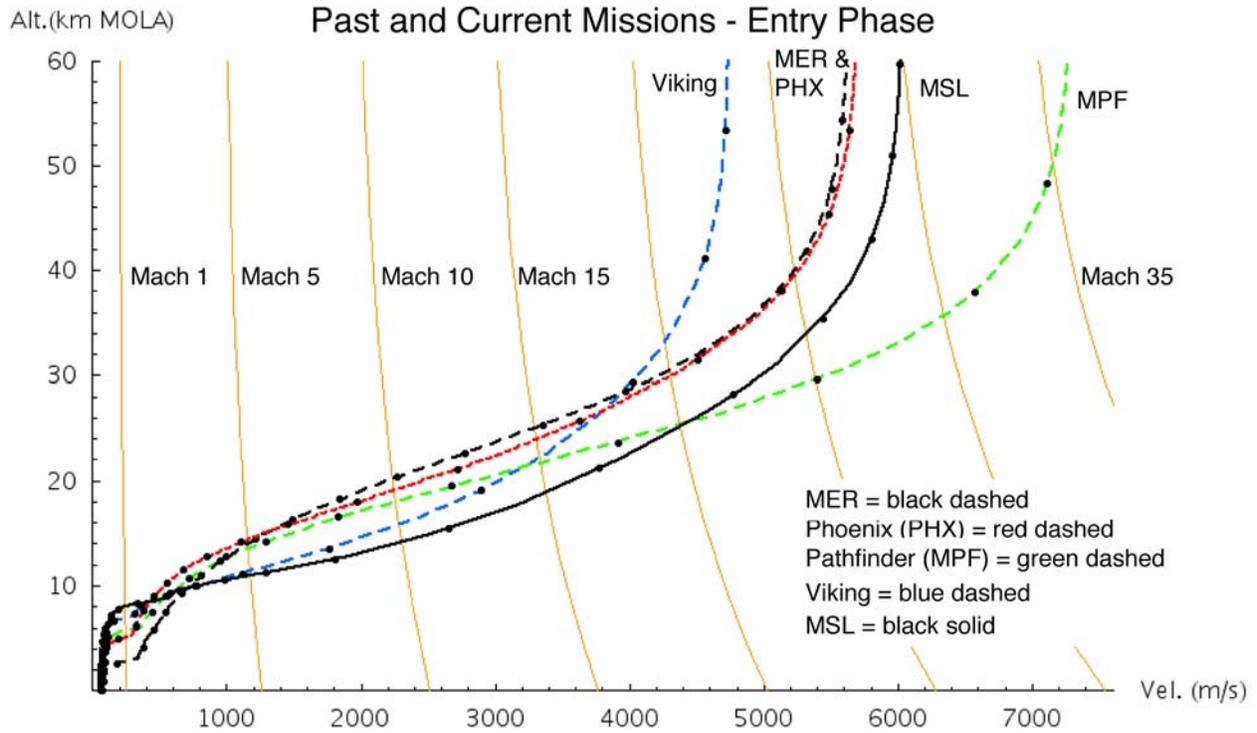


Figure 4. Phase space trajectories from past and current missions. Black dots are on 10 s intervals.

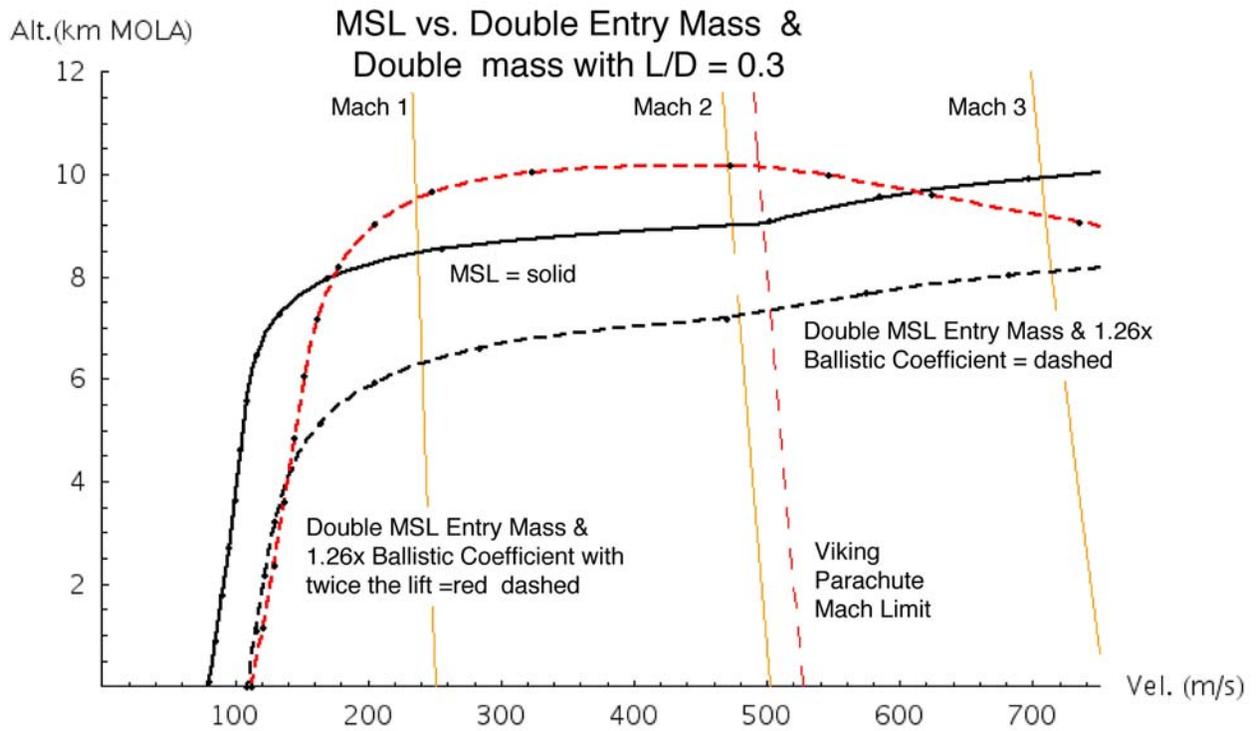


Figure 6. Phase space trajectory for an entry vehicle with twice the entry mass and a ballistic coefficient 1.26 times that of MSL (black dashed) and that same vehicle with twice MSL's lift (red dashed). MSL's trajectory is shown for comparison (solid). Note the parachute deployment altitude differences at Mach 2.

To date, β has ranged from 63-94 kg/m². The largest now being planned is MSL, with its much larger 4.6 m diameter heatshield, it is expected to grow to about 100 kg/m².

It is not surprising that the ballistic coefficient for Viking-heritage entry shapes would go up as the diameter of the aeroshell grows. Since the mass density of the entry vehicle's internal payload is likely to remain somewhat constant (at least for robotic craft), and as the mass is proportional the vehicle's diameter cubed and the drag area is proportional to the diameter squared, to first order, β will grow in proportion to the diameter. (This rule of thumb was strained by the extraordinarily high mass density of the MER rovers which were nearly a factor of two higher than Viking. The MSL mission is wisely returning to the Viking density regime.) This trend is shown in Figure 5.

For larger proposed landed systems, like Mars Sample Return or the proposed Astrobiological Field Laboratory (AFL) with an estimated entry and landed mass a factor of two larger than MSL's, if their aeroshell internal mass density is similar to MSL's, the diameter will grow by a factor of 2^{1/3} or x1.26 to 4.6 m x 1.26 = 5.8 m. This will force these missions to be launched on vehicles with very large fairings that do not yet exist. Likewise the ballistic coefficient will grow to 1.26 x 100 kg/m² = 126 kg/m². Can the Viking entry system, with its average lift-to-drag ratio limit of 0.18 perform with β as high as 126 kg/m²?

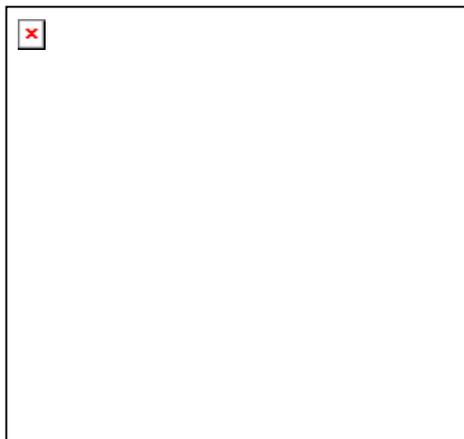


Figure 5. Trend of increasing ballistic coefficient with heatshield diameter.

Fig. 6 shows a trajectory for a vehicle with a ballistic coefficient of 126 kg/m² that uses the maximum lift to drag ratio available to the Viking shape (about 0.18). It is clear that the 2.5 km lower parachute deploy altitude will reduce the ability of that system to land at high elevations compared with MSL.

(Recall that MSL can land no higher than +2 km.) This system, with its higher ballistic coefficient, will only be able to land at -0.5 km or lower, out of reach of the Ancient Highlands of Mars.

Additional lift could benefit both elevation and/or mass. If a vehicle with twice the mass of MSL and a ballistic coefficient of 126 kg/m² could be built with twice the lift-to-drag ratio of MSL (as high as 0.3), the resulting system could deploy its parachute 2 km higher than MSL (see red dashed line on Fig. 6). Unfortunately there is no low-cost way to modify the Viking shape to get the lift-to-drag ratio that high. Another constraint is the shape and volume of the Viking-derived entry vehicles. For stability, the Viking 70 deg architecture requires that the center of mass of the entry vehicle remain within about 0.3 diameters of the nose. For very large entry masses, this volumetric and mass property constraint may pose excessive constraints on the design and packaging of human scale payloads.

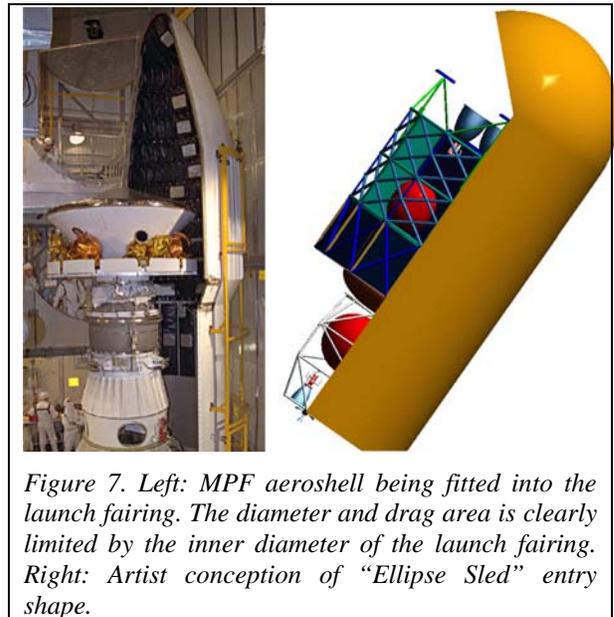


Figure 7. Left: MPF aeroshell being fitted into the launch fairing. The diameter and drag area is clearly limited by the inner diameter of the launch fairing. Right: Artist conception of "Ellipse Sled" entry shape.

One proposed solution, the so-called "Ellipse Sled" configuration, packs much more payload mass within the aeroshell shape. This shape is also much more compatible with Earth's aerodynamic launch vehicle fairings (and in fact could double as a launch fairing) than the "flying saucer" shaped Viking entry aeroshell (see Fig. 3). This shape has an effective (usable) lift-to-drag ratio of about 0.5. As its intent is to pack more into a sleeker and larger volume, the Ellipse sled is expected to have a much higher ballistic coefficient than the Viking blunt body vehicles flown so far. However for the same diameter, estimates range from 200 to 500 kg/m². While this shape offers improved lift-to-drag ratio,

the higher ballistic coefficient easily could overwhelm the benefits. At the very least, these entry systems may be forced to utilize supersonic deceleration systems that do not exist today.

Other proposals use inflatable structures that allow the drag area to be enlarged just prior to entry. These systems reduce the ballistic coefficient to regimes where the hypersonic deceleration occurs at very high altitudes (>35 km). These systems show great potential for mass and elevation improvement. However thermal protection and flexible structures interaction with the control system pose significant challenges for future EDL designers.

Finally, future very large entry systems will result in higher radiative heating that may exceed the capabilities of Viking's SLA (with a heating rate limit somewhere between 100 and 200 W/cm²). While not affecting the shape, qualification of a new Mars TPS system is expensive.

Mars Descent Systems

The entry system terminal velocity of these systems in the Martian atmosphere is typically a few hundred meters per second. While that is much slower than the several km/s entry velocity, it leaves something to be desired as an impact velocity. When conditions permit, a supersonic parachute is deployed to increase the ballistic coefficient of the system and slow it to subsonic speeds, around 100 m/s, and facilitate the use of small rocket systems for the final velocity reduction. Besides simply the added drag, the parachute also provides for vehicle stability through the subsonic regime. In addition, the increase of ballistic coefficient allows for the positive downward separation of the heat shield, a critical step in the reconfiguration of the system for landing.

Analogous to the entry system, all of the Mars landing systems in Table 1 use parachute systems derived directly from the Viking parachute development. In 1972, high-altitude, high-speed qualification tests of the Viking parachute in Earth's atmosphere were successfully conducted. These tests showed the parachute design would robustly deploy, inflate, and decelerate the payload in the expected flight conditions. Due to the expense of these tests, their like has not been attempted since. Instead, all of the subsequent parachutes rely on the qualification of the Viking design combined with lower-cost subsonic and static testing to verify deployment and strength characteristics.

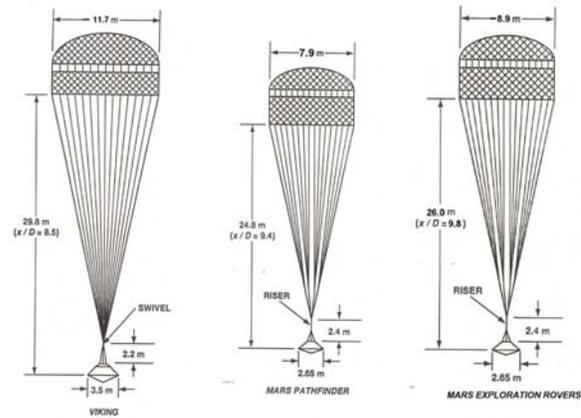


Figure 8. Viking-derived parachute systems.

The Viking project selected a “disk gap band” or DGB design for the parachute, shown in Figure 8, whose acronym directly describes the construction of the parachute from a disk that forms the canopy, a small gap, and a cylindrical band. The Viking parachute system was qualified to deploy inside the rectangle on a Mach / Q plot between Mach 1.4 and 2.1, and Q between 400 and 700 Pa.

Post-Viking applications of the DGB design varied the size and some proportions of the parachute, being careful to not invalidate the Viking qualification. The Viking, Mars Pathfinder, and Mars Exploration Rover parachutes all performed their functions admirably. MSL will be the first application with a parachute larger than what Viking flew. However in this case, the Viking qualification program tested a parachute of the size planned for MSL, and so those Viking test results are significant for the planned MSL parachute qualification.

As we look to larger, greater than one metric ton delivered systems, we will break out of the Viking qualification regime with respect to parachute size. Figure 9 shows another trend for higher ballistic coefficient entry systems, where the Mach limit is reached at significantly lower altitudes. So in addition to larger size, a higher deployment Mach will likely be required. These greater requirements will mandate a new high-altitude supersonic qualification program to enable those missions.

Once subsonic conditions are achieved, a larger parachute that is less expensive to qualify can be deployed to reduce the velocity further and hence the requirements on the terminal descent system, as well as potentially provide more time for the lander reconfiguration and sensing events. Such staged parachute systems may provide compelling enough system benefits to outweigh their complexity and risk.

For piloted missions with very high entry ballistic coefficients, an entirely new regime is entered for this stage of deceleration. Instead of deployments around Mach 2, we now would have to consider deployments around Mach 4 to 5. Entirely different decelerator approaches will need to be considered for hypersonic operation since the traditional parachute is very inefficient at those speeds, deployment will be problematic, to say the least, and heating issues will challenge the soft good materials that can be used. Various semi-rigid inflatable concepts have been proposed, possibly with staging from the hypersonic parachute to either a supersonic or subsonic

parachute that would operate more efficiently at the lower speeds.

Alternatively, one could forgo a deployable decelerator completely for these very high ballistic coefficient entries, and instead transition directly to a propulsive descent beginning at Mach 4 to 5. That would incur a mass penalty for propellant, and a development program to qualify the operation of the propulsion system at those ram-air speeds. That all-propulsive approach would need to be traded against the cost and risk of a hypersonic deployable decelerator development.

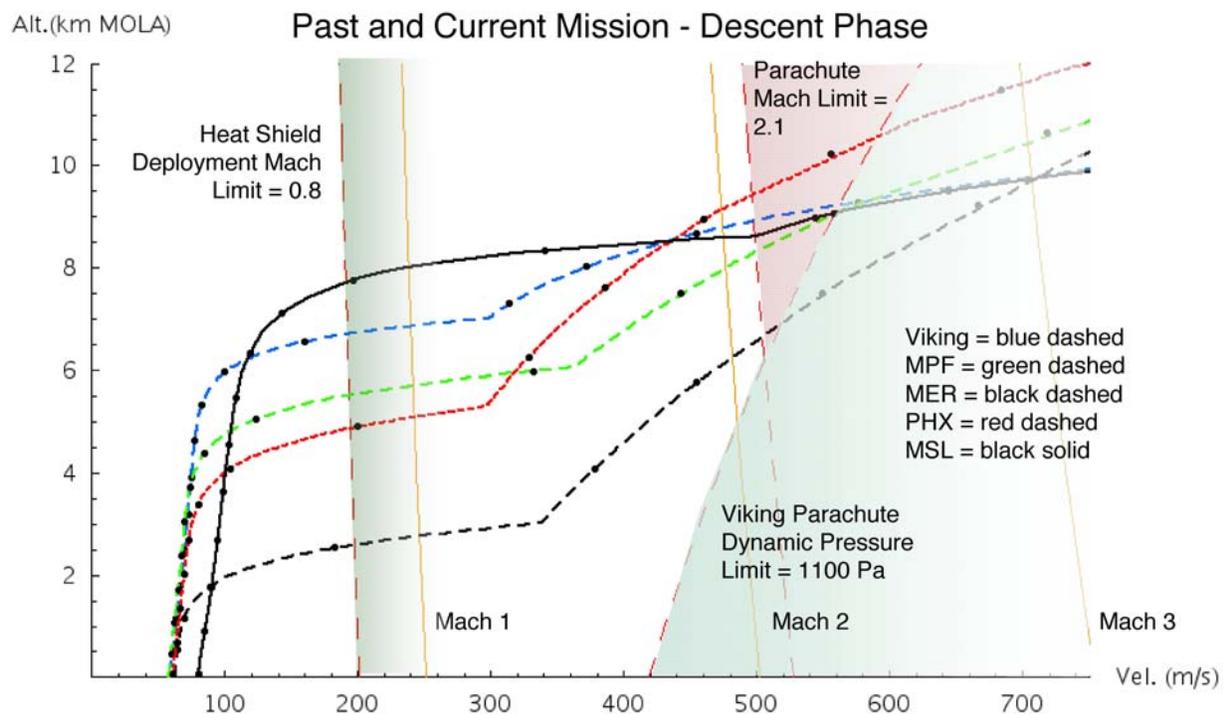


Figure 9. Descent Trajectories in Altitude / Velocity Space.

Mars Terminal Descent and Landing

The terminal descent systems used to date and in development have provided the largest source of EDL variety. Despite the large visual differences, these systems have far more in common than meets the eye. All of these systems are initiated while suspended on a parachute near terminal velocity (between 55 and 90 m/s) and below 1 km above the ground. They are all designed to deliver their payloads within the horizontal and vertical velocity envelopes of their touchdown equipment.

The Viking missions of 1976 were largely influenced by the design of lunar landers (like Apollo) and were not constrained by today's very small budgets (see Fig. 10). Viking's low mass design choice was to use landing legs with small clearances for rocks, Radar altimetry and Doppler Radar to detect horizontal velocity and bi-propellant throttled engines that brought the lander to within 2.4 m/s +/- 1 m/s vertically and <1 m/s horizontally. The high cost to develop new throttled engines that diffused the plume to prevent excessive trenching was of relatively little consequence to the overall project cost. This choice was made easier by the impression that the selected landing surfaces of Mars were relatively flat and

rock-free. Once on Mars however, the designers were surprised to see large rocks so near the lander (see Fig. 11).



Figure 10. The Viking Lander.

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TIFF (LZW) decompressor
are needed to see this picture.

Figure 11. Big Joe at the Viking 1 landing site.

Mars Pathfinder in 1997 was influenced by the need for extreme cost savings and the design of past Lunar and Mars landers as well as US Army payload delivery systems. MPF's approach to reduce cost was to use the Viking entry and descent systems (with passive attitude control) and the use of low cost solid rocket engines that would deliver the lander to much larger range of touchdown velocities than legged landers could typically handle. This would also eliminate the need for horizontal velocity estimation with Doppler Radar. The consequence was the need for a heavy and difficult-to-test 4-pi steradian airbag system that could handle initial vertical velocities as high as 16 m/s and horizontal velocities as high as 22 m/s with the potential for several tens of bounces on rocks as high as 0.5 m and 30 deg slopes (see Fig. 12).

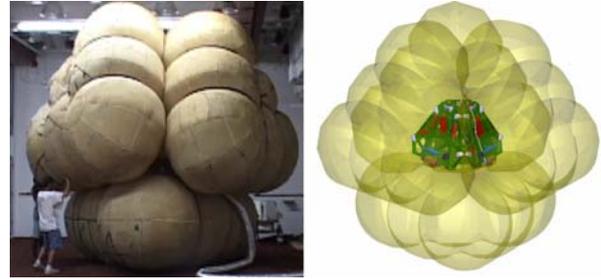


Figure 12. Mars Pathfinder and MER airbags.

The MER missions, arising from the programmatic turbulence suffered after the loss of two Mars missions in late 1999, were most affected by schedule and secondarily by cost. As these missions (proposed in April 2000 by the authors) were intended to use the MPF EDL design for the most part "designed-to-print" so that the schedule to the 2003 launch date could be achieved, there was no initial expectation of modifications of MER's EDL. However as further information was gained (higher suspended mass - 50% higher mass density over MPF, and higher anticipated winds - based on global circulation models and recently acquired topography models), it was discovered that the MPF terminal descent heritage was insufficient to be able to deliver the MPF airbags to an acceptable velocity envelope. New horizontal control systems (inertial measurements and small solid rocket motors in the backshell) and new horizontal velocity estimation using descent imagery were added to ensure sufficient EDL system reliability. In addition, the MPF airbags were redesigned and toughened to handle the higher mass of the payload, and to survive higher impact velocities, up to 26 m/s.

The upcoming Phoenix mission is almost entirely based on the design of the Mars Polar Lander mission that ended in loss during its landing attempt in 1999 (see Fig. 13). This mission was also driven by the need for cost savings. Relatively expensive horizontal Doppler radar velocity measurement was avoided by using canted multi-beam radar. Expensive throttled engines were avoided by using off-pulsed engines at high duty cycles. While not as tolerant of rocks and slopes as the MPF/MER touchdown system, the ability to find areas on Mars less rocky and with less slope will allow Phoenix to land safely. Recent full-scale testing of the duty-cycle modulated propulsion system has demonstrated that pulsed mode engine firing is safe.

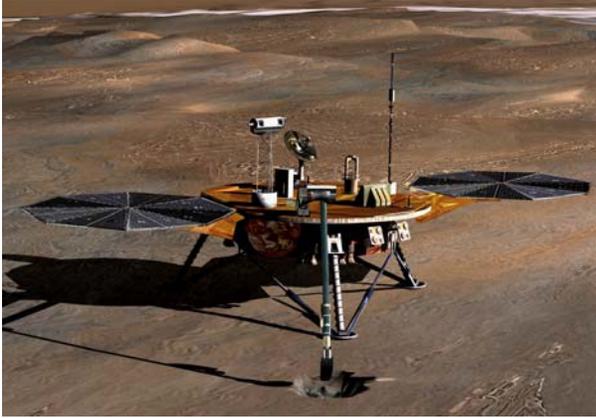


Figure 13. Phoenix Lander

The MSL landing system (proposed after Phoenix was selected) forges new ground in touchdown system design. For landers (like Phoenix) where the descent engines fire very close to the ground, in order to avoid creating hazardous pits and throwing rocks and dirt at and on top of the delivered payload, one of the design constraints is to make certain that either the engine plume's surface pressure is low or that the firing engines spend a minimum amount of time in the vicinity of the surface. The latter is accomplished by descending as fast as the landing gear will allow. This conflicts with the need for high ground clearance for high rocks under the vehicle, and slope tolerance. Positioning the terminal propulsion system and its propellant tanks under a rover presents egress-ability challenges as well. The realization that the MPF/MER terminal descent propulsion system (the solid rocket motors) in the backshell suspended above the lander could be "upgraded" to throttled bi-propellant engines resolved the conflict. By virtue of their relatively large distance to the surface, descent engines suspended above the lander (rover) could deliver its payload to the surface with much lower velocity without a significant increase in propellant.



Figure 14. MSL's Skycrane Descent Sequence

This descent system (dubbed the "Skycrane" after its namesake helicopter) could completely eliminate the need for heavy landing gear (like airbags) while at the same time increase tolerance of the lander to slopes and rocks (see Table 1). In fact MSL is

planning to land the rover directly onto its wheels without affecting the design of the rover mobility system (see Fig. 14). Due to the partitioning, this system has the potential to someday allow Mars EDL systems to be designed to be generic deliver systems without regard to the robotic system being delivered much as launch vehicles are today.

Will the Skycrane become the Mars touchdown system of the future? While it is well suited to deliver 700 kg rovers to the surface, as EDL payloads get larger still, it is so far unclear how these touchdown systems will evolve. It is conceivable at least, that the terminal descent propulsion will be positioned so that the engine plume is not so near the ground and so mobile systems are closer to the surface after landing. Other configurations are possible.

Conclusions

While there is significant variation in the terminal descent and landing systems flown and in development today, the entry and descent systems are quite similar and are based on the Viking legacy. That legacy is also the largest constraint on the ability to land larger payloads to higher elevation, and so the next steps are unclear. With improved supersonic decelerators, such as with larger, higher-Mach parachutes or the possible use of supersonic propulsive decelerators, the Viking entry shape and its TPS could retain its vitality for years to come. It depends on the demand for larger payloads and especially on the availability of financial resources for subsystem development and qualification. For human-scale landers that must deliver orders of magnitude more mass than today's Viking-derived systems, the story is even murkier. Only radically new systems that today are in conceptual form, at best, will be able to slow down the tens of tons of payload screaming through the thin atmosphere of Mars.

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