Second Generation Mars Landed Missions

James Graf, Howard Eisen, Tom Rivellini, Dara Sabahi, Sam Thurman
Jet Propulsion Laboratory/California Institute of Technology
4800 Oak Grove Drive, M/S 264-440
Pasadena, CA 91109
818-354-4765
james.e.graf@jpl.nasa.gov

Abstract—Mars future landed missions include safe, accurate landing of payloads large enough to accomplish a sample return mission or to accommodate both a comprehensive science instrument suite and extensive in situ resource utilization payloads. In addition, the landers may be fixed (immovable) or have sufficient mobility capability to rove multiple kilometers on the surface. Accurate landing, coupled with extensive roving capability that exceeds landing error ellipses, enable "Go to" missions in which a specific, selected feature (e.g., seepage site) on the surface can be investigated with a major payload complement. This paper addresses some of the candidate missions being considered for the next generation projects, discusses the new approaches being developed to implement safe and accurate entry, descent and landing (EDL) to the Martian surface, and describes the rover technology that enables the long distance and duration surface mission.

TABLE OF CONTENTS

1. INTRODUCTION

The planet Mars never ceases to amaze. Each mission seems to answer a few questions, uncover more secrets, tantalize with new mysteries and, in the end, generate more questions than were answered. In order to make headway in understanding the planet, more capable science payloads need to be landed on the surface with vastly increased engineering functionality. At the same time, the landed mission must be delivered safely to more scientifically exciting, but also more rugged, regions. A group of engineers from National Aeronautics and Space Administration (NASA) centers, academia, and industrial contractors have been forging a new path to provide the engineering capability to get significantly greater payloads (upwards to 300 kg) safely and accurately to the surface. Called the "second-generation landing and roving concept," it builds on some of the technology from previous and ongoing missions, including that from Mars Pathfinder (MPF), Mars Exploration Rover (MER), and Viking and also pioneers new ground in many areas such as hazard detection and avoidance and greater landing gear robustness.

This paper discusses the evolution of the landing and roving technology to the next generation capability and its applicability to the large landed missions envisioned over the next decade. Particular emphasis is placed on the EDL system and on the rover capability. EDL has changed dramatically from previous missions in order to increase both landing robustness and payload mass fraction as well as to address the need for more accurate landing precision. The design of the landing gear itself has also undergone a revision. Legged landers have given way to airbag landers with roll arrest or to crushable pallets.

To have the ability to truly explore large reaches of the planet in situ or to go to specific sites of interest, such as potential sites identified by Mars Global Surveyor (MGS), accurate, safe landing needs to be augmented with an increased mobility capability. New and physically larger rover concepts are being tested that enable ranges up to tens of kilometers, depending on the power source. These roving science platforms are self contained: (1) they transmit data to Earth directly or via orbiting asset; (2) contain energy conversion hardware to extend their life on the surface; (3) do not need to waste time retracing their steps to a home base but can move to new sites of interest; and (4) carry large scientific payloads, in order to conduct extensive in situ science investigation. The rover wheels are large enough to surmount obstacles up to 0.75 meters in height, thereby requiring fewer obstacle avoidance maneuvers and enabling more time for science acquisition or roving. Figure 1 shows a rough comparison of the size of the Pathfinder rover (landed in 1997), the MER (under development for launch in 2003), and next generation rover.

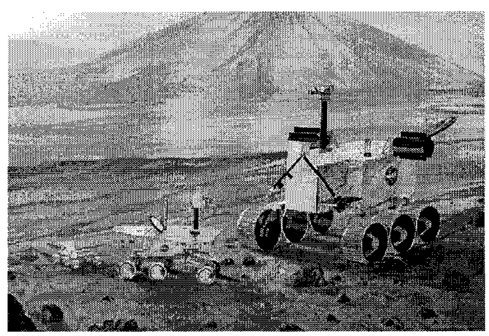


Fig. 1. Size comparison of Rover concepts.

Once on the surface, the ability to explore is generally restricted by the energy conversion hardware. MPF experienced ~ 0.3% per sol degradation on its solar arrays caused by what is believed to be dust deposition on the cover glass [1]. New methods are under development to understand and overcome the degradation mechanism. In addition, new concepts for radioisotope power sources are being assessed. These devices would enable several years of operation on the surface and free the lander from solar illumination constraints.

2. SECOND GENERATION MISSION OBJECTIVES

Science missions to Mars are becoming more challenging in their objectives: (1) some operate instruments at the surface performing in situ science data acquisition; (2) others (called "Go to" missions) transport uniquely designed payloads to a specific feature on the planet's surface; and (3) still others return scientifically selected samples of the planet to Earth for further study. One thing in common is that the payloads for all these missions are growing in terms of the physical size, mass, and power requirements over previous missions to the surface. Further, high priority missions like Mars Sample Return (MSR) require the safe landing and nurturing of moderate sized ascent boosters as well as clean and sterile sample handling equipment to levels not previously achieved in space missions.

The in situ surface mission payload might consist of stereo imagers, spectrometers, rock corers, in situ resource utilization experiments, sample analysis devices, environmental monitoring experiments, drills with capability to perform downhole science, and sample handling equipment to get the samples to the deck-mounted instruments. In second-generation systems, arms to reach the surface and mobility of the entire lander are included in the mission as engineering devices and are not included in the payload. The lander mobility can vary from zero (i.e., a fixed, stationary lander) to tens of kilometers.

Sample return missions would use "hyper-clean" sample handling equipment (clean and sterilize to level 4B as defined by the NASA Planetary Protection Provisions [2] to: (1) acquire a scientifically selected sample, (2) seal it in a canister, (3) sterilize the outside of it and 4) load it into a device called an orbiting sample (OS) that would eventually be orbited around Mars or sent directly towards Earth. The OS is contained in the nose cone of a Mars ascent vehicle (MAV). The MAV is maintained in an environmentally controlled volume within the lander prior to launch. In addition to the MAV-related equipment described above, the mission also supports in situ instruments. With the ascent vehicle launched via a method used for recoilless missile launch techniques, such as the Tomahawk missile, the lander would survive MAV launch and continue to rove the surface of Mars.

"Go to" missions deliver a payload to a specific site of interest at the surface of the planet. Similar to the in situ mission, it has accurate and safe landing capability with a landing ellipse major axis of 6km (3σ). It also has a mobility range large enough to reach the site of interest from the small landing ellipse and has special engineering equipment onboard to enable the emplacement of the science package in the precise location of interest. In order to visit a specific site like that on a crater wall, the lander would first land safely, rove up a site of interest (i.e. a crater wall), install an instrument package by either raising it up the cliff wall or lowering it down from the top of a crater, acquire data, and transmit it back to Earth. To go physically to the "water" all of the key elements of the second generation capability would be needed.

Based upon informal inputs from the science community of candidate instrument sets and from the potential MAV developers, a set of generic set of payload requirements were generated and are shown in Table 1. This list is representative and is not meant to define the specific set of requirements that an individual mission would use. The dominating resource estimates are mass (300kg), energy on the surface (650 W-hr/sol), and volume to accommodate an ascent vehicle with a characteristic length of approximately 2 m. In comparison, the first-generation landers have a capability of 20 to 70 kg.

3. TYPICAL MISSION DESCRIPTION

Mars lander missions are proposed for opportunities starting in 2007 and culminating in an MSR mission in the 2011 to 2013 opportunities. These missions would be launched on medium class EELV vehicles (Delta IV 4450-14 or Atlas-V 511) with an injected mass requirement of 2600 kg for direct entry missions. In addition to large payloads, second generation landers enable access to a larger extent of the Mars surface. These landers have narrow landing ellipses, and

Table 1. Strawman Payload Resource Estimate By Mission Type.

Mission Type	# of Instruments	Mass (kg)	Payload Energy (W-hr/sol)	Physical Size/Mounting
In Situ Payload	7	300	650	External and Internally Mounted
Sample Return	4 plus MAV & sample handling hardware	70 for inst. plus 230 for sample return/MAV	650	~2 m length for MAV within Thermal Enclosure
Go to Mission	6	300 including transport hardware	650	External and Internally Mounted

the capability to rove outside of this ellipse. This combination of EDL and rover system capability can enable pinpoint access to predetermined destinations. The primary constraint is solar power and direct entry trajectory constraints. These constraints would be mitigated with options for RPS power and delivery from orbit.

The earliest a second-generation lander can fly under the present Mars program is the 2007 opportunity. The lander most extensively studied for this opportunity is a "Go to" mission with a 2-year life, 6-km (3σ) landing ellipse and roving capability of 30 km. The three major elements of this referenced landed mission are the cruise, EDL, and surface phases, which are described below.

Cruise Phase—In this phase, all missions use a Type-II transfer trajectory. Launch is in September of 2007 with a three-week launch window and a maximum C_3 of 14.7 km^2/s^2. Arrival is no later than September of 2008. Mars arrival is in late spring in the Northern Hemisphere. The cruise duration is 11 to 12 months and the V_∞ is 2.8 km/sec. The cruise phase utilizes a passive, sacrificial cruise stage with independent mono-propellant propulsion and optical navigation capability to support the lander during this phase. For this opportunity and for a direct entry mission, the Mars local solar time at landing is 1:00 pm.

For a variation on the reference mission, a relay orbiter replaces the cruise stage. In this concept, the orbiter provides orbit insertion capability for the combined lander/orbiter vehicle and allows for lander entry from orbit. The mass penalty for chemical propulsion insertion is large and requires a larger launch vehicle. After lander release, the orbiter can provide telecom relay capability future missions.

EDL Phase—This phase is the most critical phase of the mission and requires significant technology development in order to meet reliable landing requirements. Defined in the next section of this paper, the key EDL requirements are:

- 6.0 km/sec entry velocity
- ballistic coefficient of $120kg/m^2$
- 5.0-km landing radius
- 1.0-meter rock tolerance
- 30-deg slope tolerance
- 2300 kg entry mass
- 1700 kg landed mass

The EDL system meets and exceeds the above requirements by utilizing robust EDL subsystems. The EDL system utilizes the following key subsystems:

- Entry vehicle with entry guidance capability for enhanced performance.
- Subsonic parachute in addition to supersonic parachute for enhanced performance.
- Hazard avoidance capability for increased reliability.
- Throttled powered descent engines to increase reliability.
- A pallet or airbag with self-righting landing system for increased reliability.
- Avionics redundancy, selective cross-strapping and hot backup for increased reliability.
- X-band direct-to-Earth semaphores and UHF real time telemetry relay to an orbiting asset.

Surface Phase—The surface mission is a 2-year mission. The surface system would utilize radioisotope power system (RPS), which would provide complete latitude capability. The 2007 opportunity trajectory with direct entry could deliver the surface system to a latitude band of 9° South to 79° North. The surface phase of the system would utilize a dead-on-arrival lander and a large mobile rover. In all options, the rover utilizes X-band direct-to-Earth telecom link and UHF relay link to an orbiting asset. For an MSR concept, the rover can accommodate a MAV storage and deployment system, sample acquisition, sample transfer and four in-situ science instruments.

Based on preliminary studies, all mission concepts have robust margins. The 2007 "Go to" mission margins are:

• Mass Margin	30% to 37%
• Power Margins	> 45%
• Battery SOC	> 35%
• Data Margin—X-Band	25%
• Data Margin X-band & UHF	> 200%
• Landing Velocity Margin	4 times
• Propellant Margin	30%
• Surface Life Margin	100%

4. Entry, Descent, and Landing Phase

Many important scientific objectives for Mars exploration require the ability to land safely at select sites. The "first-generation" EDL systems used in previous missions imposed limitations on target site selection due to the delivery accuracy achievable and those systems' inability to recognize and avoid hazardous terrain. This section outlines key capabilities of a proposed second-generation EDL system, currently under development by a consortium of NASA centers, industry, and academic institutions.

An illustration of a representative system concept is provided in Figure 2 below. The entry capsule pictured is being designed for both direct entry, as has been done in the recent MPF and MPL missions, or delivery into the atmosphere from orbit, if it is desired to carry the spacecraft into orbit prior to landing. Hence, carrier vehicle options range from a cruise stage to an orbiter spacecraft with a mission of its own.

The entry capsule is designed to accommodate potentially large (600-1000 kg) landers while providing aeromaneuvering capability for closed-loop guidance to within ±3 km (3σ) or better of a designated target site. A biconic backshell is used to obtain high volumetric efficiency in payload packaging (a large rover is shown in Figure 2 as an example). A two-stage parachute system is employed, enabling deceleration of very large spacecraft while allowing time for terminal sensing and hazard avoidance during terminal descent. Both radar and lidar

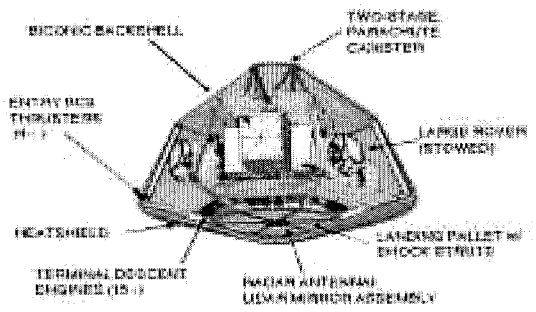


Fig. 2. Entry Capsule Cutaway View.

sensors are used for local terrain-relative navigation to identify safe landing sites to the spacecraft's guidance system.

The touchdown event itself is made as robust as possible to any residual terrain hazards. Figure 3 shows one example of a robust landing approach; a pallet-type structure augmented with webbed shock struts to help prevent tip-over. This scheme and other alternatives are discussed further in the next section and in [3].

The architecture of this system is structured not only to incorporate current sensor technology and guidance/ navigation logic, but also to readily accommodate future capabilities as warranted. Examples of potential future additions include the capability to perform onboard radio navigation via orbiting spacecraft or surface beacons, and guided parachute descent for "pinpoint" delivery to a designated target site.

The key events occurring during EDL are illustrated in Figure 3. This figure also provides approximate values of the altitude, velocity, and timing of each event for a representative direct entry mission.

Approach Phase (not shown)—Prior to entry, the spacecraft must be guided to the target entry corridor. The spacecraft's own propulsion system and guidance system are capable of doing so, or the entry capsule may be augmented with a propulsion system external to the lander itself if desired, controlled by the onboard guidance system. The accuracy of the entry into the atmosphere is enhanced by the use of optical navigation. The spacecraft in its cruise configuration uses a camera to observe the location of moons of Mars and uses that information to perform final maneuvers to adjust its trajectory.

Entry/Atmospheric Deceleration Phase—Once the spacecraft begins to encounter the atmosphere, its entry guidance logic is activated. The guidance system computes bank angle commands to steer the capsule's lift vector such that the correct parachute deploy conditions will be achieved at a desired position relative to the target landing site. This guidance scheme is a derivative of the Apollo entry guidance approach [4], and has been tested extensively in a high fidelity simulation environment [5] for use at Mars.

Parachute Descent Phase—Deployment of the supersonic parachute is triggered by the entry guidance logic at approximately Mach 2.2. This parachute is a derivative of the MPF mortar-deployed parachute, and serves as a drogue parachute here, decelerating the spacecraft quickly to subsonic speeds. Once the vehicle reaches Mach 0.8, the backshell and supersonic parachute are jettisoned (eliminating mass that is no longer needed), and a much larger (30 m) subsonic main parachute is deployed. This parachute is designed to quickly bring even large vehicles to low (40-50 m/s) terminal velocities that provide sufficient time for terminal sensing prior to powered descent.

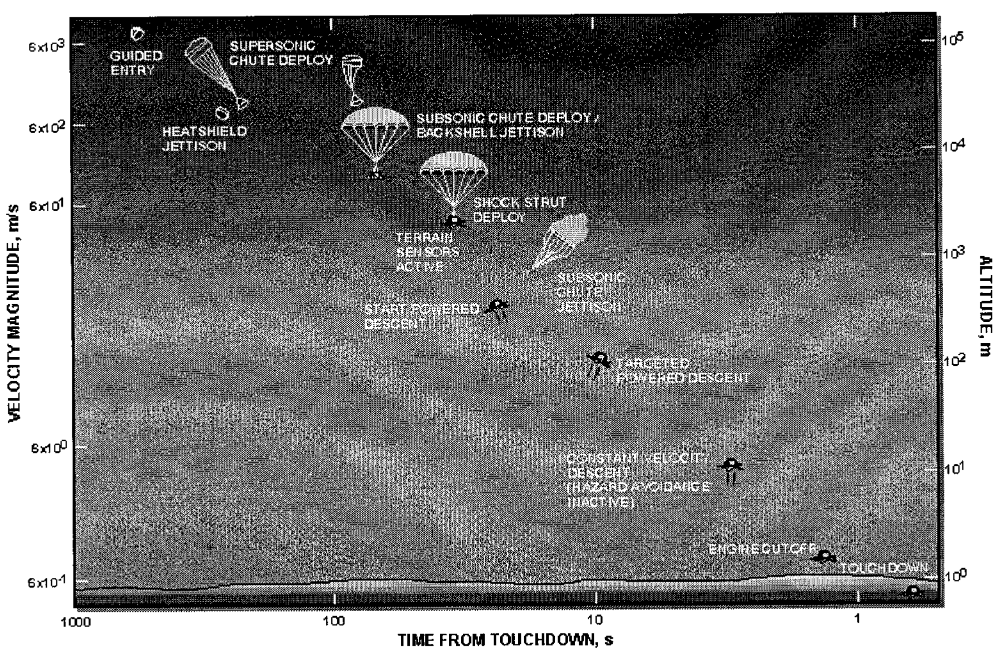


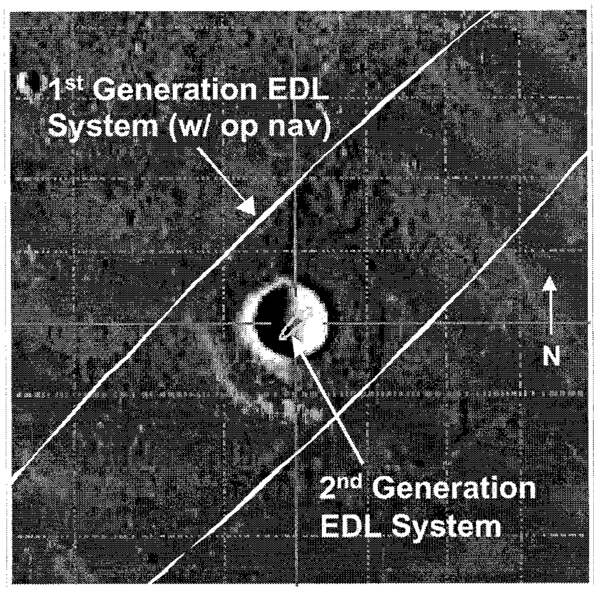
Fig. 3: EDL Sequence of Events.

During parachute descent, terrain-relative navigation is initiated. The landing radar acquires the surface at an altitude of 3700 m, allowing the onboard navigation system to accurately determine the spacecraft's surface-relative altitude and velocity. In the 1500 to 1000 meter range, a scanning lidar begins periodically generating local elevation maps of the surface, in the area surrounding the guidance system's current projected landing site. The lidar elevation maps are used within the guidance system to identify any potential hazards near the projected site, and to redesignate the target site to a safer location if necessary.

Powered Descent Phase—Once the navigation system and hazard identification logic have designated a safe and reachable local target site, the lander's guidance system computes an appropriate time to separate from the subsonic parachute and begin powered descent. This computation establishes a trajectory that will reach the designated target site while maximizing the amount of available performance margin. The radar and lidar sensors, along with the hazard detection and retargeting logic, continue to operate during powered descent, scrutinizing the target site and the surrounding area as the effective resolution of the lidar-generated terrain maps improve, re-designating the target site as needed. The guidance system periodically computes a new reference trajectory leading to the current target site, using a set of algorithms derived from the powered descent guidance logic for the Apollo Lunar Module [6].

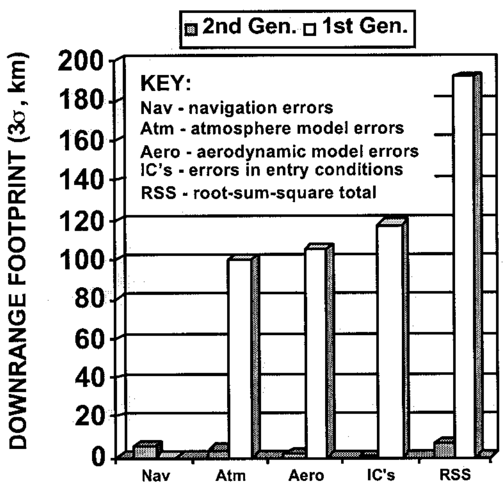
Touchdown—Powered descent concludes with thrust termination approximately 1 m above the surface, resulting in velocity components at touchdown of approximately 3 m/s (vertical) and a tolerance of ±0.5 m/s (horizontal), well within the capabilities of the landing/arrest approaches under consideration.

Delivery Accuracy—The results of a statistical analysis of a hypothetical 2005 mission scenario are shown in Figure 4. The target landing site assumed in this case is at the center of a 10 km diameter crater located in the Elysium Planitia region of Mars, at a latitude of approximately 37° North, 153° West. This crater is representative of many geological features on Mars of scientific interest and contains one of the seepage sites identified by MGS. This site is an example of a "Go to" mission. Figure 4a compares the 3σ dispersion ellipse for a second-generation system with a representative ellipse for a 1st generation system, such as the MPF spacecraft. Figure 4b provides a comparison of an error budget for the two systems, showing the contribution of the principal error sources to the downrange component of the dispersion ellipses shown in Figure 4a. The key difference between the first and second generation systems is the entry guidance capability incorporated into the latter. As shown in Fig. 4b, the delivery error budget for a first-generation system is heavily influenced both by errors in delivering the spacecraft to the correct entry condition and by uncertainties (principally atmospheric and aerodynamic modeling) in the flight environment. The second-generation system, with its onboard navigation capability, is able to sense the effects of modeling errors and correct the flight path, limited only by quality of the navigational information computed onboard. At this point, the limiting error sources for the second-generation system are the onboard navigation accuracy, and modeling errors associated with the few kilometers of unguided parachute descent.



NOTE: grid squares are 10 × 10 km

a) Dispersion Ellipse (3σ)



b) Error Budget

Fig. 4. 2nd Generation EDL System Delivery Accuracy.

5. LANDING GEAR

The EDL sequence ends with safe touchdown on the surface of Mars. The design goal for the optimal touchdown system for the second generation EDL is to develop a touchdown system capable of landing on any terrain ranging from 0° slope with a 1 meter high rock to a 30° slope with a 0.5 meter high rock, with large velocity margins (2 to 4 times the expected velocity). This goal was set to bound most terrain features found in nature with the exception of a very small minority of exceptionally extreme features. It is estimated that this type of landing capability could enable safe landing in over 93% of Martian terrain classified as heavily cratered terrain. This is a vast improvement over all previous landing systems which were designed for lightly cratered terrain.

Three distinct classes of landing gear were assessed: 1) multi-legged (e.g. Viking, Apollo, Surveyor), 2) airbags (e.g. MPF) and 3) pallet (which has no flight heritage). The major difference between the three classes is their approach to surviving landing hazards. The multi-legged systems place the propulsion system and all the sensitive equipment and payloads high above the footpads in an effort to prevent them from ever contacting the ground at touchdown. The pallet system places all of the sensitive equipment and payloads needed after the landing phase well above the ground on shock absorbers, but it leaves the entry and descent-related hardware in a low slung propulsion module, which is specifically designed to impact the ground and absorb damage, but to not fail catastrophically. The airbag systems are designed to provide uniform protection on all sides of the payload, and to discard the entry and descent systems such as propulsion just prior to touchdown.

The multi-legged landing gear (Figure 5a) represents the simplest and most straightforward system to implement and has the greatest heritage of all the systems. The high center of gravity (CG) created by placing all of the payload and EDL mass high above the surface creates a considerable mass penalty when designing this system to land in the required terrain. Even after a successful landing, the surface science payload, rover, arm or drill, is still required to descend to the surface by some means, thereby adding more mass and risk to the mission.

The airbag system (Figure 5b) has the next highest level of heritage deriving from the MPF mission. Airbags have proven themselves to be an extremely robust landing system capable of withstanding repeated impacts at highway speeds. In order to increase the landed mass and still provide a robust level of protection, a throttleable propulsion system providing three-axis control was incorporated to bring the airbag system to a stop within several meters of the surface prior to release of the combined lander/airbag system. This landing system has the potential to provide the highest level of landing robustness of all the concepts considered, theoretically enabling touchdown on the rim of craters with a safe rollout onto flat ground. Self-righting and airbag release of a system of this size (discussed below) represent the largest developments required to implement this system.

The pallet system (Figure 6) has the least amount of heritage of the three classes of landing gear, yet it offers advantages that bridge the previous two systems. The pallet system is able to land in extreme terrain without suffering a large mass penalty by creating an extremely low CG to footprint ratio. It does this by placing the EDL avionics and propulsion hardware in an expendable core structure configured in the lowest part of the system. Only the equipment critical to the extended surface-mission, i.e. rover or other science and engineering hardware, are held up above the surface. In addition, six cable-stayed outriggers are deployed horizontally to the core structure, thereby creating a larger effective footprint for a small mass penalty. The outriggers function to absorb the rotational energy induced when the lander touches down on sloped or rocky terrain. After landing, the low profile core structure enables easy access to the surface for either a rover, arm or drill. Mass is saved by designing the core structure to survive the touchdown event with controlled but non-catastrophic damage, much like the front end of a modern automobile.

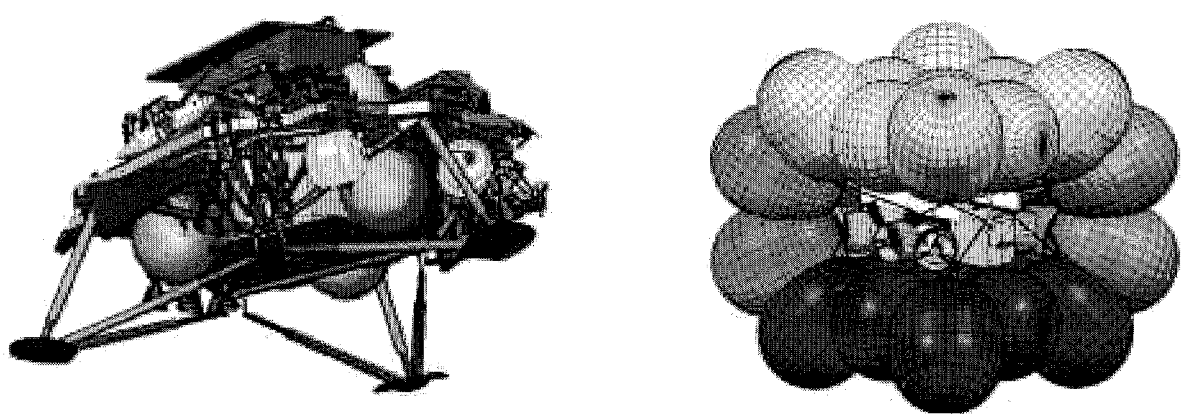


Fig. 5. a) Multi-legged lander concept; b) Airbag lander concept.

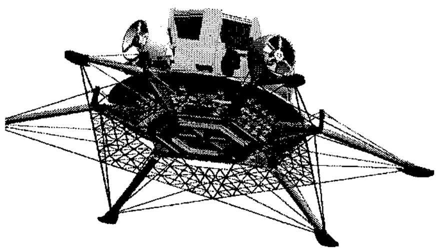


Fig. 6. Pallet lander concept with outriggers.

Currently the pallet and airbag landing gear concepts are under continued study to better understand their performance capabilities. The multi-legged concept is not being pursued due to the risk generated by a high CG, the added difficulty of the payload access to the surface, and the lack of a clear advantage in mass. Prediction and validation of the landing dynamics and performance envelope is the primary focus of the pallet landing gear study. A dynamic math model was built to simulate the performance to the pallet on Mars for the terrain requirements described above. A sub-scale test series is being designed in order to validate the results of the model. To accurately simulate dynamic events on Mars here on Earth, the Freud number is used to scale the ratio of inertial forces to gravity forces. Freud number scaling requires that the physical size of a terrestrial model be reduced proportionally to the ratio of the Earth-Mars gravities, 1:0.375. The 3/8 scale model will be drop tested to validate the results from the computer model (Figure 7). By correlating the instrumented and recorded results of the drop tests with the model predictions, the reliability and sensitivity of the model predictions can be estimated and used to better estimate the performance of the full scale vehicle on Mars.

Due to its large size, the currently envisioned airbag landing system does not make use of a rigid exoskeletal structure, like the Pathfinder tetrahedron. This results in a significant mass saving but requires a different system to self-right and remove the airbags from the lander. This function is performed with a secondary set of airbags, termed the self-righting airbags. These airbags are separate and distinct from the impact bags and lie between the lander/payload and the impact airbags. After touchdown and rollout, the impact bags are deflated and their attachment to the lander/payload is severed. The self-righting airbags are designed to begin inflation at this point and, from any initial orientation, to safely place the lander/payload: (1) right side up, and (2) clear of the impact bags, regardless of any obstacles like rocks and slopes. Testing currently under development simulates the dynamic behavior of this system (Figures 8a and 8b). By performing Freud number scaling as was done with the pallet system, accurate estimates can be made of the performance envelope.

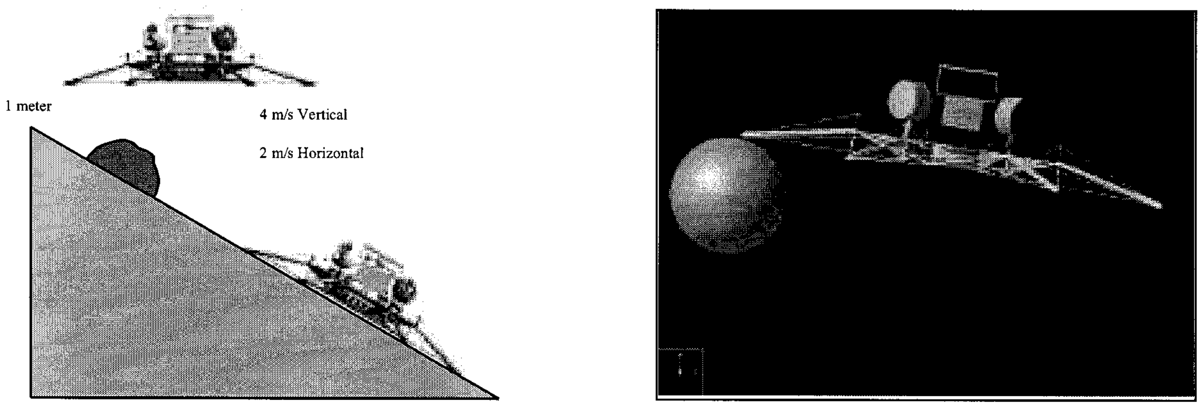


Fig. 7. Simulated pallet landing on a 30° slope with a 1 meter rock

Fig. 8.

a) Simulated airbag lander with minimum landing velocity system

b) A self-righting concept using airbags.

6. Landed Mission Mobility

The first generation Mars landing system, Viking, was a pair of fixed landers. These vehicles arrived to find exciting terrain full of rocks of different sizes and windblown soils. As Viking had no direct mobility system, its access to the terrain was limited to the range of the sampling arm. This allowed Viking to interact with a territory of a few square meters. While this permitted some digging in the soil and the overturning of a few rocks, it did not allow for close-up investigation of diverse rocks. Furthermore, the imaging system was not able to change perspective, thus there was no ability to look over the local horizon.

Since the early 1980s, follow-on missions to Mars have been proposed which involved the use of rovers. These rovers would have many of the core systems inherent in any spacecraft such as power, telecommunications, science instruments, avionics, navigation, structures and mechanisms with the distinct addition of mobility. Mobility allows for direct contact with a much larger area of the surface. In 1997, the Sojourner rover, as a payload on the MPF mission, became the first rover on Mars. Sojourner very quickly proved the value of rovers and roving technology. In its 84-day mission, Sojourner was able to travel over 100 meters, interact with a dozen different science targets and investigate an area 100 times that of Viking. It provided imaging from a variety of perspectives including images of targets that were outside the MPF lander's field of view.

The two planned 2003 MER missions will again significantly increase the science target area of a landed mission, each having a range of approximately 1-km and will carry a significant science payload aimed at understanding the local geology. The increase in vehicle scale (MER is approximately twice Sojourner's size in each linear dimension), coupled with advances in vehicle navigation and the operational experience gained with Sojourner, all contribute to the increase in total range. Unlike Sojourner, MER is not a payload to the lander. Instead, it is the computer on MER that controls the spacecraft during cruise and EDL. When MER explores the surface of Mars, it is not leaving a fully functioning spacecraft behind. Instead, all that is left is landing gear whose purpose was to safely land the MER. This approach is known as a "dead on arrival lander" and there is less duplication between rover and lander engineering systems, thereby providing more mass for science payloads.

While Sojourner and MER are good for exploring the diversity within a landing site, they do not have the range to explore areas of significant geologic diversity. In other words, their mobility limits them to a single geologic unit. When coupled with the large landing ellipse associated with the MPF EDL system (described above), it is not possible to use these rovers to explore a particular target. A rover with significantly more range, greater than the semi-major axis of the landing ellipse, is necessary to enable a "Go-to" mission. "Go-to" missions allow for mission planners and scientists to select a specific target on the surface and plan a mission that delivers a science payload to that exact target. For the second-generation lander, the landing ellipse semi-major axis is about 3 km. Adding in factors for site characterization, biasing the ellipse to minimize landing hazards and path-planning obstacles with a target mobility capability of 7 km is needed. The desire to explore multiple geologic units would change that number to 50-100 km.

In the sample "Go-to" mission shown in Figure 9, the second-generation EDL system delivers a rover to an ellipse inside the same 10-km diameter crater in the Elysium Planitia described above. The rover path shown assumes a starting point corresponding to a 3-sigma dispersion in the worst direction. The rover mobility allows for a traverse from the landing site over to the target area, which in this example is a liquefaction zone identified by the MGS orbiter. Once investigation of the potentially water-formed gullies is complete, the rover continues around to investigate dry-landslide features for comparative studies.

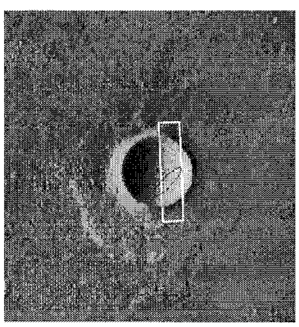


Fig. 9. Representative "Go to" landed mission scenario.

The second-generation class of rover missions is being designed to meet the following baseline characteristics:

- Mobility: 6-wheel Rocker-Bogie (like Sojourner & MER)
- Wheel diameter: 0.65 m
- Navigation hazard: > 0.5 m
- Obstacle capability: > 1.0 m
- Speed: 30-60 mm/sec
- Range: 10-50 km/year (depending upon science needs)
- Navigation: Stereoscopic Imager/Sun Sensor/IMU

The large size of this vehicle increases the apparent flatness oof the terrain. Very few natural hazards are obstacles to a vehicle of this scale, resulting in a longer mean-free path. This minimizes navigation errors as well. A comparison of obstacles is shown in Figure 10. The "MPF Rocks" images show the rocks identified in one hemisphere of the MPF landing site. The subsequent images show the reduction in rock obstacles as the rover wheel size increases from the original MPF rover (Sojourner) to the MER class and final to the second-generation rovers.

There are other advantages to this large vehicle size apart from mobility. The thermal control of small rovers such as Sojourner and MER is difficult due to the large ratio of area to mass. These smaller vehicles lose heat through radiation and convection across all exterior surfaces. Their small thermal inertia means they need replacement heat during the Martian night to stay above minimum temperatures for critical avionics (e.g., batteries). For Sojourner and MER that heat is provided in the form of Radioisotope Heater Units. For the larger-class rovers, there is enough thermal mass to survive the night without any replacement heat at all. For the Sample Return Mission, the rover can keep the MAV temperature stable to within 10 °C without the use of any electrical heater power.

7. Lander Power Generators

Two types of power generation systems have been used on the surface of Mars. The 1970s Viking dual lander mission used Radioisotope Thermoelectic Generators (RTG) which utilized PbTe-TAGS (tellerium, antimony, germanium and silver) thermocouples to convert the heat from Pu^{238} decay to DC power. The 1997 Sojourner rover used GaAs photovoltaic cells to convert solar energy to DC power. Both of these systems have severe limitations, and a new system is under consideration for the next generation system.

RTGs have been a key power generation source of the US space program. They were used on robotic probes such as Pioneer 10 and 11, Viking, and Voyager. The Apollo astronauts took them to the moon as part of the long-term lunar surface science instrument experiments. RTGs are solid-state devices with long lifetimes due to the long radiological half-life (87 years) of this Plutonium isotope. The specific technology used for the Viking RTG was low in system specific power (3W/kg) and is no longer in use.

In the 1980s, Plutonium-Oxide was packaged into General Purpose Heat Source (GPHS) modules which encapsulate the fuel into a series of heat and impact resistant shells. These protective measures increase the safety associated with using this alpha-emitting material and decrease the probability of a biological hazard in the event of a launch or spacecraft failure. The GPHS-RTG (used on Galileo, Ulysses and Cassini) is a 295We unit that uses SiGe thermocouples for converting heat from Plutonium Oxide to electrical power but is still only 7% efficient (Figure 11). Since there is no current domestic Pu^{238} production capability and the existing inventory is limited, efficiency is very important. The GPHS-RTG design produces 27 W/kg. Although it can be adapted, the present GPHS-RTG design is not easily made compatible with the Martian atmosphere CO_2 environment.

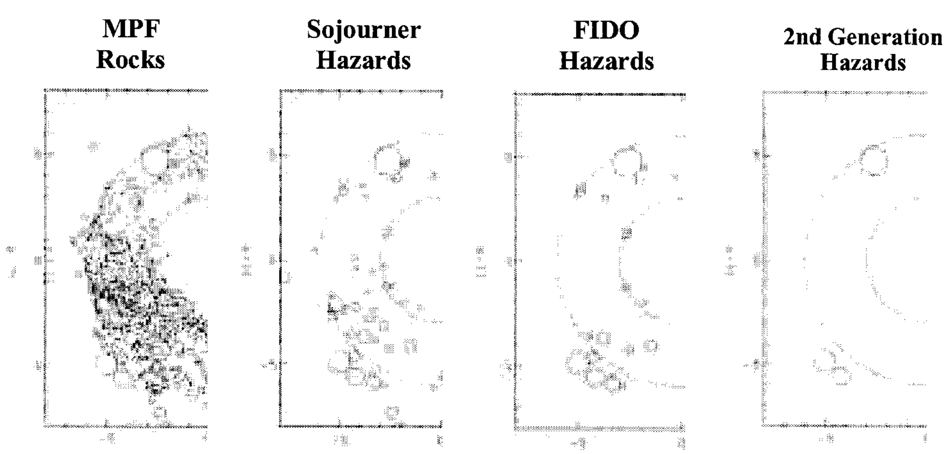


Fig. 10. Hazard comparison between different Rover options.

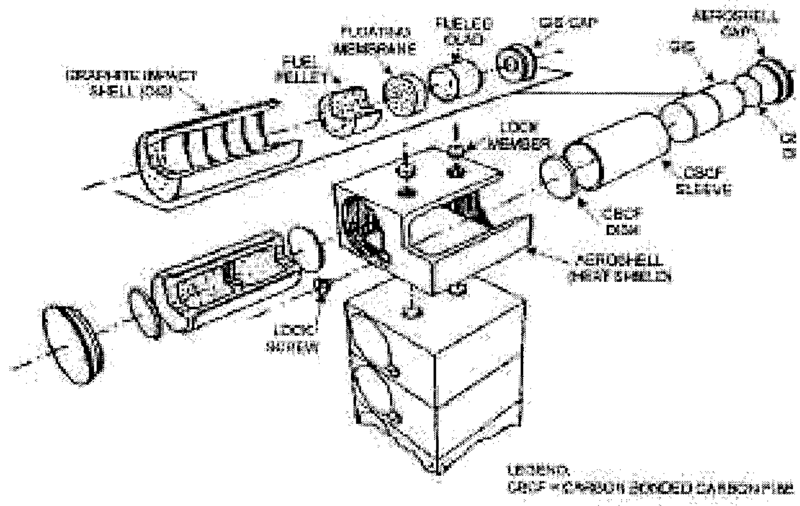


Fig. 11. General Purpose Heat Source (GPHS) module.

Solar arrays are a good source of power for many space missions. They are lightweight and reliable. In orbit around Earth or Mars, solar arrays can provide power for 10 years or more. However, on the surface of Mars, solar arrays have a more challenging environment. The most dominant characteristic is in solar insulation. The amount of sunlight that reaches a given spot on the surface is effected by the time of day, the season, the latitude of the landing site, the horizon mask due to terrain and, the opacity of the atmosphere. While some of these parameters can be well understood in the planning phases of a mission (like latitude), they may place severe limits on the accessible areas of the planet or be in conflict with other constraints (e.g., telecommunications relay orbiter visibility). If the scientific investigation requires a long lifetime (perhaps a Martian year to characterize full seasonal variations) then seasonal variations in solar flux make missions in the polar regions impossible. Although arrays can be used in specific locations for particular types of missions, they do not match the intended goal of near-global access for second-generation landers.

The motion of the Sun across the Martian sky places needs on the landed spacecraft. To gain enough area to capture enough energy during the ~ 8 hours per sol of peak sunlight, the arrays would have to be deployed after landing. A 3000 W-hr/sol reference mission required 9 square meters of array. It takes significant mechanization to deploy and point such an array. Furthermore, if the landed asset is a rover, it is even more complicated to point the array on a moving vehicle. Imaging and communication systems tend to need to be on tall deployable masts, which cast shadows on the panel and render some strings temporarily unusable. It is a very difficult task to balance the needs of solar array management with the science instrument fields of view, Sun/glint shields, mobility, navigation and packaging in launch and EDL configurations.

Perhaps the most troubling limitation of photovoltaic systems is the poorly understood dust environment. Instruments on the MPF mission recorded an average 0.28%/sol reduction in solar flux on the array due to dust accumulation. This measurement was taken with limited instrumentation in one location for a very limited period of time. It is not clear if the effects elsewhere on the planet would be better or worse, but if this number is used as a benchmark, it is clear that missions longer than 100 days are impractical without some dust mitigation measures.

For the 2007 reference mission, the Stirling Radioisotope Power System (SRPS) is being evaluated to convert heat from Pu^{238} decay to mechanical power to AC power (Figure 12). The SRPS is an advanced radioisotope power system (RPS) that uses the heat from Pu^{238} decay to drive a Stirling thermodynamic cycle. Since a thermodynamic cycle's efficiency is limited by Carnot efficiency, it is desired to have a large temperature ratio between the hot and cold sides of the SRPS. The cold CO_2 atmosphere makes Mars a good environment for this type of system. In fact, unlike an 8-hour/sol solar system, the SRPS works all day and then works even better at night. With around-the-clock power production, the SRPS changes the science data acquisition and roving strategies. Sojourner and MER are daytime systems that mostly sleep during the night. The next generation rover would never have to go to sleep (a big reliability enhancement) and could even drive at night!

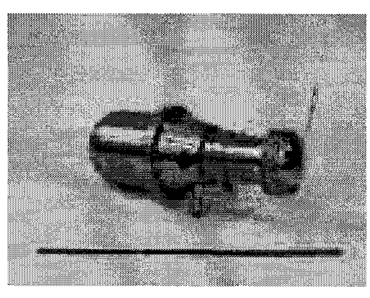


Fig. 12. Stirling Technology Company's 55W demonstration converter.

The SRPS is currently under development by the Department of Energy with technology validation assistance from NASA's Glenn Research Center. The SRPS would use the same GPHS modules as the RTG for safety but is expected to operate at around 3.7W of electrical power per kilogram but with an efficiency of 20-25% and therefore would use only 1/3 the Plutonium of a similarly sized RTG. For the next generation missions, two ~ 100 W electric SRPS assemblies (each including 2 GPHS modules with 2 converters) would yield 5000 W-hr/sol for about the same mass as the deployable 3000 W-hr/sol solar array system. The SRPS has the added benefits of configurational freedom, multi-year operation and far less sensitivity to the dust environment.

As with all NASA missions, no final decision on what power source will be made until after all safety and environmental reviews are completed.

8. Conclusions

The second generation landers enable larger, more comprehensive in situ payload missions, sample return missions, and "Go to" missions. Lander characteristics include landed masses of up to 1700 kg with payload masses of up to 300 kg, landing ellipses of 6 km, roving capability of 10 to 30 km, depending on the power sources, and lifetimes of 180 sols (solar powered) or years (RPS). The ability to rove beyond the landing ellipse enables the second-generation lander to investigate specific surface features within the direct landing latitudes of a particular launch opportunity. The use of the RPS would also free up the landing site selection from solar illumination constraints. The landing gear of the second-generation landers is being designed to survive impact on 0.5-m rocks on a 30° slope, thereby greatly increasing the landing tolerance and the number of available landing sites.

9. Acknowledgements

The authors would like to recognize the contributions of EDL team members at NASA's Ames Research Center, Moffett Field, CA, Johnson Space Center, Houston, TX, and Langley Research Center, Hampton, VA, along with the Naval Air Warfare Center at China Lake, CA. They also acknowledge support from the Lockheed Martin Astronautics team in redesigning the EDL concepts. The authors would like to thank Janis Norman for manuscript preparation.

10. References

[1] R. Ewell & D. Burger, "Solar Array Model Corrections from Mars Pathfinder Lander Data," Proceedings of the 28th Photovoltaic Specialists Conference, Anaheim, CA, 9/30/97–10/3/97.

[2] NASA Planetary Protection Provisions for Robotic Extraterrestrial Missions, NPG 8020.12B, April 16, 1999.

[3] Rivellini, T. P., Oritz, G. M. and A. D. Steltzner, "Safe Landings in Extreme Terrain," Proceedings of the Concepts and Approaches for Mars Exploration Workshop (Part 2), pp. 269-270, Lunar and Planetary Institute, Houston, Texas, 18–20 Jul., 2000.

[4] Carman, G. L., Ives, D. G. and D. K. Geller, "Apollo-Derived Mars Precision Lander Guidance," Paper No. 98-4570, AIAA Atmospheric Flight Mechanics Conf., Boston, Massachusetts, 10–12 Aug. 1998.

[5] Striepe, S. A., Queen, E. M., Powell, R. W., Braun, R. D., Cheatwood, F. N., Aguirre, J. T., Sachila, L. A. and D. T. Lyons, Paper No. 98-4569, AIAA Guidance, Navigation, and Control Conf., Boston, Massachusetts, 10–12 Aug. 1998.

[6] Klumpp, A. R., "Apollo Lunar Descent Guidance," Automatica, Vol. 10, pp. 133–146, 1974.

11. Biography

Jim Graf received a BSE from Princeton University in 1972 and an MS from Colorado State University in 1976. He has been employed in various space-related development for 26 years ranging from the development of ion thruster technology to the management of the Quick Scatterometer Mission, an Earth orbiting satellite which was ready to launch within one year of formal go ahead. He is the recipient of NASA's Outstanding Leadership Medal and an Aviation Week's 1999 Laurel for Space. Currently, he is the manager of the Mars Smart Lander Development team.