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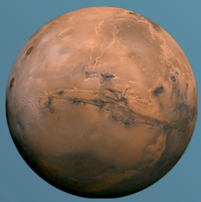

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Moon to Mars
Architecture

white paper

# Mars Entry, Descent, and Landing Challenges for Human Missions

## Introduction

History provides numerous examples of the challenges of landing on Mars — only 12 out of 19 attempted robotic landings have been successful.[1] Human missions to Mars will introduce new challenges that must be addressed.

To land humans on the Red Planet and then safely return them to Earth, NASA must pursue advances in flight testing, atmospheric deceleration systems, propulsive descent systems, characterization of rocket interactions with the surface, guidance and navigation systems, and modeling and simulation of these elements. Only then can Martian astronauts begin to meet NASA's Moon to Mars Objectives.[2]

This white paper introduces atmospheric entry, descent, and landing (EDL), discusses some of the unique challenges of Mars exploration, and provides insight into the advancements necessary to land the first human explorers on the surface of the Red Planet. This is a high-level overview, with referenced publications providing further detail into landing systems and engineering challenges.

## What is EDL?

EDL is one of the highest-risk phases of spaceflight. During EDL, the spacecraft enters and transits a planetary atmosphere, decelerates, and touches down onto the planetary surface. Through EDL, NASA will place astronauts and payloads at planned surface locations for exploration and science, as well as near surface infrastructure such as habitats, supplies, surface mobility vehicles, and Earth-return vehicles. **Figure 1** shows the concept of operations for the most recent NASA Mars EDL system, the robotic Mars 2020 mission, which landed the Perseverance rover and Ingenuity helicopter.

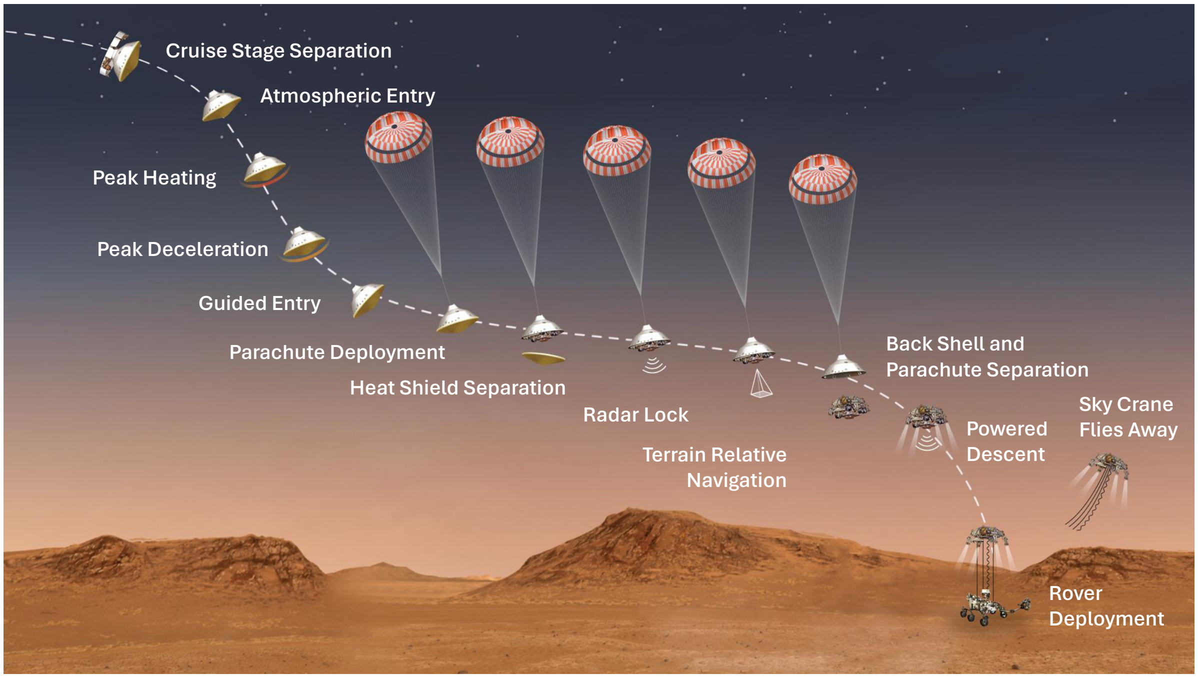


**Figure 1:** *Illustration of EDL for the NASA Mars 2020 mission. (NASA/JPL)*

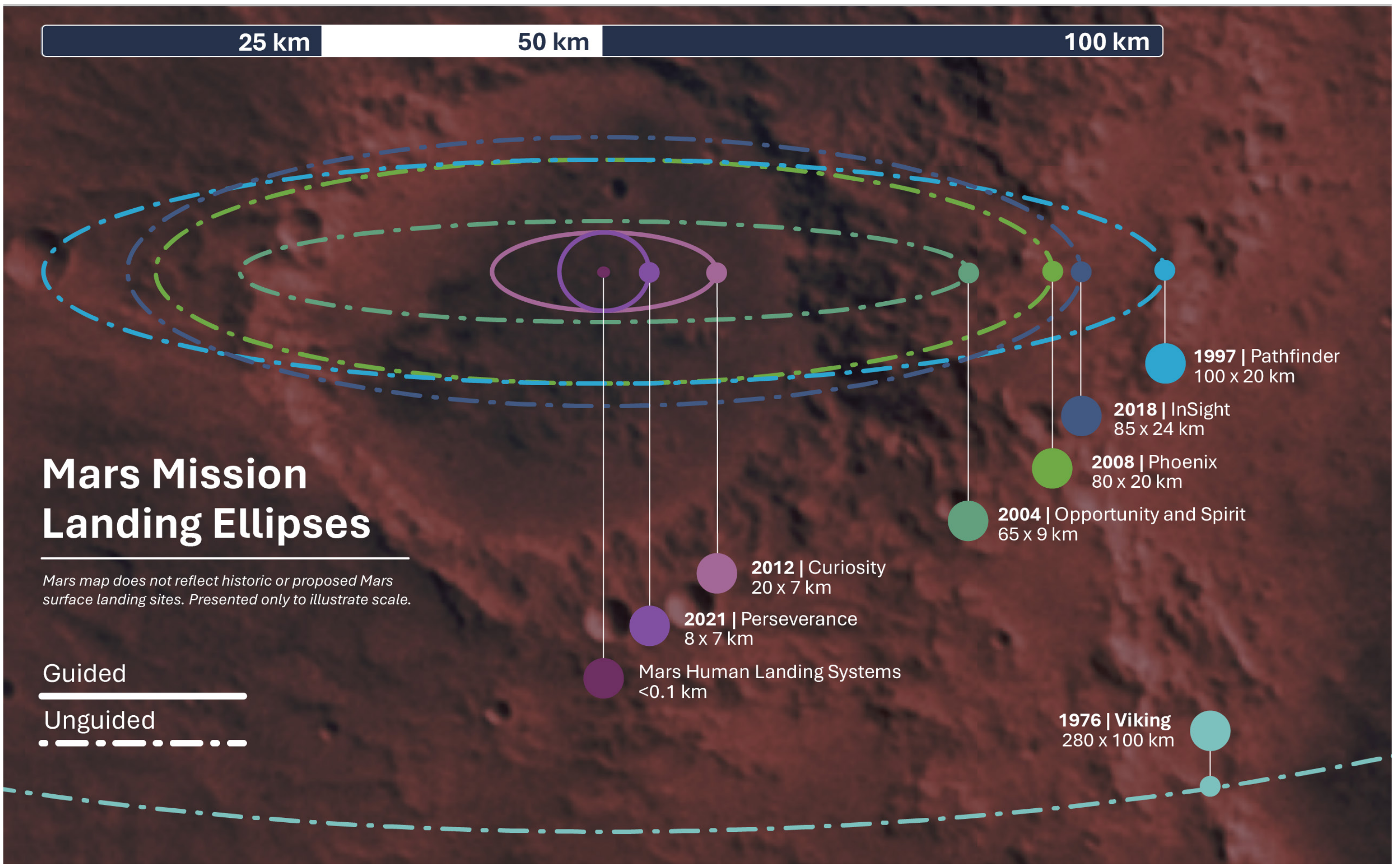


**Figure 2:** *Overlay of NASA Mars operational landing ellipses, shown at Gale Crater. Landing ellipses for human missions to Mars will be smaller than any previous robotic missions. (NASA)*

### Entry

The entry phase begins at atmospheric entry interface, when vehicle aerodynamic forces and aerothermal heating induced by the atmosphere become non-negligible. During this phase, a spacecraft must manage aerodynamic forces and thermal loads to successfully decelerate the vehicle from hypersonic velocities.

Large variabilities in the atmospheric entry point, atmospheric density, and vehicle aerodynamic predictions contribute to large landing errors, as shown in **Figure 2**. Implementing active guidance and reaction control systems aboard recent Mars EDL systems has helped to achieve much smaller landing ellipses than prior missions.

### Descent

The descent phase begins with deployment of a dedicated deceleration system. The transition from entry to descent depends on the specific mission and vehicle, but typically occurs during supersonic flight.

Heritage Mars descent approaches include parachutes and retropropulsion systems, thrusters that fire against the direction of travel.

- Heritage parachute systems are inherently un-steerable, and wind drift can add a kilometer or more of landing error.
- Retropropulsive system maneuvers can help avoid hazards and reduce touchdown distance from the intended landing site, relying on vehicle navigation sensors to refine onboard knowledge of surface-relative position and velocity during deceleration.

### Landing

The landing phase takes place after the vehicle slows to touchdown velocity, chosen for soft and safe landing near the identified destination. Vehicle designs must handle the touchdown loads, velocity, and final orientation to ensure surface operations can proceed after landing.

Previous Mars missions have leveraged either retropropulsion or airbag systems for touchdown. Retropropulsive landing system engines induce plume-surface interaction (PSI) with the ground. PSI can lead to surface erosion below the lander and ejected debris, which pose a risk to the landing vehicle and nearby surface assets.

## Historic Challenge of Mars EDL

NASA has performed successful EDL at planets and moons throughout the solar system.[3] EDL systems for Earth benefit from a well-characterized atmosphere for deceleration, well-known terrain for landing, and Earth-based navigational capabilities like GPS for guidance.

On airless bodies such as the Moon, the atmospheric entry phase does not exist. Ergo, landers do not need heat shields or aerodynamics-based deceleration systems. Instead, onboard retropropulsion fully decelerates and lands spacecraft. Landings on the Moon provide valuable insight for Mars EDL, although Mars possesses several unique characteristics that create new EDL challenges.

### Atmosphere

The Martian atmosphere is thin but provides enough aerodynamic drag to decelerate an entry vehicle while still inducing non-negligible aerothermal heating. An entry vehicle must mitigate this overheating, which is substantial enough to result in loss of mission.[4]

The atmospheric density at the Martian surface is comparable to Earth's atmospheric density at approximately 30 kilometers in altitude. Atmospheric density and wind variability for any Mars EDL produce large uncertainty in predicted touchdown location. The resulting variability in descent timelines limits reachable surface site altitudes.

**Figure 2** shows how landing accuracy at Mars has improved over time and highlights the kilometers of improvement still needed for human missions. Several improvements have reduced the ellipse sizes: improved interplanetary navigation that better target the initial entry point, the use of capsule aerodynamics during entry to steer toward the target, and enhanced transition-to-descent parachute trigger methods.

The remaining challenges in landing accuracy for heritage systems stem from:

1. errors in onboard navigation accuracy during the entry phase, which limits steering accuracy,
2. parachute sensitivity to wind variability, which occurs after the entry steering is complete, and
3. aeroheating, as necessary heatshields complicate the use of navigation sensors during entry to improve onboard navigation.

### Surface Hazards

Many Martian surface regions of scientific interest have terrain features that pose risks to safe lander touchdown. Landing site selection includes surface hazard risk assessments based on orbital imagery and planetary geology models.

The best images from the Mars Reconnaissance Orbiter provide 25 cm resolution. At that resolution, mission planners can identify rocks and features as small as 1 meter in size. Even when select landing ellipses that minimize hazards, some Mars landers have touched down near large rocks that would have caused a landing failure if struck. For example, **Figure 3** shows a 1-meter-tall boulder within 8 meters of Viking 1's landing location.

NASA must address landing system surface hazard tolerance either via pre-flight analysis — based on knowledge of the planned touchdown area — or sensors to detect and avoid hazards during descent and landing. Landers with retropropulsive rockets further complicate surface hazard considerations, as PSI erosion of surface regolith (**Figure 4**) could produce unstable or unacceptably sloped landing surfaces and eject debris, dust, and regolith at and away from the lander. Additionally, both PSI and naturally occurring Mars atmospheric dust affect EDL sensor measurements and, in turn, EDL navigation.

### System Validation

Validation of Mars EDL systems presents significant challenges. There are no Earth-analog test conditions that completely mimic Mars EDL. The Martian EDL environment comprises different atmospheric pressures, temperatures, chemistry, wind, dust, humidity, gravity, and surface composition. Hence, a "test as you fly" approach is simply not possible to validate Mars EDL systems prior to a mission.

Past missions to the Red Planet have approached validation by combining high-fidelity, system-level modeling and simulation in parallel with terrestrial component-level tests in Mars-representative conditions. NASA uses facilities and testbeds including wind tunnels, vacuum chambers, arc jets, suborbital rockets, and aircraft to validate models and build confidence in EDL components and systems.[4] This testing, combined with the data collected from past robotic Mars missions, will help NASA develop subsequent Mars missions.

**Figure 3:** *Lander-size 'Big Joe' boulder 8 meters away from Viking 1. (NASA/JPL)*

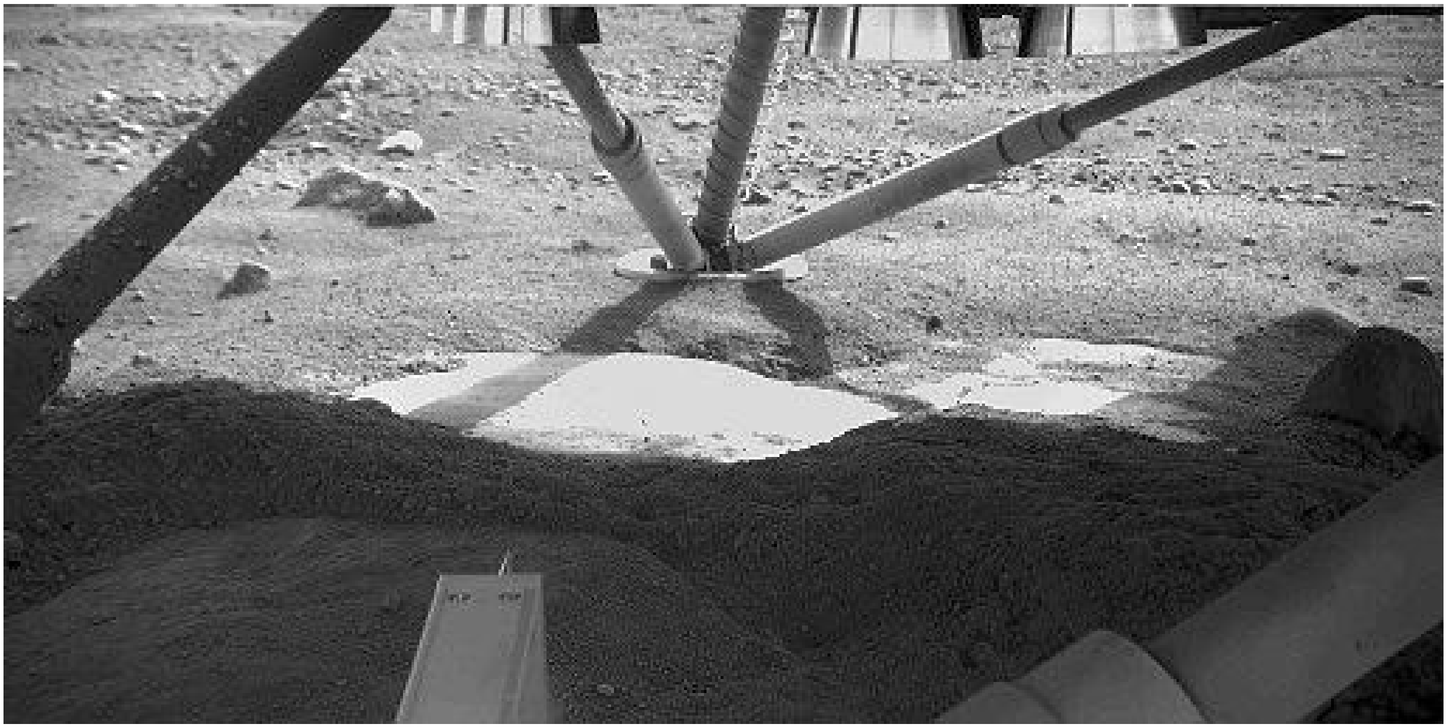

**Figure 4:** *Subsurface ice exposed by 2008 Phoenix landing engines. (NASA/JPL)*

**System Scalability**

Since the 1970s, NASA Mars EDL systems have leveraged scaled variations of the original Viking entry capsule and parachute designs. Component testing has been necessary to qualify heavier and higher-velocity Mars EDL systems, but, because of cost, there has not been an extensive redesign.

Recent Mars missions have approached the payload mass limit of the Viking design, and future missions will exceed it. **Figure 5** highlights the evolution of NASA Mars EDL systems since Viking. All flown EDL systems to date have had landed masses between 0.3 and 1 metric tons. The projected jump for human-class Mars EDL requires an increase to landed masses in excess of 20 times greater, or over 20 metric tons.[4] This is well beyond what a scaled-up Viking design could achieve.

## Transition to Human-Class Mars EDL

The Mars 2020 EDL in **Figure 1** represents the current state of the art for Mars EDL systems. Each successive Mars robotic EDL has drawn from the knowledge and experience of past missions. Those lessons learned are informing ongoing studies to meet the requirements of human-class Mars landers. Areas of ongoing research include entry modeling and instrumentation, new deceleration systems, guidance and navigation, and new landing systems.

The projected mass of human-class landers (**Figure 5**) requires advancements in entry systems design and modeling. Numerous NASA design studies[4, 5, 6, 7] are using high-fidelity simulations to investigate concepts for large, inflatable aerodynamic decelerators and higher-lift aerodynamic bodies to inform and gain insight into industry development efforts (**Figure 6**). EDL simulations are using the latest data on the Martian atmosphere and vehicle technologies to assess the viability of designs for human-class systems.

Deceleration systems cannot be validated with test articles at Mars, but subscale development and high-altitude flight testing on Earth can produce valuable data for developing human-class systems. Larger entry vehicles will need to manage significant aerothermal heating, transition from hypersonic to subsonic flight, and decelerate for a soft touchdown, all of which may require new technologies and concepts of operation (**Figure 7**). Terrestrial testing can validate these new systems to ensure they are ready for crewed missions.

Robotic Mars missions have continuously advanced state-of-the-art guidance and navigation capabilities, contributing to the landing error reductions shown in **Figure 2**. However, the need for more precise accuracy for human-class landers will require further advancements in guidance and navigation sensors and algorithms, alongside supersonic retropropulsion and aerodynamic performance.[7] New sensors and systems can enable advanced terrain relative navigation, allowing spacecraft to use visual reference data to establish their location and navigate to avoid landing hazards in a variety of conditions (**Figure 8**).

Landing systems will also need to evolve beyond robotic Mars and human lunar systems to account for the constraints of human Mars missions (**Figure 9**). Higher-thrust engines on human-scale landers will likely create significant PSI ejecta and obscure landing sites. Understanding and modeling PSI-induced changes to the surface will inform mitigations to protect landers and other assets close to the landing site. While lunar PSI data can be valuable, the Martian regolith behaves differently than the lunar regolith, requiring Mars-specific modeling and ground testing.

Steady Progression of “In Family” EDL Systems → New Paradigm

| Entry Capsule *(to scale)* | Viking | Pathfinder | MERs | Phoenix | Curiosity | InSight | M2020 | Human-Scale Lander *(Projected)* |
|---|---|---|---|---|---|---|---|---|
| **Diameter** *(m)* | 3.505 | 2.65 | 2.65 | 2.65 | 4.52 | 2.65 | 4.52 | 16+ |
| **Entry Mass** *(metric ton)* | 0.930 | 0.585 | 0.840 | 0.573 | 3.153 | 0.608 | 3.368 | 49 - 65 |
| **Parachute Diameter** *(m)* | 16.0 | 12.5 | 14.1 | 11.8 | 21.5 | 11.8 | 21.5 | N/A |
| **Landed Mass** *(metric ton)* | 0.603 | 0.360 | 0.539 | 0.364 | 0.899 | 0.375 | 1.050 | 26 - 36 |
| **Landing Altitude** *(km)* | -3.5 | -2.5 | -1.4 | -4.1 | -4.4 | -2.6 | -2.5 | +/- 2.0 |
| **Landing Technology** | Retropropulsion | Airbags | Airbags | Retropropulsion | Sky Crane | Retropropulsion | Sky Crane | Supersonic Retropropulsion |

**Figure 5:** *Evolution of Mars EDL systems. (NASA)*

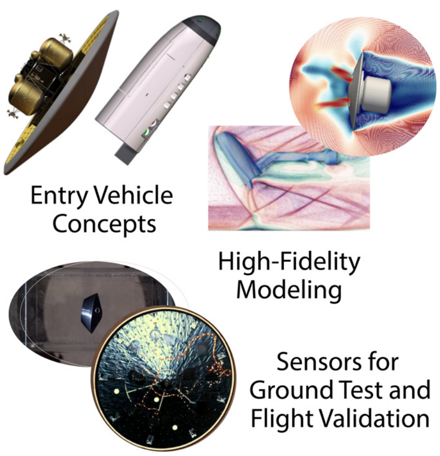


**Figure 6:** *Entry modeling and simulation. (NASA)*

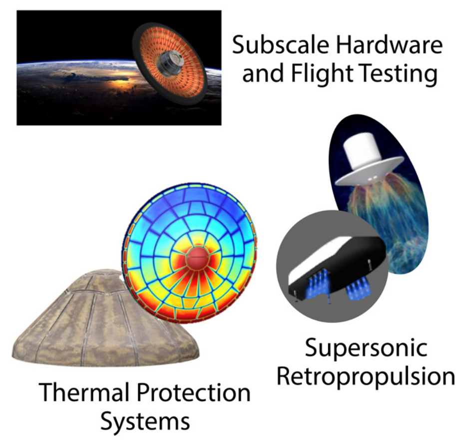


**Figure 7:** *New deceleration systems must be developed. (NASA)*

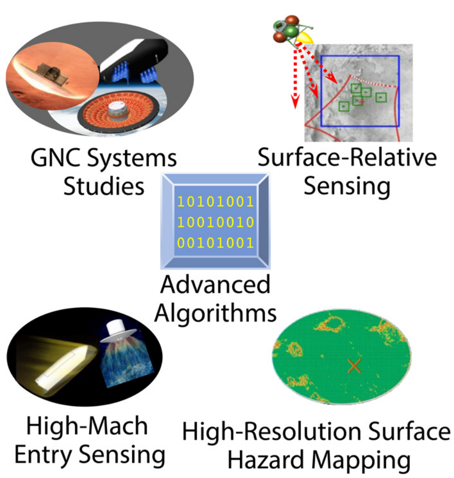


**Figure 8:** *Development areas for guidance and navigation systems. (NASA)*

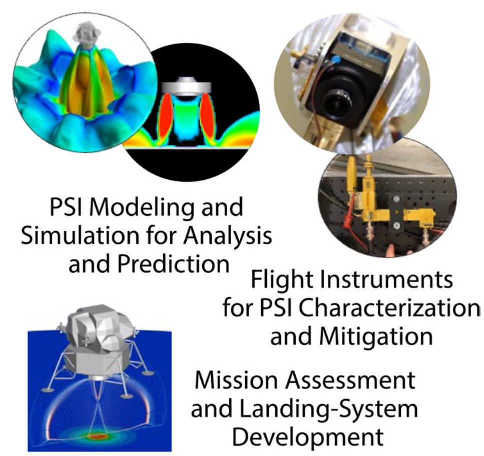


**Figure 9:** *Capability needs for landing systems and environments. (NASA)*

## Key Takeaways

While lunar landings help prepare NASA for the journey to the Red Planet, Mars landers encounter a variety of unique challenges not present on the Moon that must be understood and addressed. This includes the Martian atmosphere, surface hazards, plume-surface interaction, and terrestrial validation of systems intended for Mars.

Robotic Mars landers have used variations on heritage designs that do not scale to the mass requirements of human-class Mars landers. To land larger vehicles on the Martian surface, NASA and its partners must develop and validate new technologies, including entry instrumentation, deceleration techniques, and navigation systems.

Advances and testing by NASA and its partners will enable the agency to overcome the challenges of Mars EDL and successfully land humans on the Red Planet.

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