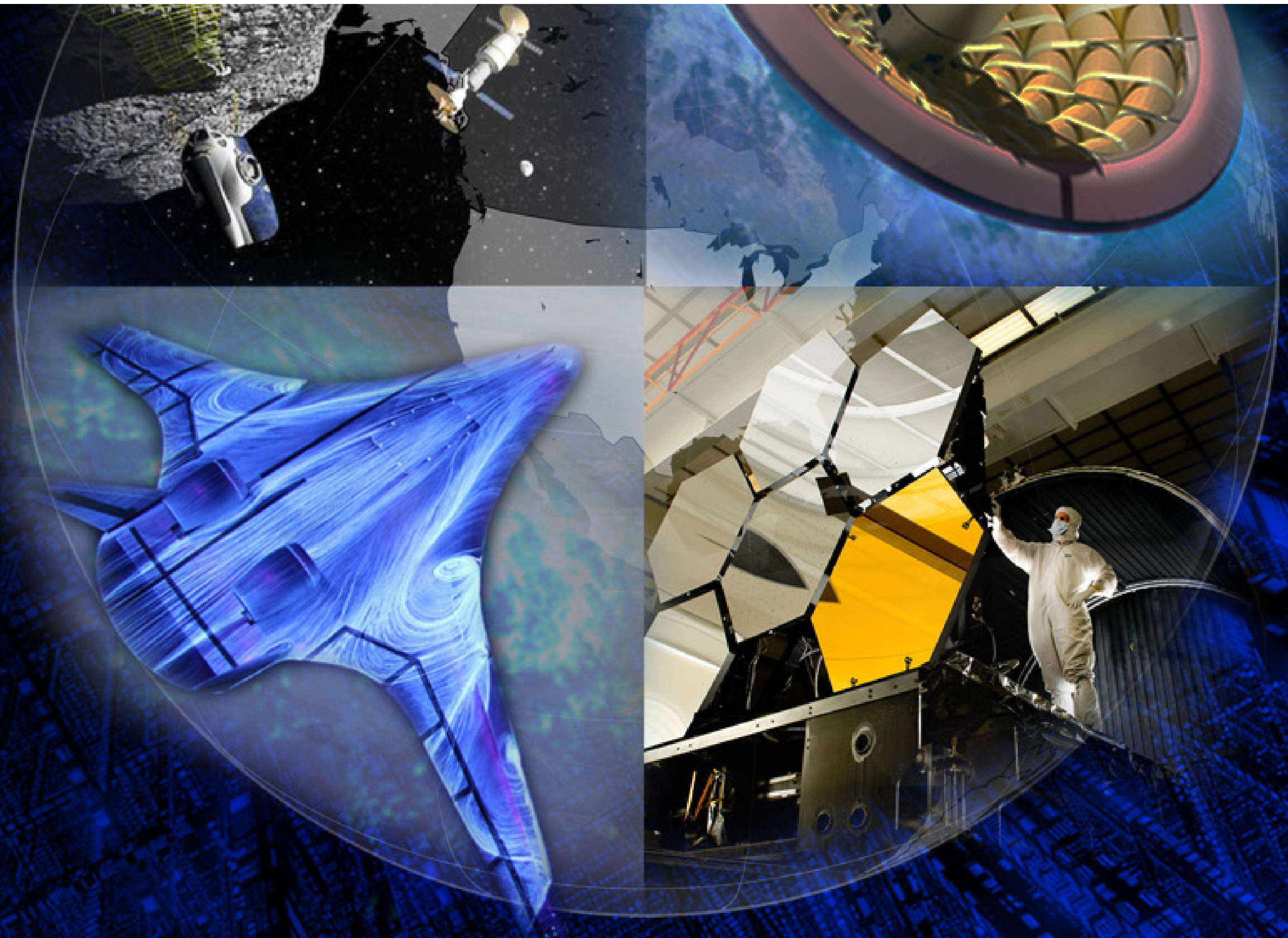
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 9: Entry, Descent, and Landing Systems

The 2015 NASA Technology Roadmaps have been replaced with the 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework.

Note: The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current Internet address as well as via the new 2020 NASA Technology Taxonomy Internet page. Please visit https://www.nasa.gov/offices/oct/home/taxonomy to see the Taxonomy.



July 2015

Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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Executive Summary

This is Technology Area (TA) 9: Entry, Descent, and Landing, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on "applied research" and "development" activities.

NASA developments in fundamental atmospheric flight and entry, descent, and landing (EDL) technologies in the 1960s and 1970s serve as a basis for many of our current EDL capabilities of today. For example, the state of the art (SOA) for a fully reusable capability supporting human-scale Earth entry is defined by the Shuttle Orbiter, constructed in the 1970s. In addition, multiple Apollo-derived technologies are being extended to the scale required for the Orion crewed exploration vehicle. Some of those capabilities, including skip entry guidance, will be employed for the first time in a flight implementation. NASA's ability to land robotic payloads on the surface of Mars is largely reliant on the EDL technology set developed for the Mars Viking Program (1970s) and utilized in large part on all of the robotic Mars landers since. Thermal Protection System (TPS) technologies developed for Apollo and the Space Shuttle in that same timeframe are being recycled or re-qualified today for current human spacecraft concepts. Other recent capabilities developed by NASA are being adopted by companies that will provide NASA commercial crew access to the International Space Station (ISS). NASA's pioneering entry missions to Venus and the giant planets were also designed in the 1970s, and current Science Mission Directorate (SMD) concepts largely identify derivative technologies from those missions for mission planning. Currently, advances in EDL capabilities are generally driven by individual mission performance requirements and near-term schedule demands, and often require high technology readiness level (TRL), low-risk technologies for mission infusion. Flagship class mission objectives have been the only exception, where the required technologies have been matured from a low TRL (e.g., Sky Crane, which provided terminal descent for the Mars Science Laboratory (MSL)) and the risk posed by these technology infusions has been managed with budget and schedule accommodations. For all other mission classes, there continues to be a large reliance on heritage technology with limitations that are effectively constraining science objectives for desired SMD missions. However, even when heritage technology is used, system performance is not accurately known, due to the inability to replicate EDL flight conditions on the ground. In addition, there is insufficient flight data with which to anchor predictions. Consequently, the application of existing EDL technology could be enhanced by better understanding of performance margins—understanding that is a function of knowing both the performance limits through testing, and the actual flight conditions. Ground testing capabilities need to be improved through new technologies and diagnostics, to support this future understanding.

Mars Science Laboratory, NASA's flagship Mars mission launched in 2011, defines the SOA for Mars EDL systems. MSL used Viking-derived EDL technologies and architecture with heatshield material developed for the Stardust mission, augmented by the Sky Crane touchdown delivery system, to deliver approximately 1 metric ton (t) of surface payload. Current estimates on the extensibility of the MSL architecture indicate that it is limited to roughly 1.5 t delivered mass. In contrast, estimates for human scale Mars missions, the ultimate goal in NASA's human space exploration plans, will require 20-60 t of landed payload mass. Thus NASA cannot continue to rely on the EDL technology investments of the 1960's and 1970's as a baseline to enable future missions. NASA must develop new and innovative technologies to solve this problem, and this roadmap provides the strategy for achieving this goal.

Goals

Strategic EDL technology developments, conducted in a coordinated and sustained manner, are needed to enable not only the current planned set of missions, but also the mission sets and science goals that may not be realizable based on current and near-term evolving technologies, nor by heritage technologies that are no longer available.

A continuous effort to develop system design and analysis capabilities will need to be funded for both the human and robotic exploration mission sets in order to provide an evolving assessment framework for EDL technology development. As information is gleaned from ground and flight testing, this information will feed back into the studies and influence subsequent technology developments and flight demonstrations, and inform the science communities of mission feasibility and possibilities for the future.

In addition to Earth ground and flight testing, the science robotic, precursor robotic, and human missions to the Moon, Mars, and asteroids, as well as utilization of the ISS, can help lay the groundwork for future technology developments. It is crucial to acquire and analyze data on the performance of these technologies in their flight applications in order to enable further development and use in later missions.

To support NASA's goal to send humans to the surface of Mars, sustained and coordinated developments over a period of decades in new EDL system technologies must be made. Given that the probability of loss of mission during EDL tends to be comparable to that during launch, it is imperative that technology developments in EDL be motivated by a mindset of enabling a mission by providing robust, reliable, and Earth-testable solutions.

The key performance characteristics that EDL technology developments will target are landed mass, reliability, cost, landing site elevation, and landing accuracy. Like EDL subsystems, these characteristics interact with each other. Reliability results from thorough testing and analyses of component technologies, such as thermal protection systems, deployable decelerators, landing hazard tolerance, and separation systems. In addition to these component tests, simulations that integrate models of these components are required to show that the components form a viable EDL solution. Reliability might also be improved by increasing the duration of controlled descent as a result of larger drag devices applied earlier and technology development for precision landing (reliant on detailed site information for *a priori* hazard identification), hazard avoidance, and the mitigation of site hazards created by terminal descent propulsion. For missions like Mars sample return, the planetary protection requirement places higher emphasis on robustness and reliability. Low cost is enabled by improved simulation and ground-to-flight extrapolation, and by incorporating high-g landed systems into mission architectures where applicable. On the other hand, lower-g entry systems, such as deployables, can enable sensitive science instrument and human delivery, enabling new and exciting science and exploration opportunities. Delivered mass can be increased or enabled by using more capable TPS for the more difficult environments presented by larger entry vehicles, larger drag and/or lift devices applied at higher speeds and altitudes, descent phase (supersonic) retropropulsion, and more efficient terminal descent propulsion. Landing site access can be increased by using a TPS that permits higher entry speeds (allowing a wider range of targets), small body proximity operations, increased altitude performance by increasing drag early in the descent, and increased trajectory range and crossrange with higher precision, allowing a wider range of safe sites. Greater control authority, particularly in the case of large deployable systems, also enables higher precision in the entry phase. Both precision landing and hazard avoidance are enabled by a combination of more advanced terrain sensing and algorithms with more capable terminal descent propulsion and guidance to divert the lander to the desired target. All of the objectives benefit from improved modeling of the systems and the natural environments.

Table 1. Summary of Level 2 TAs

9.0 Entry, Descent, and Landing Systems	Goals:	Enable heavier payloads travelling at faster velocities to enter and descend through atmospheres and land safely with higher precision than currently possible
9.1 Aeroassist and Atmospheric Entry (AAE)	Sub-Goals:	Provide highly reliable AAE systems for human and science missions that are capable of higher entry speeds, greater payload mass, improved approach navigation, and operation in extreme environments.
9.2 Descent and Targeting	Sub-Goals:	Provide greater deceleration in the supersonic and subsonic regimes in a manner that does not reduce landing accuracy or result in transient unsteadiness or loss of performance in the transonic regime.
9.3 Landing	Sub-Goals:	Extend robotic landing system capabilities to enable landing on very rough and uncertain terrain, and highly reliable landing for human-scale Mars vehicles with large masses.
9.4 Vehicle Systems	Sub-Goals:	Provide a thorough understanding of the flight environment for vehicle design and develop accurate tools for analyzing the end-to-end vehicle performance.

Benefits

New EDL technologies, both revolutionary and evolutionary, will also enable future robotic missions to solar system destinations and enable sample return from these remote worlds, including asteroids, comets, Venus, Mercury, Mars, icy moons, the gas giant planets, Titan, and others.

In general, the benefits of focused EDL technology activities include:

- Reduced launch vehicle requirements and cost,
- Increased mass delivery to a planet surface (or deployment altitude),
- Increased planet surface access (both higher elevation and latitudes),
- Increased delivery accuracy to the planet's surface,
- Expanded entry speed envelopes at Earth and other planets,
- Expanded EDL timeline to accomplish critical events,
- Increased robustness of landing system to surface hazards,
- Enhanced safety and probability of mission success for EDL phases of atmospheric flight,
- Enhanced human safety during return from missions beyond low Earth orbit (LEO), and
- Improved sample return reliability and planetary protection.

Low-TRL EDL technology advancements, from laboratory and computer simulation through development, qualification, and flight test also provide a fertile training ground for young systems engineers and the next generation of technical workforce.

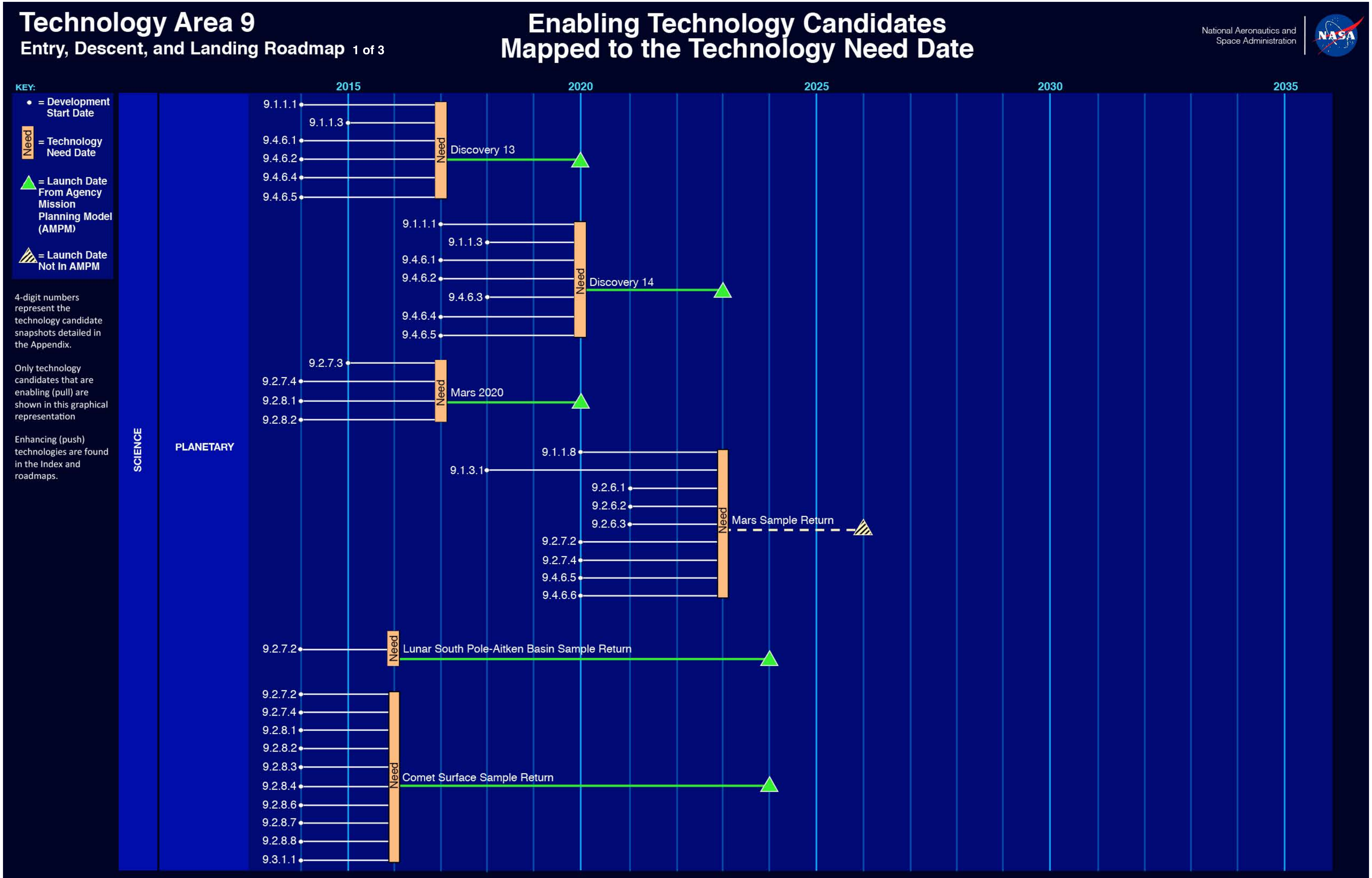

Figure 1. Technology Area Strategic Roadmap

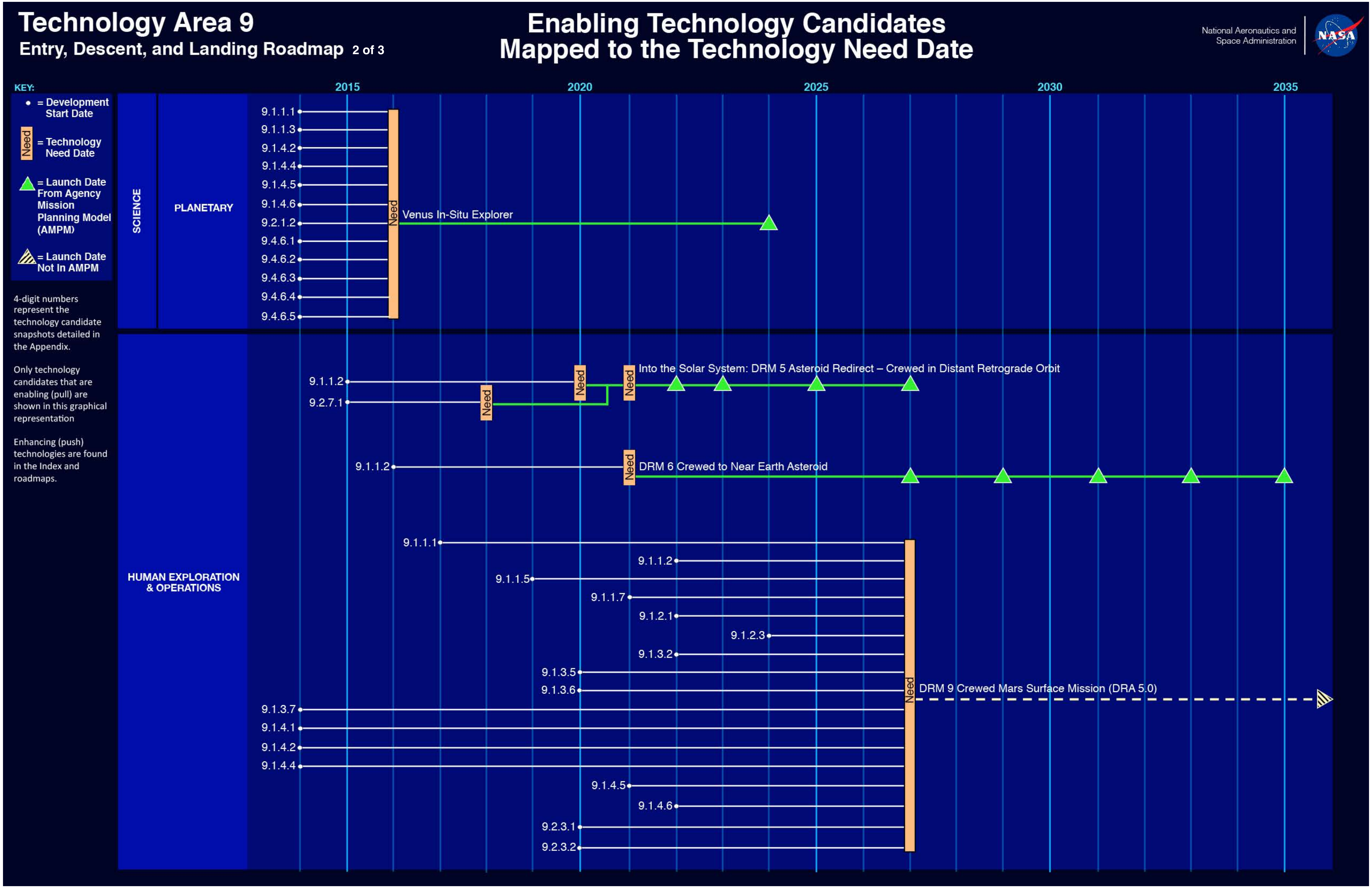

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 9
Entry, Descent, and Landing Roadmap 3 of 3

Enabling Technology Candidates Mapped to the Technology Need Date

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KEY:
- • = Development Start Date
- Need = Technology Need Date
- = Launch Date From Agency Mission Planning Model (AMPM)
- = Launch Date Not In AMPM

4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

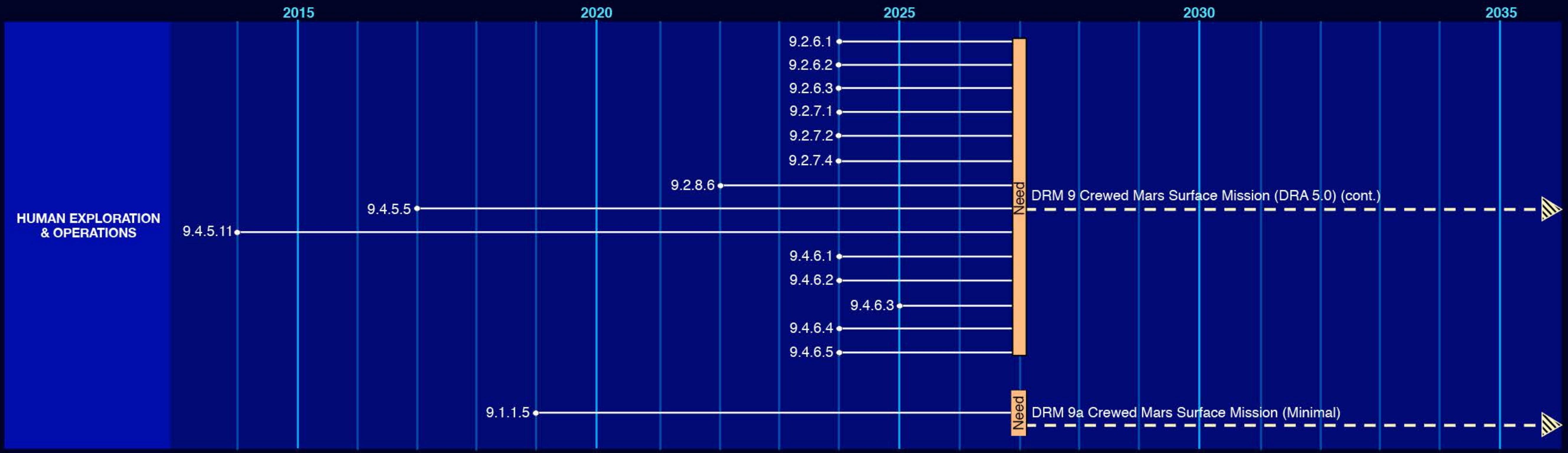


Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

For the purposes of this 20-year technology roadmap, shown in Figure 1, entry, descent, and landing (EDL) encompasses components, systems, qualification, and operations to safely and usefully bring a vehicle from approach conditions to contact with the surface of a solar system body, or to transit the atmosphere of the body. In addition to landing from space on the surface of a body with an atmosphere, EDL includes those missions that enter and then exit the atmosphere of a body for aerocapture or aerobraking ("entry"), landing on small or large bodies with no substantial atmosphere ("landing"), and missions that end in the atmosphere, such as probes, or that deploy aircraft into the atmosphere ("entry and descent"). This roadmap does not address aircraft or aircraft technologies, such as balloons or powered airplanes (see TA15 Aeronautics), nor does it address in-space propulsion preceding atmosphere entry (see TA 2 In-Space Propulsion Technologies). Figure 2 shows the sub-TAs that comprise TA 9 Entry, Descent, and Landing Systems. Note that Thermal Protection Systems technologies are also found in TA 14 Thermal Management Systems.

9.1 Aeroassist and Atmospheric Entry

Aeroassist and atmospheric entry (AAE) systems are defined as the intra-atmospheric technologies that decelerate a spacecraft from hyperbolic arrival through the hypersonic phase of entry. The mission requirements range from high-speed entries of scientific probes at Venus and Saturn, to sample return capsules to Earth (Mars sample return being the most challenging), and human missions to Mars.

- **9.1.1 Thermal Protection Systems for Rigid Decelerators:** Rigid decelerators are the tried and true way of entering planetary atmospheres to date. TPS, a component of the rigid decelerator, offers a mass-efficient way of achieving mission success by protecting human or science cargo from the extreme entry environment encountered during rapid deceleration. Improved robustness along with mass efficiency will serve both robotic and human missions.
- **9.1.2 Thermal Protection Systems for Deployable Decelerators:** The materials that provide thermal protection for deployed decelerators must be lightweight, robust, and able to be stowed and deployed prior to operation.
- **9.1.3 Rigid Hypersonic Decelerators:** Mass-efficient rigid aeroshells are required for most robotic entry missions of the future.
- **9.1.4 Deployable Hypersonic Decelerators:** Deployable entry systems provide a means by which the ballistic coefficient at entry is relatively unconstrained by launch shroud limitations.
- **9.1.5 Instrumentation and Health Monitoring:** This content is now found in TA 9.4.6 Instrumentation and Health Monitoring.
- **9.1.6 Entry Modeling and Simulation:** This content is now found in TA 9.4.5 Modeling and Simulation. TPS modeling and simulation is also contained in TA 14 Thermal Management Systems.

TA 9 Entry, Descent, and Landing Systems

9.1 Aeroassist and Atmospheric Entry

- 9.1.1 Thermal Protection Systems for Rigid Decelerators
- 9.1.2 Thermal Protection Systems for Deployable Decelerators
- 9.1.3 Rigid Hypersonic Decelerators
- 9.1.4 Deployable Hypersonic Decelerators
- 9.1.5 Intrumentation and Health Monitoring
- 9.1.6 Entry Modeling and Simulation

9.2 Descent and Targeting

- 9.2.1 Attached Deployable Decelerators
- 9.2.2 Trailing Deployable Decelerators
- 9.2.3 Supersonic Retropropulsion
- 9.2.4 GN&C Sensors
- 9.2.5 Descent Modeling and Simulation
- 9.2.6 Large Divert Guidance
- 9.2.7 Terrain-Relative Sensing and Characterization
- 9.2.8 Autonomous Targeting

9.3 Landing

- 9.3.1 Propulsion and Touchdown Systems
- 9.3.2 Egress and Deployment Systems
- 9.3.3 Propulsion Systems
- 9.3.4 Large Body GN&C
- 9.3.5 Small Body Systems
- 9.3.6 Landing Modeling and Simulation

9.4 Vehicle Systems

- 9.4.1 Achitecture Analysis
- 9.4.2 Separation Systems
- 9.4.3 System Integration and Analysis
- 9.4.4 Atmosphere and Surface Characterization
- 9.4.5 Modeling and Simulation
- 9.4.6 Instrumentation and Health Monitoring
- 9.4.7 GN&C Sensors and Systems

Figure 2. Technology Area Breakdown Structure (TABS) for Entry, Descent, and Landing

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

9.2 Descent and Targeting

Descent and targeting subsystems and technologies are defined as those that bridge the hypersonic portion of the entry sequence with the terminal phase of landing. The presence of an atmosphere is inherently assumed. Descent is generally considered to include flight through supersonic and high subsonic conditions. Initiation is predicated on a staging event such as a parachute deployment that may not exist in every mission sequence. Descent ends with the initiation of terminal descent propulsion or a landing system. Targeting occurs during terminal descent; this is the phase of EDL in which terrain-relative decisions and final preparations for landing are made. The transition from descent to terminal descent could include the disposal of supersonic decelerators, vehicle reorientation to facilitate surface sensing, and using propulsion to divert away from sensed hazards.

- **9.2.1 Attached Deployable Decelerators:** Large increases in the drag area of an entry vehicle can be achieved through the use of deployable decelerators. These devices differ from the entry variant in that they are deployed endo-atmospherically after the peak heating and peak deceleration phases of flight.
- **9.2.2 Trailing Deployable Decelerators:** Trailing deployable decelerators are necessary for providing stabilization and deceleration of the entry vehicle through low supersonic and subsonic flight and into terminal descent, and often have secondary applications for events like stage separation.
- **9.2.3 Supersonic Retropropulsion:** Utilizing a propulsive terminal descent stage higher in the atmosphere and at higher speed may provide velocity reduction at a lower cost and risk than developing a separate, new aerodynamic decelerator system.
- **9.2.4 Guidance, Navigation and Control (GN&C) Sensors:** This content is now found in TAs 9.2.6 Large Divert Guidance, 9.2.7 Terrain-Relative Sensing and Characterization, and 9.2.8 Autonomous Targeting.
- **9.2.5 Descent Modeling and Simulation:** This content is now found in TA 9.4.5, Modeling and Simulation.
- **9.2.6 Large Divert Guidance:** Numerical algorithms are used to guide the vehicle to a target that is relatively far away, given the vehicle's altitude from the surface.
- **9.2.7 Terrain-Relative Sensing and Characterization:** These are the sensors used to determine position and velocity relative to a surface or surface feature.
- **9.2.8 Autonomous Targeting:** The vehicle makes an onboard decision, based on sensor data, about its desired target point for that phase of the trajectory.

9.3 Landing

The landing phase begins with the final preparations for touchdown (such as the deployment of surface interaction systems) and ends with the landing event itself, which is complete when the kinetic energy of impact has been dissipated and the vehicle is at zero velocity relative to the surface. The landing event may also include an egress or deployment phase to bring the system to operational state. The landing phase surface sensing may begin before the descent phase ends, resulting in an overlap between the two phases. The key areas of technology development are the systems to sense the surface, descent propulsion motors and plume-surface interaction mitigation, touchdown systems, high-g survivable systems, and small-body guidance.

- **9.3.1 Propulsion and Touchdown Systems:** Systems that enable safe, robust contact with a solid surface. In some cases, the touchdown could be destructive for some objective (e.g., a penetrator).
- **9.3.2 Egress and Deployment Systems:** These are methods to allow a robotic element or a human to exit the landed vehicle and commence surface operations. Information on other egress and deployment systems technologies can be seen under TA 7.3 Human Mobility Systems.
- **9.3.3. Propulsion Systems:** This content is now found in TA 9.3.1, Propulsion and Touchdown Systems.

- **9.3.4 Large Body GN&C:** This content is now found in TA 9.4.7 GN&C Sensors and Systems.
- **9.3.5 Small Body Systems:** This content is found in TA 9.2.8 Autonomous Targeting and in TA 4.6 Autonomous Rendezvous and Docking.
- **9.3.6 Landing Modeling and Simulation:** This content is now found in TA 9.4.5 Modeling and Simulation.

9.4 Vehicle Systems

A comprehensive understanding of component-, subsystem-, and system-level performance is inherent to all successful entry vehicle systems. Systems technology capabilities perform a key role for identifying, characterizing, and maturing system-level integration and design. Although subsystem technology readiness level (TRL) maturation is meant to address maturity and risk mitigation at the subsystem level, high-TRL advancement also requires maturation and risk mitigation at the system level. Although in some cases the integration of new TRL 5 or 6 subsystems into flight capabilities can be accomplished with standard engineering approaches, until a new technology is successfully integrated into a flight system, there is development risk that an unforeseen system level capability is required. The maturation of vehicle systems, as an integrated capability, is also required for the infusion of new capabilities into flight vehicles. In the case of EDL, new technologies often have very significant impacts on the integrated vehicle and for this reason vehicle systems technology maturation often requires high-TRL risk mitigation at the integrated vehicle level. In most cases, this requires atmospheric flight-testing of an integrated EDL concept and data collection during operational missions; demonstrating near-flight scale at appropriate flight conditions is necessary for the highest-reliability systems. Inflatables and deployables are more complex, requiring additional multifunctional designing, and are by nature different than other AAE elements, such as thermal protection systems. The integration of these more complex technology elements with descent and landing segment technologies requires greater attention to integration and may pose challenges different than heritage systems. Vehicle systems technologies will thus be segmented into seven areas that have implications across the entire EDL architecture:

- **9.4.1 Architecture Analyses:** In this roadmap document, architecture analyses are not considered a technology unique to EDL. Computational advances from TA 11 will be utilized as appropriate to enable architecture analyses for future missions.
- **9.4.2 Separation Systems:** For the purposes of this roadmap document, transition and separation systems are considered to be an engineering design problem, not thought at this time to require new technology.
- **9.4.3. System Integration and Analysis:** EDL vehicle implementation requires integration of multiple unique subsystems into a system-level capability. System integration and analysis picks up where architecture analysis ends by accomplishing subsystem-level design and performing subsystem-level design trades based on detailed engineering assessments. Moderate levels of engineering fidelity should be expected that rely on validated engineering approximations or engineering design capabilities.
- **9.4.4. Atmosphere and Surface Characterization:** Atmospheric modeling is important to all aerodynamic phases of flight, including aerocapture, aerobraking, entry, and descent. Precise landings require guided vehicles to navigate through variations in atmospheric density and winds. Controlled terminal descent and landing requires an accurate knowledge of the surface characteristics. Instrument-focused technologies needed to fill this strategic knowledge gap for sending humans to Mars can be found in the roadmap for TA 8 Science Instruments, Observatories, and Sensor Systems.
- **9.4.5 Modeling and Simulation:** Improved multi-disciplinary simulations that can capture the complex flows of larger, heavier vehicles are needed to enable risk quantification and design decision-making. EDL systems are reliant on robust and efficient modeling and simulation capability because it is generally not possible to adequately test all aspects of an EDL system in a truly relevant environment prior to use. Simulation capability is thus on the critical path of defining system design, margins, and reliability.

- **9.4.6 Instrumentation and Health Monitoring:** EDL instrumentation for both engineering data and vehicle health monitoring provides a critical link between predicted and observed performance of the AAE system; it is crucial for improving the design of current systems and for ensuring sufficient system reliability prior to deployment or use. EDL instrumentation provides the final validation for modeling and simulation capabilities, which drives down uncertainties and improves overall prediction reliability for future missions.
- **9.4.7 GN&C Sensors and Systems:** This area is an integral component of the EDL systems maturation to meet the full operational requirements for most systems of the future. For components of these systems, refer to TAs 9.1.3 Rigid Hypersonic Decelerators, 9.1.4 Deployable Hypersonic Decelerators, 9.2.6 Large Divert Guidance, 9.2.7 Terrain-Relative Sensing and Characterization, and 9.2.8 Autonomous Targeting.

TA 9.1: Aeroassist and Atmospheric Entry

Over the next 20 years, NASA mission objectives will require significant advances to the state of the art (SOA) in AAE in the following areas: higher entry speeds (crew and sample return from beyond low-Earth orbit, or LEO), larger entry systems for human exploration, extreme environment systems for Venus and giant planet exploration, high-reliability systems for human and sample return missions, and improved approach navigation. Future robotic science missions and human missions to Mars may use aerocapture followed by EDL. Sub-systems like rigid and deployable decelerators and elements like rigid and flexible TPS need to be capable of efficient and robust performance under dual hypersonic entry, namely aerocapture followed by entry. The unique challenges of large payloads (> 1 t) at Mars will require revolutionary changes to the SOA. Other mission classes will benefit from, or in some cases be enabled by, evolutionary or revolutionary improvements to the SOA.

Sub-Goals

As NASA looks towards expanding human presence into the solar system, reliability and scaling will be key factors. In addition, our robotic missions are being called to more exotic destinations, where extreme-environment TPS will be enabling. High-energy direct entry missions, such as crew return from Mars or entry into a planetary atmosphere, will require enhancement to current facility capabilities. Integrating these advanced materials with vehicle structures will require addressing manufacturing and integration challenges. Efficiencies are possible with multifunctional materials that serve a dual purpose during flight. Finally, manufacturing and verification methods will play a key role in certifying the systems of the future.

Table 2. Summary of Level 9.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
9.0 Entry, Descent, and Landing Systems	Goals:	Enable heavier payloads travelling at faster velocities to enter and descend through atmospheres and land safely with high precision
Level 2		
9.1 Aeroassist and Atmospheric Entry	Sub-Goals:	Provide highly reliable AAE systems for human and science missions that are capable of higher entry speeds, greater payload mass, improved approach navigation, and operation in extreme environments.
Level 3		
9.1.1 Thermal Protection Systems for Rigid Decelerators	Objectives:	Develop lower areal mass TPS concepts with extreme environment capability, high reliability, improved manufacturing, and lower cost.
	Challenges:	Sustainability of material supply, TPS integration onto multiple low- and mid-lift/drag configurations, high-fidelity thermal response models, availability of suitable ground test facilities, ground-to-flight traceability, high uncertainties in input aerothermal environments, and the inherent conflict between low mass and robust performance.
	Benefits:	Reduces overall mass and enables missions with extreme entry environments.
9.1.2 Thermal Protection Systems for Deployable Decelerators	Objectives:	Develop packable systems that can withstand 20-250 W/cm^2 heating.
	Challenges:	Maintaining thermal and structural properties after long-duration storage in space, packaging efficiency, performance under aeroelastic and shear loading, and ease of handling.
	Benefits:	Enables larger payloads, increased landed mass, and access to higher landing elevations than traditional rigid systems. Reduces the complexities of system qualification.

Table 2. Summary of Level 9.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
9.1.3 Rigid Hypersonic Decelerators	Objectives:	Develop optimized, controllable rigid aeroshells for multiple mission applications.
	Challenges:	Lightweight structures, effecting non-propulsive control for low-to-mid lift/drag bodies, and high-fidelity aero and aerothermal databases, including dynamic stability.
	Benefits:	Improves performance, increases landing accuracy, and/or increases landed payload capability. Offers extremely high-reliability entry, ensuring a mono-stable shape that will reorient automatically to the proper entry orientation.
9.1.4 Deployable Hypersonic Decelerators	Objectives:	Develop systems that fit in launch shrouds and deliver 10s of metric tons to Mars.
	Challenges:	Scalability, reliable deployment, aeroelastic and aerothermoelastic effects, advanced guidance algorithms, and aerodynamic stability and controllability of large deployable or flexible structures.
	Benefits:	Enables large-mass payloads with lowest arrival mass penalty. Reduces heating and g-loads during entry, potentially lowering instrument development cost to meet the desired science objectives. Does not inhibit science operations, communications, and thermal management during cruise.
9.1.5 Instrumentation and Health Monitoring	This section covered in TA 9.4.6 Instrumentation and Health Monitoring.	
9.1.6 Entry Modeling and Simulation	This section covered in TA 9.4.5 Modeling and Simulation.	

TA 9.1.1 Thermal Protection Systems for Rigid Decelerators

For many exploration missions, such as near-Earth asteroid and Mars missions, ablative materials are needed for dual heat pulse reentries and for high-velocity entries (> 8 km/s at Mars, > 12 km/s for Earth return). However, the current inventory of rigid TPS materials is inadequate for future mission objectives due to insufficient thermal performance, high areal mass, lack of a qualified constituent material source (in the case of chop-molded carbon phenolic), or lack of proven robustness due to limited testing.

The SOA employs TPS installed on a rigid aeroshell or structure, ranging from the reusable tiles on the Shuttle Orbiter to ablative systems employed for planetary entry and Earth return from beyond LEO. Only a limited number of ablative materials have been used for previous missions.

Recent development of ablative materials, primarily in support of Orion, has resulted from NASA efforts to revive the Apollo-era TPS. Robotic science missions to Venus, high-speed sample return missions that are beyond Phenolic Impregnated Carbon Ablator (PICA) capability, or outer planet probe missions, require extreme entry environment TPS. Human return from asteroids at speeds higher than current performance limits (> 12 km/s) or Mars sample return missions will require robust, mass-efficient and highly reliable TPS. Beyond TPS functionality, structural load bearing capability is often needed, and multifunctional material solutions offer overall system mass efficiency.

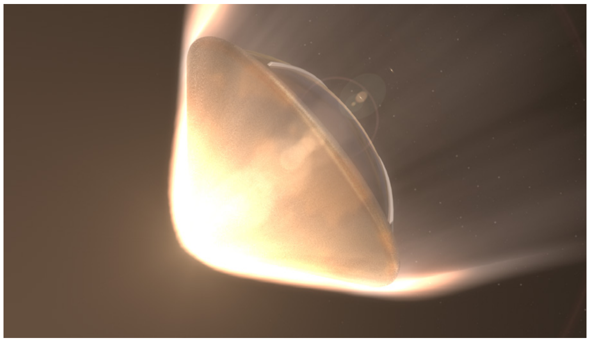
Three-dimensional woven TPS is showing great promise for replacing carbon phenolic in the near term with a mass-efficient, tailorable ablator. Three-dimensionally woven TPS is extremely robust and can be tailored through the thickness by varying yarn types, thicknesses, and weave density. To date, woven TPS has exhibited no failures when tested up to 8,000 W/cm^2 radiant heat flux (without convective flow) and at 2,000 W/cm^2 and 14 atmospheres pressure convective flow conditions. This material concept, integrated onto a rigid aeroshell, may help NASA reestablish and sustain its ability to perform high-speed robotic entries at Venus or the giant planets, or higher-speed Earth return missions. A woven TPS-derived material has been developed to meet Orion's needs for a multifunctional (structural and TPS) compression pad. A multifunctional capability would go beyond what is typically implemented in spacecraft, where the TPS and structure have separate functionality.

Conformal TPS based on carbon felts is showing great promise as a robust and compliant material that could replace PICA in the future and offer cost-effective, mass-efficient, and easier-to-integrate material solutions.

For mid- to high-lift/drag (L/D) configurations, a single TPS will most likely not be mass efficient for either conventional or unconventional shapes, and the integration challenges of multiple TPS systems will require multiple TPS options and additional integration development focus.

Technical Capability Objectives and Challenges

Advances are required to significantly lower the areal mass of TPS concepts; demonstrate extreme-environment capability, high reliability, and improved manufacturing consistency with lower cost; develop manufacturing techniques that are sustained by a commercial base; manufacture larger integrated aeroshells in a cost-effective manner; and demonstrate dual-heat pulse (aerocapture plus entry) capability. These advances will have long lead times due to the need to understand complex nonlinear performance and failure modes.



Rigid Venus Entry Probe

Larger mass savings may be possible with tailored materials that reflect a component of incident heating (radiation), include a coating that prevents release of heat at the surface (catalysis), vary material properties as a function of depth, or employ new reinforcement or additive concepts. Entry to Titan, robotic entry to Mars, and LEO return missions can be accomplished with existing high-TRL TPS when the entry speed is within the off-the-shelf material capability, although evolutionary advances may have mission benefit. Current development in conformal TPS will address integration challenges either on the heat shield or back shell and at the same time provide a mass-efficient solution for moderate conditions, such as on the back shell of rigid decelerators for Venus or outer planet missions. Push technologies, such as TPS materials that reflect incident shock-layer radiation or materials that attenuate solar or deep space radiation or materials that are chemically-designed to self-heal or affect boundary layer modification (such as delay of transition), are currently very low TRL, but have the potential to significantly enhance future mission performance. When integrated into systems, all of these material solutions can benefit from improved non-destructive evaluation to validate manufacturing processes and workmanship.

As a push technology, the extension of conformal systems to higher heat flux ($q > 400$ W/cm^2) may have game-changing benefits for a variety of proposed NASA missions. Finally, it should be possible to tailor the surface chemistry of these systems via impregnants or additives in order to reject heating from surface catalysis or shock-layer radiation, which may provide strongly-enhancing mass savings for all NASA missions.

Rigid Aeroshell Entry into Saturn

Major technical challenges include the development of fundamentally new material concepts with sustainability in mind, approaches to addressing TPS integration onto multiple low- and mid-L/D configurations, development of high-fidelity thermal response models, availability of suitable ground test facilities, ground-to-flight traceability, high uncertainties in input aerothermal environments, and the inherent conflict between low mass and robust performance. Concept maturation to TRL 5 will require extensive ground testing, while maturation to TRL 6 may require a small-scale component or a subsystem-level flight test. See also TA 14 Thermal Management Systems, for additional TPS technologies.

Benefits of Technology

Advances in ablative thermal protection for extreme environment and conformal ablators will benefit robotic science missions to Venus, Saturn, and higher-speed sample return missions in the near term. High-reliability thermal protection systems will benefit human missions from asteroids and Mars, as well as sample return missions from Mars, Enceladus, or other moons of gas and ice giants. Multifunctional materials have the potential to impact overall mass, primarily for human missions that require larger entry systems compared to robotic science missions.

Table 3. TA 9.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
9.1.1.1	Extreme Environment Ablative Thermal Protection System (TPS)	Ablative TPS materials for blunt aeroshells operating in extreme entry environments.
9.1.1.2	High-Reliability Thermal Protection System (TPS)	High-reliability TPS to meet requirements for human mission robustness and sample return mission contamination prevention.
9.1.1.3	Conformal Ablative Thermal Protection System (TPS)	Provides conformal ablative thermal protection for low to moderate entry conditions for both heat shield and backshell applications.
9.1.1.4	Multifunctional, Shock Layer Radiation-Reflective Material	Reflects radiant energy back to space to protect large blunt bodies during extreme entry (see also TA 14 Thermal Management Systems).
9.1.1.5	Multifunctional, Micrometeoroid and Orbital Debris (MMOD)-Tolerant Materials	TPS materials that provide thermal protection after a MMOD strike. See also TA 14.3 Thermal Protection Systems.
9.1.1.6	Solar and Space Radiation Attenuating Materials	TPS materials that also shield against solar flare radiation and cosmic rays. See also TA 6.5 Radiation, TA 10.1 Engineered Materials and Structures, TA 12.2 Structures, and TA 14 Thermal Management Systems.
9.1.1.7	Multifunctional Thermo-Structural Materials	Protects spacecraft from the environment during entry, descent, and landing by integrating thermal protection materials and structure. See also TA 12.2.5 Innovative, Multifunctional Concepts and TA 14 Thermal Management Systems.
9.1.1.8	Non-Destructive Evaluation (NDE)	Inspection and certification of materials and systems.

TA 9.1.2 Thermal Protection Systems for Deployable Decelerators

Hypersonic deployable (inflatable or mechanical) aerodynamic decelerators are deployed outside the atmosphere and require a TPS to survive the heat pulse of atmospheric entry. The SOA for a deployable (inflatable) decelerator TPS is the multi-layer insulating system used on the Inflatable Reentry Vehicle Experiment (IRVE-3). This system has an areal mass of 3.3 kg/m^2, a heat rate capability of 40 W/cm^2, and a maximum heat load capability of 7.5 kJ/cm^2. The TPS consists of two layers of fabric over multiple layers of pyrogel, and is backed by a laminate gas barrier.

Current NASA development includes evolution of the IRVE-3 system. The ultimate goal of this evolved capability is to provide an areal mass of 5 kg/m^2 with a maximum heat flux of 50-100 W/cm^2 and heat load capability of 15 kJ/cm^2, which allows implementation of a hypersonic inflatable aerodynamic decelerator for human Mars missions. Flexible ablators (either silicone- or carbon-based) that could exceed the 100 W/cm^2 heat flux limit of non-ablating flexible materials might address this challenge.

The SOA for a mechanically-deployable decelerator is the multi-layer, 3-dimensionally woven, flexible and foldable carbon fabric. The carbon fabric functions both as a TPS and as a rigid structure when held in tension after deployment of the mechanical decelerator frame. The carbon fabric TPS has been demonstrated for the thermo-structural capabilities in specialized arcjet testing, at heat fluxes up to 250 W/cm^2. Current developments also include maturing a carbon cloth TPS system intended to serve as a hot structure ablator.

Technical Capability Objectives and Challenges

The TPS for hypersonic deployables must be flexible to allow for packaging within the launch vehicle shroud, stowed for months in space, and then deployed into an entry configuration that can withstand heating of 20-250 W/cm^2, depending on the mission application. These are envisioned as single- or dual-use (aerocapture plus entry) systems. Both non-ablating and ablating concepts may be suitable, where the key trades are TPS development complexity, system scalability, aerodynamic shape stability, and areal mass. Non-ablating concepts will either be multilayer insulative systems or possibly transpiration-cooled fabrics. Ablative systems may include organic resins as impregnants or as woven fibers. Advanced weaving techniques can be employed to tailor material properties for given mission requirements.

While the challenge for inflatable decelerators is the integration of packable, foldable TPS capable of insulating the inflated structural system, the challenge for mechanically deployed systems is the multifunctionality of the single element that is both a TPS and a structural, load-bearing subsystem. Major technical challenges include maintaining thermal and structural properties after long-duration storage in space, packaging efficiency, performance under aeroelastic and shear loading, and ease of handling. Concept maturation to TRL 5 will require extensive ground testing, while maturation to TRL 6 may require a small-scale component-level flight test.

In the case of inflatable decelerators, this TPS must provide sufficient thermal insulation to ensure the operational temperature of the structure is not exceeded. For mechanical deployables, heating may be radiated to the wake via the flexible TPS between rigid elements (so that only localized thermal protection of the mechanical structure and/or payload may be required). For either application, performance-enhancing coatings (such as reduction of surface catalysis) and additives (to reflect shock layer radiation, for example) are of interest.

Benefits of Technology

Flexible TPS is enabling for large entry systems that cannot fit within launch shrouds and must be deployed at the destination. These systems enable larger payloads, increased landed mass, and more planetary access than traditional, rigid systems. The more capable the thermal protection systems are, the smaller the deployable systems can be, reducing the complexities of system qualification.

Table 4. TA 9.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
9.1.2.1	Non-Ablative Concepts for Thermal Protection	Protects spacecraft during entry, descent, and landing using highly-flexible, stowable, non-ablative (insulative or transpiration-cooled) thermal protection.
9.1.2.2	Flexible Ablative Concepts for Thermal Protection	Ablative materials suitable for deployables decelerator, including systems that rigidize in-space or during entry.
9.1.2.3	Flexible Thermostructural Thermal Protection System (TPS)	Flexible materials capable of accomodating aerothermal loads and load-bearing pressures as well as being flexible to be stowed during launch.
9.1.2.4	Textile Fabrics and Coatings for Catalycity and Thermal Resistance	Provides high-strength, high-temperature textile fabrics and coatings that can extend the thermal environment in which deployable decelerators can operate.
9.1.2.5	Textile Fabrics and Coatings for Radiation Reflection and Resistance	Provides high-strength, high-temperature textile fabrics and coatings that can extend the radiation environment in which deployable decelerators can operate.

TA 9.1.3 Rigid Hypersonic Decelerators

Most entry missions of the last two decades have made use of traditional (Viking- or Apollo-era) aeroshell shapes and technologies. Consequently, there has been relatively little effort within NASA to develop new entry aeroshell shapes or aeroshell technologies beyond the conceptual stage. However, human exploration of Mars will require a fundamentally new aeroshell design due to large landed mass requirements. In addition, optimized aeroshells for specific mission classes to other destinations may provide evolutionary advances in current mission capabilities, and self-righting, highly-stable designs are desirable for sample return missions.

The SOA for blunt low lift-to-drag configurations is the classic sphere-cone (70° at Mars, 60° at Earth, 45° at Venus and giant planets) and the truncated sphere (Apollo and Orion). The Space Shuttle Orbiter represents the SOA for mid lift-to-drag configurations. Typically, these aeroshells are either metallic or composite, with the TPS bonded to the structure with high-temperature adhesive. The carrier structure is designed to bear all aerodynamic loading (without reliance on the TPS). Control of low lift-to-drag vehicles has typically been affected via reaction control thrusters or mass ejection for center of gravity shifting. Control of other vehicles with higher lift-to-drag ratios has been accomplished with a combination of aerodynamic control surfaces and reaction control thrusters with blended control laws across the Mach number regime.

Previous studies included mid L/D (biconic or ellipsled) designs for Mars entry and Neptune aerocapture; stable, chuteless designs for Mars Sample Return; and raked blunt cones for crew return and orbital transfer at Earth. Mid L/D vehicles could be designed for dual-purpose use as a payload fairing during ascent. Even for “heritage” aeroshell shapes, the SOA in several supporting disciplines, notably aerothermodynamics, has large uncertainties leading to large design margins and mass-inefficient entry systems. Non-NASA development in such systems has been restricted to slender cones for reentry vehicle applications and mid- to high-lift hypersonic cruise vehicles, which are minimally applicable to proposed NASA missions.

Technical Capability Objectives and Challenges

Major objectives include developing lightweight structures, effecting non-propulsive control for low-to-mid L/D bodies, and developing high-fidelity aero/aerothermal databases, including dynamic stability. The successful Apollo-based hypersonic guidance of Mars Science Laboratory (MSL) established feasibility and provides a solid base for improvements. Development of advanced guidance algorithms beyond the numerical predictor and corrector utilized for Orion skip entry guidance, is required for aerocapture and could enable precision landing of entry vehicles, including optimal divert for proximity operations of multiple landed assets. In most of the entry vehicle studies performed recently, the payload is expected to “eject” from the hypersonic decelerator and transition to the correct orientation for the supersonic phase. This is a major engineering challenge. Concept maturation to TRL 6 will require a mix of ground and subscale-system level flight tests.

Benefits of Technology

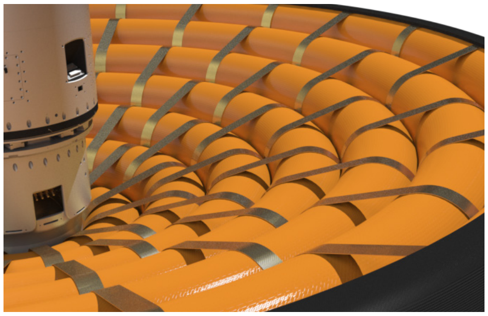
Optimized rigid aeroshells for low L/D applications have the potential to improve performance, increase landing accuracy, and/or increase landed payload capability. A shape-optimized design for sample return offers extremely high-reliability entry, ensuring a mono-stable shape that will reorient automatically to the proper entry orientation. Mid L/D rigid aeroshells in the human Mars mission architecture, such as the biconic or ellipsled, are the only alternatives to deployable decelerators that have been studied, and may offer enhanced capabilities for other applications as well. For example, a past study of Neptune aerocapture identified the need for a mid-L/D, high heat flux capability that is well-suited for a rigid aeroshell.

Table 5. TA 9.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
9.1.3.1	Sample Return Capsules	Low-mass structures, impact attenuators, and capsule systems that enable low-cost sample returns.
9.1.3.2	Entry Vehicles with Lift/Drag (L/D) 0.4 to < 2.0	Provide entry for mission applications where g-load or targeting requirements cannot be satisfied with lower L/D, or when landing opportunity intervals motivate higher-entry trajectory cross-range performance.
9.1.3.3	Enhanced Aerodynamics for Slender Vehicles	Provides a vehicle with additional lift through deployable aerodynamic surfaces (chines, wings, etc.).
9.1.3.4	Entry Vehicles with Lift/Drag (L/D) > 2.0	Enable significant downrange performance for hypersonic transport vehicles, significant plane change capability for orbital transfer vehicles, and lift sufficient to perform aerogravity assist.
9.1.3.5	Aerodynamics Modulation Hardware	Hardware that allows modulation of aerodynamics (lift, drag, etc.) for enhanced maneuverability during EDL.
9.1.3.6	Control Modulation Software	Software that commands aerodynamic control during hypersonic EDL based on vehicle and environmental state data.
9.1.3.7	Entry Guidance Software	Numerical model-based predictor-corrector entry guidance algorithms for lifting entry vehicles, which increase robustness, enhance dynamic flight constraint mitigation, and improve mission success statistics over analytic and reference-trajectory-based algorithms.

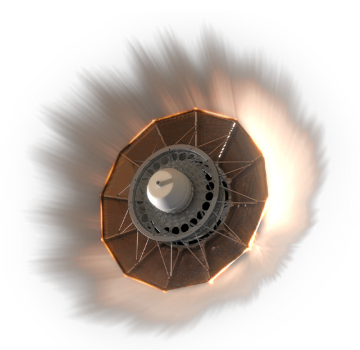
TA 9.1.4 Deployable Hypersonic Decelerators

While there has been no demonstration of flight-relevant-scale deployable hypersonic decelerators to date, the recent IRVE-3 test (2012) made significant progress in the maturation of inflatable deployable technology (e.g., the Hypersonic Inflatable Aerodynamic Decelerator (HIAD)). In addition to flight demonstration, NASA has conducted extensive mechanical and thermal ground testing of inflatable structures ranging from straight beams to large-scale wind tunnel tests of hypersonic entry shapes. NASA also recently began the development of mechanical deployables, including performing ground tests at the component and small-scale levels in support of a future flight demonstration.



Inflatable Decelerator Aerodynamic Test

Accordingly, limited development is occurring for supporting technologies, such as multi-axis center of gravity (CG) modulation for flight control; advanced guidance and control systems; and lightweight, high-temperature materials; which are all applicable to rigid and inflatable deployable decelerators. Still, significant advancements must be made in the area of large-scale deployable structures in order to fully realize their potential and understand the viable limits of their use. This is especially crucial for future exploration missions in light of multiple system analysis studies, which have shown that human Mars EDL architectures that employ deployable hypersonic decelerators may have mass advantages over rigid aeroshell concepts.



Mechanically-Deployable Aeroshell

Technical Capability Objectives and Challenges

In order to achieve the ballistic coefficients required to deliver large mass payloads of future exploration missions, deployable hypersonic decelerators will require deployed diameters in excess of 20 meters (m). This represents a significant scalability challenge, as current flight demonstrations have been limited to 3 m for an inflatable decelerator. Ground aerodynamic and load tests have been conducted on a 6 m scale article for an inflatable, and a 2 m rigid deployable has been constructed and deployed in the laboratory.

Major technical challenges include scalability, reliable deployment, aeroelastic and aerothermoelastic effects, advanced guidance algorithms as discussed in TA 9.1.3, and aerodynamic stability and controllability of large deployable or flexible structures. Concept maturation to TRL 6 will require a mix of ground and subscale-system-level flight tests, supporting the development of validated models that allow the required scaling for reasonable risk.

Inflatable Decelerator Aero Test

Benefits of Technology

This revolutionary advance has several potentially enabling benefits, particularly for large payload delivery to the Martian surface, as well as the potential to significantly enhance a variety of NASA missions ranging from ISS down-mass to crewed Earth return from beyond LEO. Of particular relevance are several architecture and systems studies, which identify hypersonic deployable decelerators as enablers of large-mass payloads with lowest arrival mass penalty. In addition, analysis shows that deployable decelerators have significant advantages for Venus robotic missions, allowing reduced heating and g-loads during entry, therefore potentially lowering instrument development cost to meet the desired science objectives. Decelerators that are stowable until the time of entry would eliminate thermal, communications, and science constraints imposed by traditional aeroshells for aerocapturing orbiters.

Table 6. TA 9.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
9.1.4.1	Inflatable Entry Systems	Deploys an inflatable rigid structure protected by a flexible TPS to increase the vehicle aerodynamic drag, thus lowering the ballistic coefficient.
9.1.4.2	Mechanically-Deployed Entry Systems	Deploys a mechanical, rigid structure protected by a structural TPS membrane to increase the vehicle aerodynamic drag, thus lowering the ballistic coefficient. See also TA 12.1.3 Flexible Material Systems.
9.1.4.3	Transformable or Morphable Entry Systems	Enable a vehicle to change shape or configuration to achieve additional functions during entry, descent, and landing, such as providing direct alpha and beta control or direct ballistic number control.
9.1.4.4	Flexible Structural Materials	Provides flexible structures that can reduce structural mass over SOA. Upon deployment the flexible materials provide the load-bearing aeroshell structure. See the technology roadmap for TA 12 Materials, Structures, Mechanical Systems, and Manufacturing.
9.1.4.5	Non-Propulsive Flight Control Effectors	Provides non-propulsive flight control effectors, including control surfaces and active modulation, which facilitate system flexibility.
9.1.4.6	Advanced Guidance and Navigation Systems	Provides advanced guidance and navigation systems that are adapted to deployable system controllers for both aerocapture and subsequent entry, descent, and landing.
9.1.4.7	On-Orbit Assembled Entry Systems	Makes use of in-space assembly to create a vehicle that might not otherwise be launched without complex, automated deployment systems. Can potentially lead to low-cost re-entry systems and upper atmosphere research. Also includes in-situ manufacturing.

TA 9.1.5 Instrumentation and Health Monitoring

These technologies are now located in TA 9.4.6 Instrumentation and Health Monitoring.

TA 9.1.6 Entry Modeling and Simulation

These technologies are now located in TA 9.4.5 Modeling and Simulation.

TA 9.2: Descent and Targeting

Historically, the descent phase of flight has focused on simply providing sufficient deceleration for landing system staging, and thus the primary technology for this phase of EDL has been the parachute. Most architectures that deliver payloads greater than 1 to 2 tons (t) to the Mars surface call for stability and drag augmentation during the supersonic phase. Some scenarios require drag areas larger than those of qualified parachute systems, deployed at higher Mach numbers and dynamic pressures than previously attempted. The risk posture associated with these increasingly expensive missions, and eventually human payloads, requires higher-performing, more readily-predictable descent systems for the future.

Terminal descent is the portion of the EDL phase of a mission in which terrain-relative decisions are made and the final preparation for landing occurs, both in terms of vehicle configuration and in terms of vehicle dynamic preparation. The SOA for this technology area is represented by the Phoenix and Mars Science Laboratory (MSL) radar-based terrain-relative sensing, divert, and touchdown preparation. This mission phase incorporates propulsive systems, terrain-relative targeting, and possible large diverts for hazard avoidance or pinpoint targeting and surface rendezvous. Terrain-relative sensing and autonomous targeting are pathways forward for future technology development to improve safety for human landings.

Sub-Goals

As planetary missions move towards larger payloads with greater emphasis on targeted landings, the SOA in descent and targeting technology will require major advances. The goal of these advances primarily focuses on providing greater deceleration in the supersonic and subsonic regimes in a manner that does not reduce landing accuracy or result in transient unsteadiness or loss of performance in the transonic regime. Although the thin atmosphere of Mars provides a challenging condition for descent technologies, advances made in this area will benefit a variety of mission concepts at other planets as well, particularly as larger and larger landed masses are desired.

Heavier payloads require increasingly larger aerodynamic or propulsive decelerators during descent. Historical experience with parachutes has demonstrated difficulties in extrapolating deployment and steady state behaviors beyond qualified scales. Addressing the uncertainties associated with the use of large-scale decelerators introduces the need to test at near-full-scale, or the need to develop test methodologies that reduce the dependence on testing at scale. Qualification testing at the needed scales and conditions is generally beyond the affordability of a flight program, inhibiting the use of anything but “heritage” systems. Thus, it is important that technology development programs not only test at applicable scales but also develop strategies for flight programs to qualify the technology at larger sizes and more stringent test conditions.

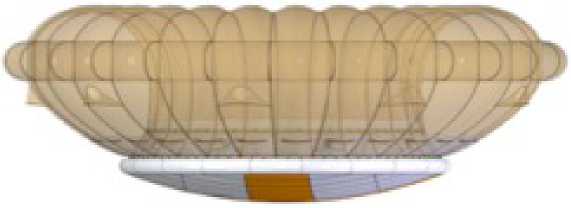
Table 7. Summary of Level 9.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
9.0 Entry, Descent, and Landing Systems	Goals:	Enable heavier payloads travelling at faster velocities to enter and descend through atmospheres and land safely with high precision
Level 2		
9.2 Descent and Targeting	Sub-Goals:	Provide greater deceleration in the supersonic and subsonic regimes in a manner that does not reduce landing accuracy or result in transient unsteadiness or loss of performance in the transonic regime.

Table 7. Summary of Level 9.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
9.2.1 Attached Deployable Decelerators	Objectives:	Provide order-of-magnitude increases in drag area at Mach numbers and dynamic pressures considerably higher than current supersonic decelerators.
	Challenges:	Scalability, deployment methodology (for non-inflatable designs), dynamic stability, and controllability.
	Benefits:	Enables increased timeline margin or increased mass delivery to higher elevation landing sites.
9.2.2 Trailing Deployable Decelerators	Objectives:	Improve drag performance over SOA parachutes and provide ability to deploy at higher Mach number.
	Challenges:	Establishing scalability, reliability, and general predictability of systems, with limited test venues.
	Benefits:	Simple detachment from the payload at the end of use. Extends the delivered payload mass range. Improves reliability and system mass in abort scenarios required for human spaceflight.
9.2.3 Supersonic Retropropulsion	Objectives:	Enable landing of large-mass payloads (> 5 metric tons) on Mars.
	Challenges:	Rocket engine startup and transient forces and moments, steady state forces and moments, and calibration of engineering models sufficient for design and development of an integrated EDL capability.
	Benefits:	Mitigates technical risk of supersonic deceleration without the large-scale flight testing program required for aerodynamic decelerator system qualification and certification.
9.2.4 GN&C Sensors	This section covered in TAs 9.1.3, Rigid Hypersonic Decelerators, 9.1.4 Deployable Hypersonic Decelerators, 9.2.6 Large Divert Guidance, 9.2.7 Terrain-Relative Sensing and Characterization, and 9.2.8 Autonomous Tracking.	
9.2.5 Descent Modeling and Simulation	This section covered in TA 9.4.5 Modeling and Simulation.	
9.2.6 Large Divert Guidance	Objectives:	Provide an onboard guidance algorithm that efficiently calculates accurate, fuel-optimized solutions for large divert maneuvers.
	Challenges:	Algorithms that quickly and robustly find a constrained, optimal divert while a vehicle is falling towards a large body at hundreds of miles per hour.
	Benefits:	Enables hazard avoidance and pinpoint landing for minimal mass increases.
9.2.7 Terrain-Relative Sensing and Characterization	Objectives:	Produce high-rate, high-accuracy measurements for algorithms that enable safe precision landing near areas of high scientific interest or predeployed assets. Minimize size, mass, and power of terrain sensors.
	Challenges:	High-resolution, space-qualified sensors, supported by high-rate computational capability.
	Benefits:	Improves accuracy and reliability of a wide range of autonomous GN&C and landing-site-targeting algorithms. Provides atmospheric measurements of interest to scientists.
9.2.8 Autonomous Targeting	Objectives:	Synthesize surface information in real-time to enable safer landings for human-rated payloads and improve targeting and science access for robotic-scale science missions.
	Challenges:	Combining terrain-relative sensor input to generate needed targeting updates.
	Benefits:	Enables robotic landing on the surface of bodies such as Europa where the topography changes between a mapping mission and a landing mission, or where a priori information is lacking.

TA 9.2.1 Attached Deployable Decelerators



Attached Deployable Decelerator

Attached decelerators can be categorized as flexible (e.g., supersonic inflatable aerodynamic decelerators (SIAD)) or rigid. Attached inflatable decelerators were originally conceived during development of the Mars Viking missions and saw extensive ground-based aerodynamic and structural testing of small-scale articles (< 1.5 m) at Mach numbers approaching 5. Larger articles (11 m) were drop-tested at low-velocity conditions, although no large-scale flight tests ever took place at supersonic conditions. Even though development of inflatable decelerators largely ceased at the conclusion of the Viking program, small-scale development, primarily in the form of wind tunnel testing of alternative configurations, continued in the mid-2000s. More recently, SIADs have been the target of a NASA development that has resurrected a supersonic, high-altitude testing capability. The SOA includes flight demonstration of a 6-m diameter SIAD at Mach 4 and Mars-relevant dynamic pressures. Development of mechanically-deployed or rigid attached supersonic decelerators is largely non-existent, except in conceptual studies.

Technical Capability Objectives and Challenges

Most envisioned attached deployable decelerators are purely drag devices, but development in lifting deployables (such as guidable or steerable systems) could have a game-changing impact in terms of landing accuracy. Key objectives are focused on providing order-of-magnitude increases in drag area at Mach numbers and dynamic pressures considerably higher than current supersonic decelerators.

Major technical challenges include scalability, deployment methodology (for non-inflatable designs), dynamic stability, and controllability. The primary application of attached deployable decelerators may be at Mars due to its tenuous atmosphere, but other applications are possible, including returning mass from the ISS and landing large payloads on other atmosphere-bearing bodies.

Benefits of Technology

Attached decelerators may enable increased timeline margin or increased mass delivery to higher elevation landing sites.

Table 8. TA 9.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.1.1	Supersonic Inflatable Aerodynamic Decelerator (SIAD)	An inflatable, deployable decelerator that provides aerodynamic (drag, L/D, or stability) augmentation in the high supersonic Mach number range (2-5+) for higher altitude deceleration, increased timeline, staging.
9.2.1.2	Mechanically Deployed Decelerators and Methods of Active Control	Provide descent deceleration using rigid, actuated deployable decelerators with or without rigid skeleton and textile membrane.
9.2.1.3	Steerable and Guided Deployable Decelerators	Allow control of a drag device to a precise landing location.
9.2.1.4	Dual-Mode Attached Decelerator Systems	A decelerator that deploys supersonically, then could operate through the subsonic regime, perhaps by changing shape or attachment geometry (for example, an attached isotensoid that when cutaway becomes a parachute).

TA 9.2.2 Trailing Deployable Decelerators

The SOA in subsonic trailing decelerator technology are ribbon and ringsail parachutes, used individually or in clusters, such as those employed on Pioneer Venus Large Probe, Galileo, Apollo and being tested for Orion. These parachutes were originally developed and qualified during the 1960s and 1970s, and extensions in size and capability have been necessary to accomplish missions such as Orion. The SOA for subsonic parachutes at Earth is 48-m diameter for a dual cluster of two parachutes and a cluster of three 35.4-m diameter parachutes for recovery of 9,100 kg, both using ringsail canopies with Kevlar/Nylon materials. Subsonic gliding parachutes continue to enjoy wide popularity with sport, commercial, and government applications. Typical canopy areas range from 6.5 to 28 square meters, with aspect ratios of two to three. During the 1990s NASA and other government agencies invested in flight testing of large subsonic parafoil systems capable of recovering payloads weighing up to 11,000 kg with reference areas as high as 700 square meters. As a result of the technology demonstration performed at that time, along with advances in control system and miniaturization of avionics, autonomous guided parafoil systems with a broad range of sizes are commonly fielded. The maximum size parafoil flight tested to date is a 930 square meter canopy.

The SOA in trailing decelerator technology for supersonic use are the disk gap band (DGB) parachute, Supersonic Planetary Experiment Development (SPED), Supersonic High Altitude Parachute Experiment, and Balloon Launch Decelerator Test flight test programs of the 1960s and 1970s. These parachutes have been the primary deployable decelerator for planetary robotic missions for the past 40 years. The SOA for Mars supersonic parachutes, established for MSL, is a 21.5-m diameter system for Mach numbers up to 2.2. Qualification limits in size and deployment conditions for these parachutes hinder the ability to land missions beyond the size of MSL. As a result, NASA is testing alternative parachute designs for potential use at Mars. The SOA for reefing and clustering of supersonic trailing decelerators is very different than that for subsonic capabilities. No current capabilities exist for reefing or clustering supersonic parachutes, and the TRL is very low. Significant challenges for defining the scope, cost, and extent of testing needed to develop and qualify reefing or clustered supersonic parachutes exist due to the limited available basis of estimate.

In addition to parachutes, inflatable aerodynamic decelerators in a trailing configuration (often termed ‘ballutes’) have been previously flight tested at Mach numbers near 10 and could provide improved stability and drag at Mach numbers above 3. Ballutes also offer the ability to act as pilots to deploy larger parachutes, as recently demonstrated in June 2014 by the successful test flight of a 4.4-m trailing ballute, which deployed at Mach 2.7 during Earth high-altitude testing. This flight demonstration also showed the feasibility of utilizing a ballute for the sole purpose of deceleration.

Technical Capability Objectives and Challenges

The amount of heritage in subsonic parachutes for other planetary applications is much larger than with supersonic parachutes, though not always in a relevant environment (e.g., temperature and density), and reflects the larger application base of subsonic parachutes at Earth. Entries to Venus and the giant planets can use traditional subsonic parachutes with good efficacy, although development of higher-temperature-capability textiles is warranted for those applications.

Trailing Deployable (Parachute) Wind Tunnel Test

Supersonic parachutes are needed that are larger and more efficient than the 21.5-m DGB used by MSL. Such parachutes also need to have the ability to deploy at higher Mach number, which requires technology advances in textile strength and thermal performance. Additional development in evolutionary concepts, like parachute clusters and multi-stage reefing, may be warranted, but is not considered a significant advance to the SOA unless focused on clusters or reefing under supersonic conditions. The ability to autonomously disreef a parachute based on vehicle state would be a major improvement in abort scenarios and may have benefit in both total system mass and overall reliability. Developing lifting trailing decelerators (such as paragliders) as descent systems does not seem warranted given proposed mission requirements. NASA development of advanced supersonic parachute technology has been limited since the Viking program. A supersonic parachute capability of approximately 30-meter diameter might provide a significant benefit for Mars landed mass or altitude.

A significant challenge for application of deployable decelerators on human-scale missions involves the size of system required to be competitive with non-aerodynamic decelerator options, and efficiently addressing reliability and redundancy requirements. Basic geometric scaling of subsonic or supersonic parachutes, singly or in clusters, implies that utilization of new, larger total drag area systems could satisfy the necessary drag requirements. However, basic feasibility of these very large-area systems has not been addressed, nor have the development and qualification testing efforts been adequately defined. In addition, no SOA for supersonic clustered aerodynamic decelerators exists. If the development and qualification costs of these very large-scale aerodynamic decelerators is ultimately determined to be acceptable, such capabilities could ultimately be competitive with other approaches.

Challenges to developing a large-scale supersonic parachute system include limits on what parachute diameters can be tested in subsonic wind tunnels. These limits create a need to perform qualification via atmospheric flight testing as well as develop physics-based computational tools to assist in defining these tests. Flight testing of subsonic parachutes is well established and is typically limited by cost and schedule. Supersonic decelerator flight testing is a significant capability that has been recently resurrected by NASA, but for any given effort will be limited to a small number of individual flight tests due to cost. A development challenge for any large supersonic parachute system will be the need to address failure mode risks via flight testing, with the limited ground test capability and the fact that no current computational capability exists to reliably predict parachute flowfields and dynamics.

Benefits of Technology

Trailing deployable decelerators are a mass-efficient, relatively low-volume method of imparting drag, and can easily be detached from the payload at the end of their use. They have extensive Earth-based heritage, and they can usually be tested at Earth in relevant environments.

Larger, more efficient supersonic parachutes will enable larger Mars robotic missions and could potentially be used as staging devices for larger human class missions. In addition, the ability to deploy such parachutes at higher Mach number may provide a significant timeline benefit for some missions. In addition to the current ringsail developments, reefing and clustering may extend the delivered payload mass range, and smart disreefing can improve reliability and system mass in abort scenarios required for human spaceflight. Trailing ballutes may have stability and reliability advantages over parachutes for high-Mach deployments.

Table 9. TA 9.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.2.1	Supersonic Parachutes	Provides more capable supersonic parachutes for low-density use, including multi-stage reefing.
9.2.2.2	Trailing Inflatable Aerodynamic Decelerators (Ballutes)	Provides a drag-only method of deceleration that trails the main vehicle for easy release. Also functions as a pilot to deploy large parachutes.
9.2.2.3	Autonomous Parachute Disreef	Provides informed disreef command to a parachute based on vehicle state.
9.2.2.4	Lightweight, High-Strength Broadcloth (Scrim)	Provides lightweight, high-strength material for supersonic and subsonic parachutes to improve mass efficiency.

TA 9.2.3 Supersonic Retropropulsion

The SOA in propulsive descent that starts in the supersonic regime includes Viking-era wind tunnel testing of a limited number of notional configurations using perfect gas jets. NASA development of the fundamental physics of supersonic retropropulsion (SRP) was reinvigorated in 2010-2012 and consisted of cold gas wind tunnel testing for computational fluid dynamics (CFD) tools evaluation. New technology development focuses on commercial partnerships to advance the application of propulsive-descent technologies for high-mass Mars missions. Current systems analysis for human Mars missions is focused on cryogenic liquid oxygen/methane systems. This approach seeks to maximize commonality with Mars ascent vehicle propulsion and take advantage of in-situ propellant generation. However, alternate fuels should also be undertaken for potential descent or combined descent-ascent applications, based on specific mission requirements. The SOA is represented by recent SRP flight tests accomplished by a commercial first stage rocket on Earth along with limited rocket sled testing with solid rocket motors.

Technical Capability Objectives and Challenges

Because the atmosphere of Mars has a low density, supersonic aerodynamic decelerator systems will be limited to delivery of landed payloads of a few metric tons. New systems are needed to support Mars landed payloads greater than approximately 5 metric tons and up through human scale.

Technical challenges and risk exist in several areas for SRP, including: rocket engine startup and transient forces and moments, steady-state forces and moments, and development or calibration of engineering models sufficient for design and development of an integrated EDL capability. Advancement of a supersonic propulsive descent capability for Mars applications will require accomplishment of TRL 6 before the close of this decade if this technology is to be incorporated into mid-2020s human precursor missions in preparation for human Mars missions in the 2030s.

Supersonic retropropulsion maturation may require advancements in algorithms and sensors to effectively stabilize and control the vehicle. For Mars precursor and human applications, the need for high thrust during the supersonic phase of flight, combined with a much lower thrust magnitude for landing, imposes the need for an enabling deep-throttling rocket engine capability. In addition to deep throttling, other system performance and implementation details, such as specific impulse (I_{SP}), throttling profiles versus time, and integration as a multi-engine system capability, will affect system performance. Deep-throttling rocket engines are a subject identified in the technology roadmap for TA 2 In-Space Propulsion Technologies.

Benefits of Technology

A supersonic propulsive descent capability can enable Mars missions by landing more mass on the surface and providing precise landing with minimal increase in fuel. When the supersonic phase is propulsively dominated the effects of winds are minimized. Most of the landing error for MSL was because of on-parachute winds. Another benefit of retropropulsion implementations compared to large flexible aerodynamic systems is the ability to mitigate technical risk sufficiently without the large-scale flight testing program required for aerodynamic decelerator system qualification and certification.

Table 10. TA 9.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.3.1	Advanced Algorithms and Sensors for Supersonic Retropropulsion	Control and stabilize entry vehicles in the presence of complex fluid dynamic interactions.
9.2.3.2	Deep-Throttling, High-Thrust Engines for Mars Descent	Provides both Supersonic Retropropulsion (SRP) and terminal descent and touchdown thrust requirements (see also TA 2.1.2 Liquid Cryogenic)

TA 9.2.4 Guidance, Navigation and Control (GN&C) Sensors

These technologies are contained within TAs 9.1.3 Rigid Hypersonic Decelerators, 9.1.4 Deployable Hypersonic Decelerators, 9.2.6 Large Divert Guidance, 9.2.7 Terrain-Relative Sensing and Characterization, and 9.2.8 Autonomous Targeting.

TA 9.2.5 Descent Modeling and Simulation

These technologies are now located in TA 9.4.5 Modeling and Simulation.

TA 9.2.6 Large Divert Guidance

The ability to land directly adjacent to previously-landed assets is a necessity to move beyond one-off missions and achieve the next leap in science and exploration return. Missions such as Mars sample return and landing for humans will require large maneuvers in order to take the lander from the end of the entry phase (either from a parachute terminal condition or a supersonic retropropulsion ignition) to a precise location on the surface. These large maneuvers or diverts necessarily consume large amounts of fuel, and therefore it is required to ensure that the diverts are as fuel-optimal as possible while ensuring all vehicle limitations are respected.

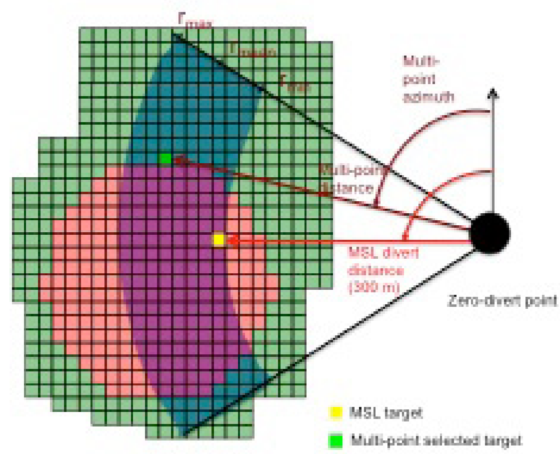
Current divert guidance algorithms are limited to gravity turns and variations on the polynomial guidance algorithms from the Apollo era. These powered descent guidance algorithms are polynomial-based and accomplish diverts of hundreds of meters. The algorithms do not scale to the 1 to 10 km range needed for pinpoint landing. In general, these algorithms do not minimize propellant use, but have been shown empirically to be efficient when lateral divert distances are less than approximately 20 percent of the altitude at which a divert is begun. As such, they cannot be termed “large” divert guidance.

The focus here is on onboard large divert guidance. With this focus, the speed of flight processors – the fastest of which is on the order of 150 MHz – also presents a significant challenge. There are several approximate large-divert algorithms in the literature, but the G-FOLD (Guidance for Fuel Optimal Large Diverts) is the only constraint-satisfying, fuel-optimal, autonomous algorithm of which NASA is currently aware.

Technical Capability Objectives and Challenges

The overall technical objective is an onboard large divert guidance algorithm and software that can simultaneously:

- Guarantee satisfying a lander’s constraints, which consist of at least a) minimum or maximum thrust, b) maximum thrust-angle from vertical, c) maximum velocity, and d) minimum glideslope angle.
- Achieve optimal or near-optimal propellant use.
- Reliably calculate a trajectory with a minimum of *a priori* information.
- Efficiently compute with a run-time of less than several seconds on a 100-MHz class processor.



Large Divert Guidance

In short, guidance algorithms are needed that quickly and robustly find a constrained, optimal divert while a vehicle is falling towards a large body at hundreds of miles per hour. To date, a promising mathematical formalism for reliably computing optimal, constrained trajectories is convex optimization. A convex optimization problem can be solved efficiently to a global optimal with convergence guarantees, and fast solvers for this class of problem are available.

Given the criticality of this onboard calculation, a fully Mars-scale demonstration of a large divert may be necessary for the technology to be adopted by a mission. Such a demonstration would consist of a rocket-powered, free-flying vehicle starting approximately 1 to 2 kilometers in altitude and diverting several kilometers laterally. This demonstration may need to be initiated at high Earth altitude to achieve aerodynamic drag forces similar to a divert on Mars.

Finally, assuming more capable flight processors become available, algorithmic enhancements can be pursued, such as incorporating angular rate constraints on the thrust vector.

Benefits of Technology

Advancing guidance for large diverts to TRL 6 would enable pinpoint landing, thus making missions like Mars sample return and human-scale landed missions possible. Additionally, any eventual landing on Europa will likely require pinpoint landing; for example, to land in a crevasse (lineae) or chaos region where surface ice may be the thinnest.

Basic research into the mathematics and mechanics of solving such multi-constrained optimization problems, combined with advances in computational power of flight computers, will allow such algorithms to fit within the time-critical computational nature of EDL.

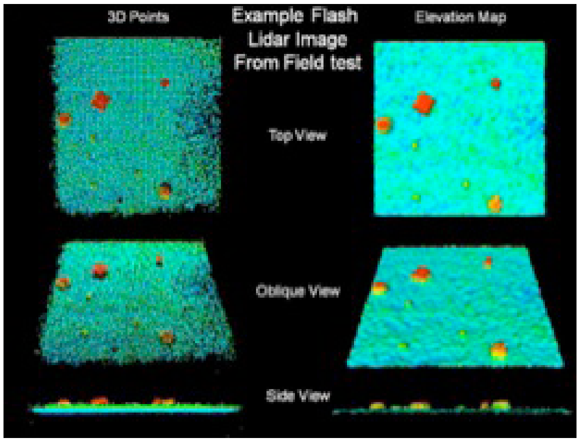
Table 11. TA 9.2.6 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.6.1	Convex Optimization Problem Solving	Research into computationally-efficient methods of solving the convex optimization problems. These methods are used for real-time solving of the fuel optimal solution for large diverts.
9.2.6.2	Guidance for Large Divert on Flight Computer	Demonstrate large divert guidance algorithm running on a flight testbed, such as the MSL testbed. This will demonstrate the algorithms operating in a flight-identical computational environment.
9.2.6.3	Guidance for Large Divert Flight Testbed	Demonstrate large divert guidance operating on a free-flying vehicle in flight-like conditions, performing flight-scale diverts.

TA 9.2.7 Terrain-Relative Sensing and Characterization

During EDL, precise knowledge of the spacecraft state, as well as the properties of the landing area, are critically important. Advances in sensors and sensor modeling are necessary to produce high-rate, high-accuracy measurements that enable advanced algorithms for safe precision landing near areas of high scientific interest.

Previous landers with terminal descent propulsion have utilized various levels of knowledge of position and velocity relative to the surface. Radars have been used to determine altitude and vertical velocity (Mars Pathfinder). In addition, horizontal velocity has been determined using Doppler radar (Surveyor, Apollo, Viking, Phoenix), as well as passive optical imaging with onboard correlation (Mars Exploration Rover).



Terrain-Relative Sensing

Technical Capability Objectives and Challenges

The particular sensors considered here are spacecraft velocimetry/altimetry sensors (e.g., Doppler or time-of-flight radar or light detection and ranging (LIDAR)-based sensors), sensors for real-time three-dimensional (3D) terrain mapping (e.g., flash/scanning LIDAR, synthetic aperture radar, or stereo vision), and sensors for terrain imaging and surface/subsurface characterization (e.g., visible/multispectral cameras, ground-penetrating radar, etc.).

Existing sensor technology either needs to be space qualified (e.g., sensors that are based on LIDAR), or requires significant reductions in size, weight, and power, or improvements in measurement frequency, range, and accuracy to be able to meet future mission requirements.

In addition, detailed physics-based models are needed to fully characterize sensor behavior and interactions with the vehicle (e.g., engine plume) and terrain (e.g., dust) during EDL. Such models in turn allow simulation tools for sensor design and verification and validation (V&V), as well as for GN&C algorithm performance evaluation.

Benefits of Technology

Improved sensor performance enables or improves accuracy and reliability of a wide range of autonomous GN&C and landing-site-targeting algorithms. These sensors can also provide atmospheric measurements of interest to scientists.

Table 12. TA 9.2.7 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.7.1	Advanced Sensors for Spacecraft Velocimetry and Altimetry	Provide low-cost, long-range, high-precision, high-rate measurements of spacecraft altitude and 3D-velocity to improve navigation accuracy and vehicle control performance. Precise knowledge of altitude and velocity can also be used to trigger events, such as backshell separation and parachute deployment, which help reduce landing site dispersion.
9.2.7.2	Advanced Sensors for Real-Time Three-Dimensional (3D) Terrain Mapping	Provide high-rate, high-precision three-dimensional (3D) measurements of the terrain shape for onboard map creation and hazard detection.
9.2.7.3	Advanced Sensors for Terrain Imaging and Surface and Subsurface Characterization	Provide data for localization, science target identification, or hazard detection at different wavelengths.
9.2.7.4	High-Fidelity Sensor Modeling and Simulation Tools	Provide advanced, integrated models and simulation tools for active and passive terrain sensors, including effects of dust and plume interactions.

TA 9.2.8 Autonomous Targeting

Autonomous targeting is currently not in use on NASA flight missions. Emerging examples of this technology include terrestrial demonstration by NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT), which has demonstrated autonomous hazard detection and avoidance, and Lander Vision System (LVS), which has successfully demonstrated terrain relative map localization.

Autonomous targeting focuses on the algorithms needed to combine terrain-relative sensor input to generate needed targeting updates. The challenges in this technology area are primarily in machine vision techniques and the creation of dedicated ultra-high performance vision system processors.

Small Body Systems

Technical Capability Objectives and Challenges

The overall objective of this technology development is to improve terminal descent technologies to allow both safer landings for human-rated payloads and improve targeting and science access for robotic-scale science missions. To enable landing at more challenging and hazardous locations, to enable surface rendezvous, and to land with greater safety for crewed missions, future landers will require knowledge of location relative to the target, the detection of landing hazards (both provided by crew on Apollo), and detection of science targets, and redirection of the terminal descent to the desired targets and in avoiding hazards. The challenges of this technology area is primarily in machine vision techniques and the creation of dedicated ultra-high-performance vision system processors (see also TA 4 Robotics and Autonomous Systems).


Electronics for Autonomous Targeting

Benefits of Technology

Landing on very difficult, or not-well-mapped, terrain or landing on well-mapped and processed terrain with reliability required for a human mission, requires large increases in terrain-relative targeting capability. This technology would enable robotic landing on the surface of Europa where the ice re-forms and the topography can change between a mapping mission and a landing mission.

Table 13. TA 9.2.8 Technology Candidates – not in priority order

TA	Technology Name	Description
9.2.8.1	Terrain/Map Absolute Localization	Enables pinpoint and multi-point landing with < 100 m position error relative to an onboard map generated from *a priori* sensing data.
9.2.8.2	Terrain/Terrain Relative Location	Enables terrain feature identification and tracking using passive and/or active imaging for navigation and targeting purposes.
9.2.8.3	Autonomous Digital Elevation Map Generation	Creates digital elevation maps autonomously during descent. Digital elevation maps need to be localized and oriented correctly relative to the rest of the target body, be high resolution, and be relatively free of noise.
9.2.8.4	Autonomous Hazard Detection and Avoidance	Enables the identification and location determination of landing hazards using just-acquired passive and/or active imaging. Also predicts and corrects landing location errors relative to a changing target from the position and hazard detection components.
9.2.8.5	Autonomous Science Target Acquisition	Identifies high-value science targets autonomously onboard a spacecraft during descent using available sensors.
9.2.8.6	Offline Reference Map Generation, Validation and Verification	Provides ability to generate high-quality, high-resolution, low-noise, and registered terrain and digital elevation reference maps.
9.2.8.7	Onboard Dedicated Compute Elements	High-performance, low-power-consumption computing is required for processing sensor data and executing computationally-intensive tasks, such as localization, terrain tracking, autonomous hazard detection and avoidance, autonomous science target identification, and autonomous guidance/trajectory optimization and design.
9.2.8.8	Small Body Proximity Operations	Develop small body specific approaches for proximity operations and targeting.

TA 9.3: Landing

In the landing phase of the mission, safe touchdown is a critical capability. Landing is the behavioral element of the EDL system responsible for the final contact with the destination surface. Given the diversity of missions in NASA's upcoming planetary portfolio, a number of solutions for anchoring and landing in treacherous or unknown terrains are possible. Historically, landing systems have included legs, as used in Viking, Phoenix, and Apollo; airbags as used in Mars Pathfinder and the Mars Exploration Rovers; and the Sky Crane system used for the MSL mission.

Icy Moon Lander Concept with Deployable Anchors

Sub-Goals

Missions like human-scale Mars landing and robotic landing on icy moons of outer planets like Europa and Enceladus require extending the landing systems' capability over the SOA. The goals include landing on very rough and uncertain terrain (Europa), and high-reliability, human-scale Mars landings with larger masses and vehicles with high centers of mass.

Table 14. Summary of Level 9.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
9.0 Entry, Descent, and Landing Systems	Goals:	Enable heavier payloads travelling at faster velocities to enter and descend through atmospheres and land safely with high precision.
Level 2		
9.3 Landing	Sub-Goals:	Extend robotic landing system capabilities to enable landing on very rough and uncertain terrain, and highly reliable landing for human-scale Mars vehicles with large masses.
Level 3		
9.3.1 Propulsion and Touchdown Systems	Objectives:	Enable robust landing in relatively uncharacterized topographies.
	Challenges:	Operation in extreme conditions, including elevated temperatures and pressures. Ability to actively avoid dangerous surface topography.
	Benefits:	Increases access for science missions and improves reliability for human missions to the Moon, Mars or other bodies.
9.3.2 Egress and Deployment Systems	Objectives:	Develop mass-efficient, reliable methods of sending forth both robotic and human occupants of landers.
	Challenges:	Tailoring to specific lander and payload needs.
	Benefits:	Provides low mass, high-reliability designs.
9.3.3 Propulsion Systems	Objectives:	Develop deep throttling capabilities for fuel efficient and safe touchdowns. Understand and model interactions between rocket plumes and the ground.
	Challenges:	Understanding the plume and plume/ground/debris interaction.
	Benefits:	Ensures that a single propulsion system can efficiently execute propulsive descent with the fine control needed for safe touchdown. Enables safe landing of spacecraft in close proximity.

Table 14. Summary of Level 9.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3	
9.3.4 Large Body GN&C	This section is covered in TAs 9.1.3 Rigid Hypersonic Decelerators, 9.1.4 Deployable Hypersonic Decelerators, and 9.2.7 Terrain-Relative Sensing and Characterization.
9.3.5 Small Body Systems	This section is covered in TA 9.2.8 Autonomous Targeting.
9.3.6 Landing Modeling and Simulation	This section is covered in TA 9.4.5 Modeling and Simulation.

TA 9.3.1 Propulsion and Touchdown Systems

Propulsion and touchdown systems represent the engineering element of the EDL system responsible for final contact with the destination surface, as well as the propulsion system(if applicable) that delivered the vehicle to that point. These destinations may include bodies with low gravity, such as comets and asteroids, as well as higher gravity bodies, like Mars or Earth. Areas of proposed touchdown technology that have yet to be developed include spikes and penetrators, and active landing gear systems. At Earth, the option exists to avoid touchdown at all, by using a mid-air retrieval to recover high-value or sensititve assets before they reach the surface.

Technical Capability Objectives and Challenges

Small Robotic Landers: Generally, small landers have and will continue to exploit their inherent ability to accept high-impact loads in order to maximize performance. This is particularly true for impactors like Mars impactors, and potential ice penetrators to Europa or Enceladus. It is also expected that continuation of this trend can make these systems more affordable and less sensitive to surface topography (see TA 8 Science Instruments, Observatories, and Sensor Systems for the sensor payloads that could help meet these requirements). Venus and the icy moons of Jupiter represent high-value scientific destinations with uniquely challenging landing requirements. The potential inability to obtain high-resolution landing site maps prior to arrival requires these systems to be designed for more extreme conditions.
Venus landers will also require terrain-sensing and staging systems capable of sustaining elevated temperatures and pressures. Icy moon landers will require means of addressing icy structures and topographies, either via soft controlled landing or penetration. Small-body landers may require advanced grappling capabilities for extremely rough surfaces, or “touch-and-go” sample acquisition capabilities, such as attempted by the Japanese Hayabusa probe. Technology developments are needed in the development of improved landing system dynamic analysis and test techniques. Application of these techniques enables rapid and thorough exploration of landing system architectures needed to meet mission specific payload and terrain requirements. Systems for safe landing on unconsolidated steep to vertical surfaces and weak surfaces including liquids, saturated granular media, and snow are needed for landing on the various moons of the outer gas giant planets.

Prototype Spike Anchor for Retaining Hold of Treacherous Terrain

Large Robotic Landers: Technology advancements should be focused on systems designed for sample-return-class payloads, multifunctionality such as landing on a mobility system, deployable structures (inflatable or rigid), and active landing gear for greater performance on rocks and slopes. As with small landers, systems for safe landing on unconsolidated steep to vertical surfaces and weak surfaces including liquids, saturated granular media, and snow are needed for landing on the various moons of the outer gas giant planets.

Human-Class: Understanding the technology needs for human-class landing systems will first require a system-level understanding of the configuration of the entry system envelope, the payloads, and the requirements on the surface mission that are not available today. The challenges for these large-scale landing systems will be those of configuration and mass fraction. Landing performance on large rocks and slopes is not anticipated to be the driving challenge due to their size and the presumption that by the time these missions are realized, the ability to actively avoid dangerous surface topography will have been achieved. Development of touchdown architectures that are compatible with launch vehicle and entry system form factors, provide ample margin on overturning stability due to residual horizontal velocity at touchdown, and minimize the need for complex egress and deployment systems is needed. The quantification of the architectural needs of the touchdown system will place constraints on the rest of the flight system. System-level design studies are needed to co-evolve human-class touchdown systems in conjunction with the rest of the EDL system and more clearly identify technology gaps, which will create more options for designers.

Benefits of Technology

Improved touchdown systems will increase access for NASA science missions and improve reliability for NASA human missions to the Moon, Mars, or other bodies. Alternative options such as mid-air retrieval at Earth could lower the cost and expand the reusability of the architectural elements to achieve these missions.

Table 15. TA 9.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
9.3.1.1	Penetrators and Spike Anchors	Provide a means of retaining a hold on a treacherous body.
9.3.1.2	Active Landing Gear	Active landing gear for greater performance on rocks and slopes.
9.3.1.3	Mid-Air Retrieval	Recovering an Earth asset before it touches land or water.

TA 9.3.2 Egress and Deployment Systems

NASA is not currently advancing any technologies within the Egress and Deployment Systems technology area within the timeframe of this roadmap. However, some discussion of this area is included below. Information on other egress and deployment systems technologies can be seen under TA 7.3 Human Mobility Systems.

Technical Capability Objectives and Challenges

Robotic-Class Egress and Deployments: Egress and deployment systems must be tailored to specific lander and payload needs. As such, it is not possible to anticipate specific systems for technology development. Instead, there are a few general categories of component technology that have broader application to this area. They are: high-power-density, short-life actuation systems including but not limited to electromechanical, pneumatic, and pyrotechnic, and rigid and inflatable load-bearing deployable structures that can be used as ramps, cranes, and leveling devices. As mobile systems become larger, this architectural feature will become more important. Alternative landing system architectures that avoid the need for egress are needed as well.

Human-Class Egress and Deployments: As landers grow in size, the criticality of addressing egress and deployment of primary payload becomes more pronounced. System design studies are needed initially to identify the architectural needs of the surface payloads, the touchdown systems, and subsequently the egress and deployment systems. These studies must be done as part of an overall system study, since the influence of the egress and deployment systems will have first-order influence on the touchdown systems and entry system configurations. It is likely that any given landed system must be self-sufficient in ensuring that it can place the desired payload on the planetary surface.

Benefits of Technology

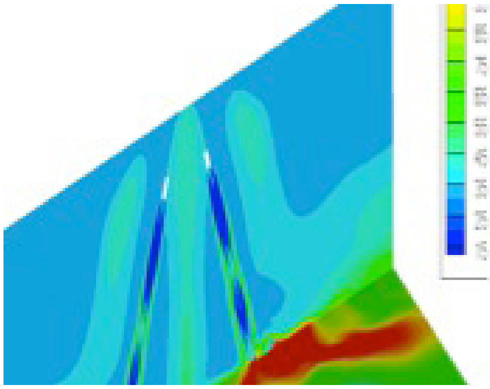
Egress and deployments are enabling for all classes of missions. As with most systems, low-mass, high-reliability designs are key development metrics that can enable a successful mission.

TA 9.3.3 Propulsion Systems

Propulsion system technology advances are required to enable Mars human-robotic and crewed landings. Because of the thin Martian atmosphere and the need for precision landing, these missions will require propulsive descent systems. State of the art terminal propulsion systems are mono-propellant hydrazine pulsed thrusters (e.g., for Phoenix), mono-propellant hydrazine throttled thrusters (e.g., for MSL) and bi-propellant throttled engines (e.g., for Apollo). Deep-throttling (> 20:1 dynamics range with > 30 percent I_{SP} improvement over mono-propellant hydrazine), high efficiency propulsion is not currently proven without shutting down engines, but is enabling for future missions. These engine developments are found in TA 2 In-Space Propulsion Systems. Technologies of interest within this roadmap include the implementation of these propulsion systems for effective EDL. In-situ landing site preparation is addressed in TA 7.6.1 Particulate Contamination Prevention and Mitigation, for these technologies (specifically, TA 7.6.1.18 and TA 7.6.1.21). Computational fluid dynamics (CFD)-based plume interaction is addressed in TA 7.6.1.22. Vehicle-based plume accelerated debris protection techniques are addressed in TA 7.6.1 Particulate Contamination Prevention and Mitigation, for surface-based technologies. Please see the MMOD protection capabilities in TA 9.1.1 Thermal Protection Systems for Rigid Decelerators, for possible application to landing vehicles.

Technical Capability Objectives and Challenges

The propulsion systems will need deep throttling capabilities for fuel efficient and safe touchdowns and an understanding of the interactions between rocket plumes and the ground. Advancement of propulsion capabilities for Mars applications will require accomplishment of TRL 6 before the close of this decade if this technology is to be incorporated into the mid-2020s human precursor missions required for human Mars missions in the 2030s.



Propulsion Systems

Benefits of Technology

Deep throttle propulsion capability ensures that a single propulsion system can efficiently execute propulsive descent with the fine control needed for safe touchdown. Understanding the plume and plume/ground/debris interaction and developing techniques to mitigate are critical for safely landing spacecraft near each other, as required by human, robotic, and human/robotic mission concepts.

TA 9.3.4 Large Body GN&C

The bulk of these technologies are contained within TA 9.2.7 Terrain-Relative Sensing and Characterization. Vehicle guidance and control aspects for the earlier phases of EDL are contained in TA 9.1.3 Rigid Hypersonic Decelerators, and TA 9.1.4 Deployable Hypersonic Decelerators.

TA 9.3.5 Small Body Systems

These technologies are located in TA 9.2.8 Autonomous Targeting. See also the technology roadmap for TA 4 Robotics and Autonomous Systems.

TA 9.3.6 Landing Modeling and Simulation

These technologies are now located in TA 9.4.5 Modeling and Simulation.

TA 9.4: Vehicle Systems

MSL provides the relevant SOA in this cross-cutting category of vehicle systems. MSL experienced many critical "transition" events during its traverse through the Mars atmosphere. Its end-to-end performance was simulated in a high-fidelity trajectory tool that was used throughout the mission development to make design and, finally, operational decisions. MSL's unique size, new guidance scheme, and new TPS system required updates to aerodynamic and aerothermodynamic tools throughout the vehicle's life cycle. In addition, MSL carried a first-of-its-kind heat shield instrumentation suite to facilitate a comprehensive evaluation and comparison to the pre-flight performance predictions. The larger, more complex EDL missions of the future will require significant improvements to all of these aspects of end-to-end vehicle systems as well as continued collection of engineering flight data to verify and validate preflight predictions. Emerging new capabilities in both the government and in the commercial sectors should be considered through the end-to-end analyses efforts.

Sub-Goals

Vehicle Systems takes the view across, rather than within, the flight regimes. This perspective is critical to the vehicle systems engineering problem. At the very top level, accurate tools for analyzing the end-to-end vehicle performance should be used early to drive technology decisions and development paths. The EDL system must be modeled across the flight phases, hypersonic through landing, to ensure adequate performance and permit an understanding of risk. Understanding how the EDL vehicle transitions or separates pieces between those flight phases is critical to identifying necessary hardware and resulting system behavior. Accomplishing the transitions probably does not require uniquely new technology, but validating the end-to-end behavior of the vehicle will likely require flight testing and the development of complex systems analysis methods. Finally, a thorough understanding of the flight environment is necessary for vehicle design, and can be acquired through dedicated scientific or precursor missions. All of the capabilities and functions described by the level 3 TAs support multiple robotic and human missions, and they are not uniquely EDL-related. A number of other roadmaps contain information on these level 3 technologies, as noted in the following sections.

Table 16. Summary of Level 9.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
9.0 Entry, Descent, and Landing Systems	Goals:	Enable heavier payloads travelling at faster velocities to enter and descend through atmospheres and land safely with high precision
Level 2		
9.4 Vehicle Systems	Sub-Goals:	Provide a thorough understanding of the flight environment for vehicle design and develop accurate tools for analyzing the end-to-end vehicle performance.
Level 3		
9.4.1 Architecture Analysis	Objectives:	Provide top-level analysis capabilities to enable informed architecture trades and technology development decisions.
	Challenges:	Model level of fidelity, data sharing protocols.
	Benefits:	Reduces analysis cycle time, minimizes architecture life cycle cost, maximizes overall architecture performance and reduces risk.
9.4.2 Separation Systems	Objectives:	Safely and efficiently separate the entry vehicle from the decelerator or other spent components at the necessary transition point(s).
	Challenges:	Obtaining detailed vehicle information early enough to design a reliable, efficient system and avoid cost and risk.
	Benefits:	Optimizes the mass and performance of the vehicle systems; reduces risk.

Table 16. Summary of Level 9.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
9.4.3 System Integration and Analyses	Objectives:	Implement and maintain a flexible simulation structure that evolves with the EDL system definition to enable performance, design, and risk decisions throughout the life cycle.
	Challenges:	Verification and validation, incorporation of heritage tools and models.
	Benefits:	Reduces analysis cycle time, minimizes mission life cycle cost, maximizes EDL vehicle performance, and reduces risk.
9.4.4 Atmosphere and Surface Characterization	Objectives:	Understand the atmospheric and surface conditions on the day of arrival adequately to design efficient, safe EDL systems.
	Challenges:	Reducing uncertainties in global atmospheric and dust knowledge to a level sufficient to improve system design.
	Benefits:	Enables efficient EDL system design and reduces risk.
9.4.5 Modeling and Simulation	Objectives:	Provide modeling and simulation capabilities with improved environment and response knowledge to reduce risk and maximize efficiency.
	Challenges:	Conducting relevant validation tests matching desired parameters (e.g., enthalpy, pressure, temperature, scale, ballistic coefficient, etc.) of the flight environment. Flight data for model validation.
	Benefits:	Allows for higher-fidelity analysis to be performed earlier, and in a shorter time, thus decreasing overall design cycle time and improving decision-making. Improves physical models thus reducing the overall uncertainty in the calculations, design margins, and overall entry system risk.
9.4.6 Instrumentation and Health Monitoring	Objectives:	Improve the mass, volume, and cost of entry vehicle instrumentation so that it can be more widely applied across mission classes. Develop non-intrusive approaches to returning EDL data.
	Challenges:	In-situ measurements for extreme environments, for both rigid and deployable systems, non-intrusive measurement techniques, and reliable calibration. Vehicle resource constraints, elimination of false positives, and the ability to initiate and monitor repair of detected damage.
	Benefits:	Returns data about system performance in flight environments that cannot be fully replicated on the ground, to validate models, and to improve future designs. Ensures the entry system is functional prior to use.
9.4.7 GN&C Sensors and Systems	This section is covered in TAs 9.1 Aeroassist and Atmosheric Entry, and 9.2 Descent and Targeting.	

TA 9.4.1 Architecture Analysis

NASA's end-to-end architecture analysis is performed by a set of geographically-dispersed experts who work on a variety of software platforms. The performance models range from vehicle-level to subsystem-level, and extend to all mission phases and elements, including Earth launch, in-space propulsion, EDL, and surface logistics. The challenge is the integration of these various models and capabilities. As yet, it is a largely manual process that could benefit from tools that improve efficiency, robustness, and maintainability.

Technical Capability Objectives and Challenges

End-to-end architecture analysis of missions that include EDL functions are critical to establishing early concept feasibility and making technology development decisions. The mass and performance of EDL vehicles tends to drive the entire mission architecture, particularly the in-space propulsion system and initial mass in LEO. Understanding this end-to-end picture in a timely and accurate manner is critical to both programmatic and technical mission success. Future EDL missions will take advantage of the computational advances and analysis best practices in use at the time, to reduce analysis cycle times, reduce cost, and ensure mission success.

Benefits of Technology

High-fidelity architecture analysis will reduce analysis cycle time, minimize architecture life cycle cost by supporting early technology development decisions, maximize overall architecture performance, and reduce risk.

NASA does not have any EDL-specific technology candidates in the Architecture Analysis technology area at this time. Architecture analysis is supported by all of the performance models developed for the various systems and vehicles in each of the 15 technology roadmaps. For information on specific information technologies that can support high-fidelity architecture analysis, please see TA 11.3 Simulation.

TA 9.4.2 Separation Systems

Exoatmospheric: The SOA includes shroud separation, vehicle rendezvous and docking, and in-space construction (e.g., the ISS).

Hypersonic-Supersonic: The SOA includes aerodynamic control surfaces and trailing vehicle separation and disposal by propulsive, pyrotechnic, or mechanically-assisted components.

Supersonic-Subsonic: The SOA includes aerodynamic control surfaces, payload bay door opening and closing, Space Shuttle Solid Rocket Booster staging and separation, subsonic heat shield separation for Mars robotic vehicles, parachute (drogue) deployment, mortar deployment or mass ejection assisted by propulsive, pyrotechnic, or mechanically-assisted components.

Terminal Descent – Touchdown: The SOA includes parachute, mortar, or landing gear deployment, or shroud separation assisted by propulsive, pyrotechnic, or mechanically-assisted components.

Technical Capability Objectives and Challenges

With any new technology development, one must address how that technology fits within an overall EDL architecture. The question of migration from one atmospheric entry phase to the next must be considered, from hypersonic entry to supersonic, transonic, or subsonic deceleration to the landing configuration. For the most part, transitions are an exercise in engineering to mature EDL systems, rather than a true technology development per se. Testing to quantify relevant physics, modeling and simulation that emulates those behaviors and allows extrapolation to flight conditions, and flight testing to validate and verify either a specific transformation or an entire end-to-end EDL sequence will likely be required before mission infusion.

Exoatmospheric: Push technologies include on-orbit component robotic construction, mechanical or inflatable deployment of staged systems, or rigidizable aeroshell sub-systems.

Hypersonic-Supersonic: Push technologies include mechanical or inflatable deployment of staged hypersonic aeroshell separation, or propulsive-based hypersonic stage separation.

Supersonic-Subsonic: Push technologies include mechanical or inflatable deployment of staged systems, supersonic aeroshell and entry shroud separation, or propulsive-based stage separation.

Terminal Descent – Touchdown: Push technologies include larger-scale tethering devices for Sky Crane-type systems (which separate the landing and propulsion systems during terminal descent).

Landing Site Surface Preparation: The potential severity and complexity associated with having a design robust to the interaction of soil and debris with large propulsive system plumes suggests that technology developments should be considered for preparing a landing zone prior to touchdown (see TA 4 Robotics and Autonomous Systems.)

Component Technologies: Other component technologies that may have significant roles to play in enabling new vehicle transition contexts include advanced pyrotechnics, springs, airbags, and drag augmentation devices.

Benefits of Technology

Transitioning or staging hardware during EDL is critical, and helps optimize the mass and performance of the vehicle systems.

NASA is not currently advancing any technologies within the Separation Systems technology area within the timeframe of this roadmap. Information on other Separation Systems technologies can be seen under TA 12.3 Mechanical Systems.

TA 9.4.3 System Integration and Analyses

The SOA in system analysis for robotic EDL is the validated simulation capability used for MSL. The event-driven environment allows integration of complex subsystem models of the vehicle and environment, and can be used from vehicle concept through mission operations. Monte Carlo and visualization capabilities are included. Another, similar set of tools exists for human entry missions like Orion.

Technical Capability Objectives and Challenges

As complex systems with special temporal requirements and dependencies, EDL vehicles absolutely must be designed and analyzed in an integrated fashion for maximum efficiency and reduced risk. However, these requirements are not unique to EDL.

The mass and performance of EDL vehicles tends to drive the entire mission architecture, particularly the in-space propulsion system and initial mass in LEO. Understanding this end-to-end picture in a timely and accurate manner is critical to both programmatic and technical mission success. Future EDL missions will take advantage of the computational advances and analysis best practices in use at the time to reduce analysis cycle times, reduce cost, and ensure mission success.

Benefits of Technology

High-fidelity systems integration and analysis will reduce analysis cycle time, minimize mission life cycle cost, maximize EDL vehicle performance, and reduce risk.

High-fidelity system analysis will reduce analysis cycle time, minimize system life cycle cost by supporting early technology development decisions, maximize overall system performance, and reduce risk.

NASA is not advancing any EDL-specific technologies within the System Integration and Analyses technology area within the timeframe of this roadmap. Information on other system integration and analyses technologies can be seen under TA 11.3 Simulation.

TA 9.4.4 Atmosphere and Surface Characterization

Atmospheric modeling is important to all aerodynamic phases of flight including aerocapture, aerobraking, entry, and descent. Currently for Earth and Mars, the SOA is adequate to provide safe aerobraking and landings within a few kilometers of the landing site.

The SOA in atmospheric modeling varies with the planetary body. At Mars, pressure cycles and atmospheric density modeling is anchored by a paucity of surface pressure measurements from the Viking landers and subsequent robotic missions, while other planets have even less data with which to anchor models. There have been three aerobraking missions at Mars. All of the vehicles successfully completed the aerobraking mission to achieve a desired science orbit despite differences between the predicted and observed atmosphere. Mars Odyssey experienced atmosphere density that was 20% of predicted; Mars Reconnaissance Orbiter encountered an atmosphere that was 500% higher than predicted.

Long-term orbiters are needed to establish weather monitoring and prediction capability, providing global and local day-of-entry data to support human missions. Post-landing data collection of pressure and low-altitude winds will provide ground truth for mesoscale wind models used to validate precision landing. Methods of measuring density and wind are common in Earth applications, though these have not been applied to other planets. There may well be opportunities to leverage current and ongoing Earth science technology developments for atmospheric measurements and characterization to help enable the same for other planetary bodies with atmospheres (e.g., advanced orbital platform LIDAR instrument development for Earth atmosphere carbon dioxide (CO_2) measurements could be extended to Mars orbiters for CO_2 atmospheric density and wind profiling). NASA's development of planetary atmospheric modeling specific to EDL capabilities is primarily in the continued development of global reference atmosphere models (recently only for Earth – Orion, and mission-specific Mars – MSL, Titan – Huygens) and in remote measurements made by orbiting spacecraft.

Technical Capability Objectives and Challenges

Characterization of the dust environment at Mars and its potential impact on entry systems will be critical for human Mars missions. Atmospheric density and constituent properties are key to predicting vehicle heating and drag levels during EDL. Both global atmospheric and dust knowledge are considered strategic knowledge gaps to be filled before human Mars missions are undertaken. The challenge for precision landing occurs when there are durations of open-loop (uncontrolled) flight (e.g. on parachute). If the parachute phase is replaced by something that allows control of range (e.g. propulsion), studies have shown that very precise landings are achievable with today's knowledge of the atmosphere. However, descent sensors to detect the surface, and determine altitude and velocity in flight are also important to achieve precision landing.

If precise landings are required using ballistic entries or uncontrolled elements such as parachutes, improved knowledge of the density and its variability through the entire atmosphere and the winds from 10 km altitude to the surface will reduce the size of the landing footprint and the amount of propellant required for landing. Terrain tracking (TA 9.2.7) will require onboard maps of the surface that are generated from orbital imagery and altimetry. Automated systems to convert orbital data to onboard maps will enable small body missions with limited time between orbital data collection and proximity operations. Finally, controlled terminal descent and landing requires an accurate knowledge of the atmosphere boundary layer, engine plume and surface interactions.

Atmosphere and surface characterization data will most likely come from either dedicated science missions or precursor missions that operate prior to landing humans on Mars. The EDL function may drive the requirements for such missions, but these items are not EDL technologies per se.

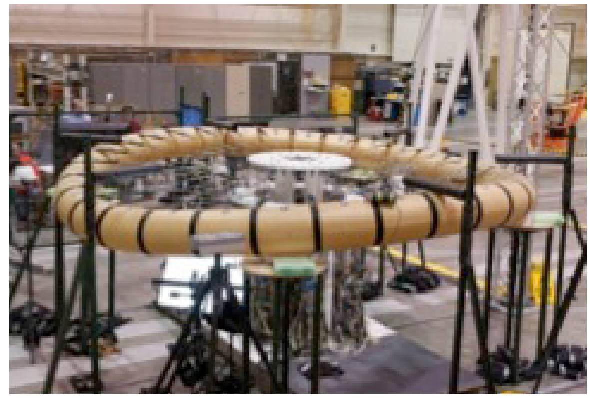
Benefits of Technology

Increased knowledge of the flight and surface environments will enable efficient EDL system design and reduce risk.

NASA is not currently advancing any technologies within the Atmosphere and Surface Characterization technology area within the timeframe of this roadmap. Information on other atmosphere and surface characterization technologies can be seen under TA 8.1.1 Detectors and Focal Planes.

TA 9.4.5 Modeling and Simulation

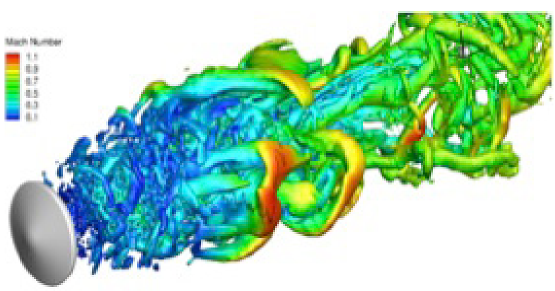
The NASA SOA in entry system modeling ranges from good (flight mechanics and 6+ degrees of freedom (DOF) trajectory) to fair (aerothermodynamics and fluid-structure interactions) to poor (dynamic aerodynamics). Most analyses are conducted in an uncoupled fashion; multidisciplinary tools are still at the cutting edge in this field. In many cases, particularly aerothermodynamics, the sophistication of the computational software outpaces the level of validation; key gaps remain in validating these codes at flight-like conditions (e.g., high enthalpy, high Reynolds number, correct gas composition). NASA currently supports some core development of modeling and simulation, as well as some validation activities.



Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Torus Loaded

Technical Capability Objectives and Challenges

In the aerosciences, specific advances are required in the area of higher-order turbulence modeling (such as direct numerical simulation methods), fully unstructured or gridless CFD approaches for hypersonic flow, improved methods for low-density flows (such as Boltzmann solvers), and higher-fidelity models for non-equilibrium high temperature physical phenomena. Next-generation NASA missions will rely on larger, heavier entry systems, which will place increased emphasis on improved understanding of turbulent heating, transition to turbulence, shock layer radiation, and complex surface-chemistry interactions. Modeling of meteors requires even greater improvements to physical models, as the extremely high possible entry velocities encountered are well beyond that for human and robotic missions, and result in much more complex thermochemical phenomena. These phenomena must be modeled in the context of a hypersonic non-equilibrium chemically-reacting environment, which places additional constraints on the methods employed. Many improvements to the SOA for low-speed flows are not applicable to entry systems because they cannot accurately capture the embedded strong shocks that are so prominent in this flight regime. In addition, NASA entry systems typically fly in a regime where one or more of the basic physical disciplines are physically coupled. The development of a true multidisciplinary simulation capability is a critical aspect of this technology area. The primary challenge impeding development of these capabilities is the ability to conduct relevant validation tests matching desired parameters (e.g., enthalpy, pressure, temperature) of the flight environment. Flight data are the ultimate gold standard for final model validation, but there are very little available at the current time. Without relevant validation data, newly-developed models have large, frequently unquantified uncertainty levels, which impedes their adoption in mission planning. Performance metrics for this capability are the uncertainty levels of key design variables (e.g., heat flux, bond line temperature, recession). Required uncertainty levels are a function of the type of mission (crewed versus robotic) and its overall risk posture.



Modeling and Simulation: Wake Flow Computational Fluid Dynamics

The development of new and larger deployable decelerators and the limited ability to test them at full scale and in relevant environments places increased emphasis on the maturation of modeling and simulation codes and methods. For a majority of the descent technologies identified above, deficiencies in modeling and simulation fall into the category of aerodynamic, structural, or combined fluid-structure interaction. Reliance on empirical models for flexible decelerators, as is currently done for parachutes, results in systems that are typically mass inefficient, and produces uncertainty spreads that are prohibitively large for high-precision landings. Rigid body static and dynamic aerodynamics in the supersonic and subsonic regimes are heavily influenced by the aftbody and wake interactions flow field, which in turn dominate uncertainties in aerodynamic coefficient estimates. Progressing beyond empirical estimation for flexible decelerators inherently requires advanced fluid structure interaction (FSI) modeling capabilities that are still in their infancy. Modeling of SRP flowfield interaction is similarly at a very low level of maturity. The primary technology gap is the application and validation of the SOA CFD and structures codes to the dynamic simulation of these descent devices. At the current level of fidelity, the community does not yet know what specific advances in the SOA are required on either the CFD or the structural analysis sides, however development of low-dissipation flux methods and high-spatial- and temporal-accuracy CFD solvers with high-order turbulence closure is certainly required.

Benefits of Technology

Improved simulation capability has multiple benefits to future missions. Improvements in computational efficiency or robustness allow for more simulations to be performed in a shorter time, which decreases overall design cycle time. Efficiency improvements also allow for high-fidelity analysis to be used earlier in the design cycle, which improves decision-making. Improved numerical models enable the simulation of more complex problems. Improved physical models reduce the overall uncertainty in the calculations, which drives down design margins and overall entry system risk. Quantified uncertainties also permit design engineers to develop quantified risk and reliability models, which permit informed decision-making regarding prioritization of risk reduction activities. Finally, new physical models can also be enabling for certain missions and for accurate meteor breakup prediction in cases where the SOA does not permit accurate simulation of the key physical phenomena.

A key aspect of the roadmap is the need to validate new modeling capability, using a mix of ground test data as available and flight data returned from past and future EDL missions. Please see information on modeling and simulation technologies under TA 11.3 Simulation, and information on TPS response modeling in TA 14.

Table 17. TA 9.4.5 Technology Candidates – not in priority order

TA	Technology Name	Description
9.4.5.1	Multi-Disciplinary Coupled Analysis Tools	Development of validated multidisciplinary coupled analysis tools (bridging aerosciences, flight mechanics, material response, and structural and thermal analysis), particularly for high-reliability and extreme-environment applications. Includes models for fluid structure interaction that are capable of predicting and mitigating aeroelastic and aerothermoelastic effects, including buckling, on material and system performance.
9.4.5.2	Aerothermodynamics Modeling	Models for aerodynamics and aerothermodynamics, including shock-layer radiation and high-enthalpy ionized turbulent and separated flows, across the continuum and non-continuum flight regimes, with particular emphasis on flight-relevant experimental validation.
9.4.5.3	Ablative Material Response Models	Models for thermal response of thermal protection system materials, including physics-based modeling of ablation, internal radiation, pyrolyzation, recession, multilayer materials, gas-surface interactions, and conductivity. Models for acreage and details, including attachments and damage.
9.4.5.4	Non-Ablative Material Response Models	Models for thermal response of thermal protection system materials, including physics-based modeling of internal radiation, pyrolyzation, multilayer materials, gas-surface interactions, and conductivity. Models for acreage and details, including attachments and damage.
9.4.5.5	Thermal Protection System (TPS) Quantification Models and Processes	Quantifies thermal protection system margin and system reliability using statistical analysis, test design techniques, and archive storage of Agency thermal test data, as required for Commercial Orbital Transportation Services and NASA crewed vehicles as well as high-reliability sample return missions. See also TA 12.3.6 Certification Methods.
9.4.5.6	Numerical Methodologies and Techniques	Provides improved numerical methodologies and techniques, taking advantage of expected computer architecture and hardware improvements.
9.4.5.7	Autonomous Aerobraking	Provides autonomous control methods that can reduce "human-in-the-loop" costs and the risk of planetary aerobraking.

Table 17. TA 9.4.5 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
9.4.5.8	Orbital Debris Entry and Breakup Modeling	Models and techniques for predicting breakup of human-made spacecraft upon entry into Earth's atmosphere.
9.4.5.9	Meteor Entry and Breakup Modeling	Models and techniques for predicting breakup of extraterrestrial objects (asteroids/meteors, comets) entering Earth's atmosphere.
9.4.5.10	Fluid Structure Interaction (FSI) Tools	Enables static and dynamic assessment of flexible decelerators, including acquisition of data sets useful for fluid structure interaction validation efforts at relevant aerodynamic and aerothermodynamic environments. For subsonic chutes this is needed for multi-chute interaction. For both subsonic and supersonic, wake closure is relevant.
9.4.5.11	Supersonic Retropropulsion Modeling Tools	Provide validated supersonic retropropulsion modeling tools to reduce risk and improve efficiency.
9.4.5.12	Aerodynamic Modeling Tools	Models to compute steady and dynamic aerodynamics, with an emphasis on aftbody and wake interaction flows, including reaction control system interaction and plume impingement dynamics.

TA 9.4.6 Instrumentation and Health Monitoring

The MSL Entry, Descent, and Landing Instrumentation (MEDLI) suite performed successfully during its flight in August 2012, returning the most comprehensive set of Mars EDL data to date. MEDLI data analysis efforts are now complete; the aerodynamic and aerothermodynamic aspects of the data return have been widely published.


MSL Entry, Descent, and Landing Instrumentation (MEDLI)

The Orion capsule's first test flight in December 2014, Exploration Flight Test 1 (EFT-1), had over 1200 sensors, including microphones, accelerometers, strain gauges, pressure transducers, string potentiometers, thermocouples, resistance temperature detectors (RTDs), radiometers, calorimeters, and load cells. These data from Orion's 8 km/s entry are still being analyzed, and will undoubtedly inform future vehicle designs as well as instrumentation systems.

Technical Capability Objectives and Challenges

Mars 2020 plans to include sensors based on the MEDLI suite, augmented with forebody pressure transducers calibrated in the supersonic regime, plus limited backshell thermocouple plugs, heat flux gauges, and a pressure transducer. An upward-looking parachute camera is being considered. The next Orion test flight plans similar heatshield instrumentation to EFT-1.

In April 2014, the NASA Technology Executive Council signed a decision memo stating that all EDL missions will assess instrumentation early in the life cycle. Commensurate with that decision, NASA's Science Mission Directorate (SMD) is requiring proposers to instrument any EDL vehicles included in their missions, with the instrumentation cost provided outside the mission cost cap. The prospect of more frequently instrumenting small, cost-capped missions requires miniaturized, modular instrumentation. There is commercial activity in smaller, lighter sensors and avionics, but the products require specialized packaging for the challenging deep-space cruise and EDL environments. In addition to instrumenting science and human exploration missions, technology demonstration missions and tests absolutely require engineering data return; using the sensor suites during developmental ground testing will improve sensor reliability and ground-to-flight traceability.

Deployable decelerators whose shapes obviously change during the mission also present special instrumentation challenges. Less-intrusive methods like acoustic, wireless, distributed, and micro electro mechanical systems (MEMS) sensors can significantly improve mass, volume, and cost metrics. In addition to onboard instrumentation, remote sensing of Earth return vehicles (such as that performed in support of Stardust and Hayabusa) can provide data with no impact to the capsule, but improvements are needed to improve resolution, data quality, and cost. For future human systems, the goal is to provide data on the entire vehicle system to support real-time decision-making and reduce risk.

Major technical challenges in entry instrumentation include reducing mass, volume, and cost to enable data return regardless of the mission size, high-temperature systems capable of direct heat flux measurements, in-situ measurements (temperature and strain) in flexible TPS, advanced optical and other non-intrusive measurement techniques, and shock-layer radiation measurements in ablative TPS. Challenges in health monitoring include development of low-data, low-power networks, elimination of false positives, and the ability to initiate and monitor repair of detected damage.

Benefits of Technology

The obvious benefit of engineering instrumentation is to return data about system performance in flight environments that cannot be fully replicated on the ground, to validate models, and to improve future designs. Entry data can also enhance or enable scientific return from missions, as with the recession sensors on the Galileo probe, which were used to improve knowledge of vehicle drag as a function of time as part of the atmospheric reconstruction experiment. Advanced health monitoring instrumentation can have strongly-enhancing benefits for missions that require high reliability by ensuring that the entry system is functional prior to use.

Table 18. TA 9.4.6 Technology Candidates – not in priority order

TA	Technology Name	Description
9.4.6.1	Thermal Protection System (TPS) Instrumentation	Measures performance of entry vehicle TPS, as well as atmosphere and flight dynamics parameters, to improve design for future missions. Includes in-depth and surface temperature, surface pressure, TPS recession, and surface heat flux and catalycity measurements.
9.4.6.2	Radiometers and Spectrometers for Entry Vehicle Heat Shields	Obtain radiative shock layer energy and/or constituent/electron number density information during entry.
9.4.6.3	Distributed Instrumentation	Measures performance of entry vehicle and its sub elements with distributed sensor networks to improve design for future missions (includes integrated system health monitoring (ISHM), micrometeoroid orbital debris (MMOD), and shape change).
9.4.6.4	Miniaturized, Micro Electro Mechanical Systems (MEMS)-Based Sensors for Entry Vehicles	Provide pressure, temperature, recession, shape, and other parameters in forebody and aftbody entry environments, for minimal mass, power, and volume.
9.4.6.5	Semi- or Non-Intrusive Instrumentation Concepts	Obtain heating, pressure, and/or shape information on entry vehicles, using semi- or non-intrusive instrumentation concepts, including wireless (data and power), electromagnetic, visual, and acoustic based systems.
9.4.6.6	Remote Observation Platforms for Earth Entries	Provides multiple diagnostics on incoming Earth entry vehicles.

TA 9.4.7 GN&C Sensors and Systems

NASA does not currently have any system-level technology candidates within the GN&C Sensors and Systems technology area. These will certainly need to be included as part of maturing the decelerator systems in TA 9.1 Aeroassist and Atmospheric Entry to meet their full requirements. Information on contributing GN&C sensors and systems technologies can be seen in TA 9.1.3 Rigid Hypersonic Decelerators, 9.1.4 Deployable Hypersonic Decelerators, and TA 9.2 Descent and Targeting, specifically TAs 9.2.6 Large Divert Guidance, 9.2.7 Terrain-Relative Sensing and Characterization, and 9.2.8 Autonomous Targeting.

Appendix

Acronyms

1D	One-Dimensional
3D	Three-Dimensional
ACS	Active Control System
ADAPT	Autonomous Descent and Ascent Powered-flight Testbed
ADEPT	Adaptable, Deployable Entry and Placement Technology
AI&P	Assembly, Integration, and Production
ALHAT	Autonomous Landing and Hazard Avoidance Technology
AoA	Angle of Attack
ARRM	Asteroid Redirect Robotic Mission
ATV	Automated Transfer Vehicle
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CPU	Central Processing Unit
CSSR	Comet Surface Sample Return
CT	Computerized Tomography
CTE	Coefficient of Thermal Expansion
DEM	Digital Elevation Map
DES	Detatched Eddy Simulation
DGB	Disk Gap Band
DIMES	Descent Image Motion Estimation System
DL	Doppler LIDAR
DNS	Direct Numerical Simulation
DOF	Degrees of Freedom
DOR	Differential One-way Ranging
DRA	Design Reference Architecture
DSMC	Direct Simulation Monte Carlo
DSN	Deep Space Network
EDL	Entry, Descent, and Landing
EFT	Exploration Flight Test
EM	Exploration Mission
FOV	Field Of View
FSI	Fluid Structure Interaction
GN&C	Guidance, Navigation, and Control
GPU	Graphical Processing Unit
HALE	High Altitude Long Endurance
HDA	Hazard Detection and Avoidance
HIAD	Hypersonic Inflatable Aerodynamic Decelerator

HSIR	Human System Integration Requirements
HTT	High-Temperature Tunnel (Langley 8')
IRVE	Inflatable Reentry Vehicle Experiment
ISHM	Integrated System Health Monitoring
I_{sp}	Specific Impulse
ISS	International Space Station
L/D	Lift/Drag
LA	Laser Altimeter
LCAT	Large Core Arc Tunnel
LDSD	Low-Density Supersonic Decelerator
LEO	Low-Earth Orbit
LES	Large Eddy Simulation
LIDAR	Light Detection And Ranging
LVS	Lander Vision System
M-SAPE	Multi-mission System Analysis for Planetary Entry
MAR	Mid-Air Retrieval
MARDI	Mid-Air Retrieval Descent Imager
MEDLI	MSL Entry, Descent, and Landing Instrumentation
MEMS	Micro Electro Mechanical Systems
MER	Mars Exploration Rover
MiPS	Millions of instructions Per Second
MMOD	Micro Meteoroid Orbital Debris
MOLA	Mars Orbiter Laser Altimeter
MPCV	Multi-Purpose Crew Vehicle
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
NESC	NASA Engineering and Safety Center
NFAC	National Full-scale Aerodynamic Complex Office
OCT	of the Chief Technologist
OML	Outer Mold Line
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security - Regolith EXplorer
PBN	Performance-Based Navigation
PCAD	Propulsion and Cryogenics Advanced Development
PICA	Phenolic Impregnated Carbon Ablator
RANS	Reynolds Averaged Navier-Stokes
RCS	Reaction Control System
RSS	Root of Sum Squares
SIAD	Supersonic Inflatable Aerodynamic Decelerator
SIRCA	Silicone Impregnated Reusable Ceramic Ablator
SMD	Science Mission Directorate

SNR	Signal to Noise Ratio
SOA	State Of the Art
SPED	Supersonic Planetary Experiment Development
SRP	Supersonic RetroPropulsion
STORRM	Sensor Test for Orion Relative-navigation Risk Mitigation
TABS	Technology Area Breakdown Structure
TDS	Terminal Descent System
TPS	Thermal Protection System
TRL	Technology Readiness Level
TRN	Terrain Relative Navigation
UAS	Unmanned Aerial System
U.S.	United States
UV	UltraViolet
V&V	Verification and Validation

Abbreviations and Units

Abbreviation	Definition
°	Degrees
atm	Atmospheres
C	Celsius
cc	Cubic Centimeters
cm^2	Centimeters squared
CO_2	Carbon Dioxide
G	One Earth surface gravitational acceleration (9.81 m/s^2)
G-load, High-g	Acceleration with respect to one Earth surface gravitational acceleration (9.81 m/s^2)
g	Gram
kg	Kilogram
kJ	Kilojoule
km	Kilometer
kN	Kilonewton
lbm	Pound-mass
m	Meter
mm	Millimeter
mt	Metric Tonne
mt	Metric Tonne
N	Newtons
p	Pressure (stagnation)
psi	Pounds per square inch
q	Heat Rate
s^2	Seconds squared
t	Metric ton (1,000 kg)
W	Watts

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Technology Candidate Snapshots

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.1 Extreme Environment Ablative Thermal Protection System (TPS)

TECHNOLOGY

Technology Description: Ablative TPS materials for blunt aeroshells operating in extreme entry environments.

Technology Challenge: 1. Tailorability of materials across a wide range of conditions. 2. Manufacturing and raw material sustainability. 3. Establishing robustness with limited capability at ground test facility (need to identify predictable performance and characterized failure modes to establish robustness via testing). 4. Ground testing not adequate or capable of simulating flight and additional risk assoicated with relating ground performance to flight.

Technology State of the Art: Carbon phenolic, made from carbonized rayon yarn, is processed in two different forms (chop-molded and tape-wrapped) to result in two types or forms of material. The chop-molded carbon phenolic is used for the nose region of the blunt body and the tape-wrapped is used on the flank region of the blunt fore-body heat shield. NASA is currently developing woven TPS.

Parameter, Value:

Density: 1.25 g/cc

Peak heat flux: 10,000 W/cm^2

Peak pressure: 10 atm

TRL

4

Technology Performance Goal: 1. Mass efficiency across a range of conditions (1500 - 10000 W/cm^2 and 1 - 10 atm).

2. Sustainability of supply chain and manufacturing base.

3. Tailorable for a wide range of entry missions and destinations.

4. Robust integrated heat shield performance.

Parameter, Value:

1. Mass efficiency: 40% compared to carbon phenolic.

2. Sustainability: at least 2 domestic suppliers over 2+ decades.

3. Peak heat flux: 1500 - 10,000 W/cm^2

4. Peak presure: 1-10 atm

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Protects spacecraft from extreme heat, pressure, and other environmental conditions during atmospheric entry.

Capability Description: Ability to protect blunt aeroshells with entry conditions characterized by peak heat-flux range of 1500 - 10,000 W/cm^2 and peak pressures of 1.0 – 10 atm. Ability to tailor the TPS for specific heat load (missions) ranging from 10 KJ/cm^2 – 300 KJ/cm^2. TPS tolerance to entry atmospheric composition (Venus, Earth and Gas/Ice Giants) and insensitive to shock layer radiation for efficient performance.

Capability State of the Art: Tape-wrapped carbon phenolic (highest density) is in use in rocket nozzle applications by other government agencies. Chop-molded carbon phenolic is needed for NASA missions (for blunt body) and has not been manufactured over 40 years; the last mission use was Galileo. The precursor material, rayo- based carbon yarn, has not been manufactured since 1986 and processing and manufacturing capabilites have atrophied as a result of lack of use.

Parameter, Value:

Density: 1.25 g/cc

Peak heat flux: 10,000 W/cm^2

Peak pressure: 10 atm

Capability Performance Goal: System mass fractions less than historical Galileo and Pioneer Venus missions.

Parameter, Value:

Density: < 1.25 g/cc

Peak heat flux: 10,000 W/cm^2

Peak pressure: 10 atm

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.2 High-Reliability Thermal Protection System (TPS)

TECHNOLOGY

Technology Description: High-reliability TPS to meet requirements for human mission robustness and for sample return mission contamination prevention.

Technology Challenge: A moderate-cost, timely approach that combines limited ground and flight testing to understand not only performance but failure modes as well, and extensive computational modeling along with probabilistic sensitivity assessment to establish quantitative reliability of TPS for each given mission.

Technology State of the Art: Qualititative expert judgement is the only methodology known to date. Carbon phenolic has been the only material with enough test data sufficient to be called "high reliability."

Parameter, Value:	TRL
Verifiable TPS robustness and reliability of 0.999 for human missions and 1×10^{-7} for sample return from Mars, Europa, or Enceladus.	1

Technology Performance Goal: A ground test combined with analytical model development and flight validation approach that leverages robotic missions or focused over-test flight testing to establish quantitative robustness/reliability paradigms.

Parameter, Value:	TRL
Verifiable TPS robustness and reliability of 0.999 for human missions and 1×10^{-7} for sample return from Mars, Europa, or Enceladus.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: TPS for human and sample return missions.

Capability Description: Quantifiable reliability and robustness of TPS performance during entry.

Capability State of the Art: Avcoat is the only TPS currently qualified for human missions beyond low-Earth orbit (LEO).

Parameter, Value:

Avcoat capable of human missions around 1000 W/cm^2 and 1.0 atm pressure. Robustness and reliability of Avcoat or any other TPS, including carbon phenolic, has yet to be quantified.

Capability Performance Goal: Innovative and relatively inexpensive methodology of testing combined with extensive analytical modeling required for robustness and reliability quantification. Includes dual-pulse for Aerocapture followed by entry.

Parameter, Value:

Human mission reliability requirement of 1-in-1000 failure of loss of crew and 1-in-a-million entry system failure for sample return missions.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	5 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.3 Conformal Ablative Thermal Protection System (TPS)

TECHNOLOGY

Technology Description: Provides conformal ablative thermal protection for low to moderate entry conditions for both heat shield and backshell applications.

Technology Challenge: 1. Developing scalable conformal TPS to meet mission needs. Commercial felt thicknesses limited to about 1”, although ongoing development has resulted in ~3” thick carbon felt. 2. Efficient manufacturing. Manufacturing of large panels requires large molds or frames on which to form the material, and may require large amounts of resin/solvent mix that is wasted. 3. Lack of flight test opportunities to provide ground test to flight traceability.

Technology State of the Art: Phenolic impregnated carbon ablator (PICA): phenolic impregnated in a rigid carbon structure, very brittle, requires strain isolation pads and gap fillers, along with tiled approach that has a limited tile size.

Parameter, Value:

Conformal ablator capable of strain to failure > 2% and 1m x 1m size or larger conformable components with minimal gap beteween tiles.

TRL 5

Technology Performance Goal: Carbon felt-based systems are capable of easy integration by conforming to large, curved geometries as well as high strain-to–failure values.

Parameter, Value:

1) Environments: Heat flux > 500 W/cm^2;

2) Strain-to-failure: > 2%;

3) Manufacturing scalability: > 1m x 1m panels;

4) Response model fidelity: Mean bias error < 10%; Time-to-peak error < 10%; Recession error < 25%.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Moderate entry environment protection capability that is easy to integrate with rigid aeroshell.

Capability Description: Ablative thermal protection material capable of heat flux up to 1000 W/cm^2 and pressure from 0.05 atm to 1 atm pressures, with more compliant structural capability (higher strain-to-failure) compared to PICA or Avcoat.

Capability State of the Art: Rigid TPS is prone to cracking due to carrier structure coefficient of thermal expansion (CTE) mismatch or structural loads. Avcoat is prone to developing cracks along honeycomb cell walls.

Parameter, Value:

PICA:

Density 0.27 g/cc

Heatflux: 1200 W/cm^2

Strain-to-failure << 1.0%

Avcoat:

Density 0.5 g/cc

Heatflux: 800 W/cm^2

Strain-to-failure 2%

Capability Performance Goal: Mass efficient and higher strain-to-failure for robust integrated thermo-structural capability.

Parameter, Value:

50% areal density of PICA or Avcoat with strain-to-failure capability of > 2%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	2 years
Discovery: Discovery 14	Enabling	--	2023	2020	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.4 Multifunctional, Shock Layer Radiation-Reflective Material

TECHNOLOGY

Technology Description: Reflects radiant energy back to space to protect large blunt bodies during extreme entry (see also TA 14 Thermal Management Systems).

Technology Challenge: Shock layer radiation is not limited to optical or a specific wavelength. The energy spectrum can be both broad band and line radiation. The radiant energy spectrum generated will be very different depending on the destination, and is also dependent on the entry velocity. The non-equilibrium nature of the shock heated excitation and relaxation processes generate the radiant energy. Designing a thermal protection system (TPS) to manage both reflective and convective heating is a significant challenge. For example, ablative TPS will inject pyrolysis gas that can limit the effectiveness of the reflective part of TPS or can alter the optical properties. If the TPS is ablative, then the recession at the surface may change the character of the reflectiveness as a function of time.

Technology State of the Art: Technology does not currently exist.

Parameter, Value:	TRL
None exists.	1

Technology Performance Goal: 50% of radiant heating reflected without increasing convective heating; effective over the heat pulse duration.

Parameter, Value:	TRL
Mass efficiency better than 50% for entry where dominant mode of heating is radiation.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Multifunctional, shock-layer radiation reflective material.

Capability Description: Reflects radiant energy back to space to protect large blunt bodies during extreme entry.

Capability State of the Art: None exists today. During Galileo heat shield development, concepts were proposed.

Parameter, Value:

Radiant heating can be 10% - 50% of the total heating. Jupiter entry or potential high-speed human return from Mars (V > 13 km/s) is dominated by radiation.

Capability Performance Goal: TPS material that can reflect radiant energy for a small mass penalty.

Parameter, Value:

TPS mass fraction: < 50%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	8 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.5 Multifunctional, Micrometeoroid Orbital Debris (MMOD)-Tolerant Materials

TECHNOLOGY

Technology Description: Thermal protection system (TPS) materials that provide thermal protection after a MMOD strike. See also TA 14.3 Thermal Protection Systems.

Technology Challenge: The challenge is that no first principles models exist to predict MMOD damage for a given material, nor are there models to predict failure modes and growth of the damage in an aerothermal entry environment. This situation requires an Edisonian, trial-and-error approach where many different TPS materials would undergo MMOD impact simulations, subsequent arcjet testing, and damage growth modeling for a flight-ready, MMOD-tolerant TPS. The development costs will be high for the benefits afforded by the new technology.

Technology State of the Art: Prior attempts were to bond together layers of PICA with interspersed Kevlar to make a MMOD-resistant TPS. However, upon impact, the layers separated and the results were unacceptable. The current concept is to use woven TPS technology as the basis for a MMOD-tolerant TPS. Woven TPS could intersperse interlinked layers of MMOD-resistant materials. Such a material probably would be resistant to separation upon MMOD impact.

Parameter, Value:	TRL
Damage in heritage materials by small projectiles at 7 km/s.	4

Technology Performance Goal: Limit damage caused by SOA technology by 50% with no more than 10 percent weight growth from the baseline material.

Parameter, Value:	TRL
Reduce the size of MMOD damage by 50%, with < 10% growth in TPS density.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: MMOD protection.

Capability Description: Provides protection against MMOD.

Capability State of the Art: Generally, SOA TPS materials are arcjet tested to determine functional limits (e.g., Shuttle Wing Leading edge material is arcjet tested after simulated MMOD strikes), and a damage growth tool based on these tests is used to define allowable TPS damage for safe re-entry. Backshell TPS for Orion was sized for MMOD penetration rather than for the TPS bondline temperature limit.

Parameter, Value:

Ballistic limits: For a given TPS, ballistic range testing provides a relationship between the MMOD size and velocity to the diameter and penetration depth of the damage. Then arcjet testing is used to determine what size of damage is allowable for safe entry.

Capability Performance Goal: TPS material that can provide MMOD protection against 90+% of threats for a small mass penalty (10% additional mass).

Parameter, Value:

TPS mass fraction: < 20%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.6 Solar and Space Radiation Attenuating Materials

TECHNOLOGY

Technology Description: Thermal Protection System (TPS) materials that also shield against solar flare radiation and cosmic rays. See also TA 6.5 Radiation, TA 10.1 Engineered Materials and Structures, TA 12.2 Structures, and TA 14 Thermal Management Systems.

Technology Challenge: The challenge of including radiation shielding as a metric for TPS design is because thermal shielding requirements and low mass generally are the drivers. Evaluation of radiation shielding for the spacecraft is done by considering the shielding of crew surroundings, including the TPS. Independent evaluation of radiation shielding of TPS is costly and generally not done.

Technology State of the Art: Include radiation shielding as one metric for TPS selection for future missions involving long-duration human flight. Apply existing radiation shielding sizing tools during design trades to determine the overall benefits of candidate TPS to radiation shielding.

Parameter, Value:

Shielding effectiveness: International Space Station materials.

Mass increase: varies by mission.

TRL: 6

Technology Performance Goal: Shield radiation with minimal increase in TPS mass.

Parameter, Value:

Shielding within 10% that of polyethylene.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Solar and space radiation attenuating materials.

Capability Description: Materials that shield against solar flare radiation and cosmic rays.

Capability State of the Art: Years of study have shown that materials with high percentages of low atomic weight species afford the best radiation shielding. In view of this, carbon- and phenol (C_6H_6O)-based systems are better than silicaceous TPS for radiation shielding. However, the TPS function usually drives materials selection.

Parameter, Value:

Polyethylene is the “gold standard” for radiation shielding. Comparison of the TPS radiation shielding to that of polyethylene shielding blankets on a mass basis was used for the Orion Multi-Purpose Crew Vehicle (MPCV).

Capability Performance Goal: Shield radiation with no or minimal increase in TPS mass.

Parameter, Value:

Shielding within 10% that of polyethylene.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.7 Multifunctional Thermo-Structural Materials

TECHNOLOGY

Technology Description: Protects spacecraft from the environment during entry, descent, and landing by integrating thermal protection materials and the structure. See also TA 12.2.5 Innovative, Multifunctional Concepts and TA 14 Thermal Protection Systems.

Technology Challenge: Challenges include complex manufacturing operations and complex thermo-structural tests that are required to validate the material.

Technology State of the Art: Use of three-dimensional (3D) woven carbon phenolic for Orion compression pad (Technology Readiness Level (TRL) 4), 3D woven carbon cloth for use on mechanically deployable decelerators (TRL 2-3).

Parameter, Value:	TRL
None exists; component tests have been completed but system metrics are not yet available.	2

Technology Performance Goal: Mass reduction, improved micrometeoroid orbital debris (MMOD) resistance, improved robustness, reduced assembly and integration time, and reduced complexity.

Parameter, Value:	TRL
Mass: Reduced 15% over a classical substructure + thermal protection system (TPS). Improved resistance to particular failure modes compared with classical substructure + TPS. Reduced complexity, reduced assembly, integration, and production (AI&P) time by 20%.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Multifunctional thermo-structural materials.

Capability Description: Protects spacecraft from the environment during entry by integrating thermal protection materials into the structure.

Capability State of the Art: All designs flown to date have used TPS attached to some substructure support. Carbon-carbon and other hot structures are used for many applications.

Parameter, Value:
University analytical study.

Capability Performance Goal: Provide additional functionality to improve aeroshell mass fractions beyond SOA.

Parameter, Value:
Mass fraction: < 30%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years

9.1 Aeroassist and Atmospheric Entry
9.1.1 Thermal Protection Systems for Rigid Decelerators

9.1.1.8 Non-Destructive Evaluation (NDE)

TECHNOLOGY

Technology Description: Manufacture, inspection, and certification of materials and systems.

Technology Challenge: Challenges include scanning power and resolution, automated data analysis, and characteristics classification of defects versus features.

Technology State of the Art: Scanning 1m diameter heat shield.

Parameter, Value:
Scanning 5m heat shield with sufficient resolution.

TRL 4

Technology Performance Goal: Computerized tomography (CT) scan or other techniques capable of scanning 5 meter diameter and producing a map of defects and features.

Parameter, Value:
1mL size resolution.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: CT scan or other NDE techniques.

Capability Description: Large integrated system quality assurance requires NDE techniques that can permit documenting features from manufacturing process certification and accepting parts and sub-systems.

Capability State of the Art: CT scanning is used for TPS materials and heat shield systems; small-scale (up to 1 m has been used successfully), limited backscatter, digital X-ray used for Orion Avcoat heat shield.

Parameter, Value:
Detect porosity of 0.15 mL region 0.5 mm debond.
Detect density variations and inclusions.

Capability Performance Goal: Single scan capable of scanning 5m diameter heart shield at resolution similar at 1m or smaller scale.

Parameter, Value:
Scanning at high resolution at 5m diameter.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.2 Thermal Protection Systems for Deployable Decelerators

9.1.2.1 Non-Ablative Concepts for Thermal Protection

TECHNOLOGY

Technology Description: Protects spacecraft during entry, descent, and landing using highly-flexible, stowable, non-ablative (insulative or transpiration-cooled) thermal protection.

Technology Challenge: Challenges include manufacturability, scalability, aero-structural modeling, stowability, and durability.

Technology State of the Art: 2012 flight of Inflatable Reentry Vehicle Experiment 3 (IRVE-3), a 3 meter stowed inflatable decelerator, entered Earth's atmosphere from an apogee of 476 km; ground-based testing in National Full-Scale Aerodynamic Complex (NFAC) of 6 meter inflatable structure. Thermal testing of flexible thermal protection system (TPS) in large core arc tunnel (LCAT) and 8' High-Temperature Tunnel (HTT).

Parameter, Value:

Peak heating: 40 W/cm^2

Integrated heat load: 5 kJ/cm^2

Inflatable structure (IS) temperature limit: 250-300 C

Deployed diameter: 6m

TRL

5

Technology Performance Goal: Increased deployed diameter, higher temperature materials and structures, higher performance TPS for increased heat rate and heat load tolerance.

Parameter, Value:

Peak heating: 50-100 W/cm^2

Integrated heat load: 12 kJ/cm^2

IS temperature limit: > 400 C

Deployed diameter: 10-25m

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-ablative concepts for thermal protection.

Capability Description: Protects spacecraft during entry using highly flexible, stowable, non-ablative (insulative or transpiration cooled) thermal protection.

Capability State of the Art: First generation IS plus Flexible Thermal Protection System (F-TPS) is ready for mission infusion. Second generation is under development.

Parameter, Value:

Peak heating: 40 W/cm^2

Integrated heat load: 5 kJ/cm^2

IS temperature limit: 250-300 C

Deployed diameter: 6m

Capability Performance Goal: Large-scale, packable, moderate heat rate and load system for human-to-Mars missions.

Parameter, Value:

Peak heating: 50-100 W/cm^2

Integrated heat load: 12 kJ/cm^2

IS temperature limit: > 400 C

Deployed diameter: 10-25m

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

9.1 Aeroassist and Atmospheric Entry
9.1.2 Thermal Protection Systems for Deployable Decelerators

9.1.2.2 Flexible Ablative Concepts for Thermal Protection

TECHNOLOGY

Technology Description: Ablative concepts, including systems that rigidize in-space or during entry.

Technology Challenge: Development from concept and screening tests completed in 2009-11 will require process improvement. Other challenges include arc jet testing of instrumented materials, materials properties testing, thermal response model development, and demonstration of scale up.

Technology State of the Art: There is no SOA flexible ablator. Shuttle and Inflatable Reentry Vehicle Experiment (IRVE) have flown non-ablative, flexible thermal protection system (TPS).

Parameter, Value:
None exists.

TRL
4

Technology Performance Goal: Carbon-felt based materials: ~400 W/cm^2 or higher.

Parameter, Value:
Carbon-felt based materials: ~400 W/cm^2 or higher.

TRL
4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ablative, flexible TPS.

Capability Description: Provides thermal protection during hypersonic flight.

Capability State of the Art: There is no SOA flexible ablator. Shuttle and Hypersonic Inflatable Aerodynamic Decelerator (HIAD) have flown non-ablative, flexible TPS.

Parameter, Value:
None exists.

Capability Performance Goal:
1) Low TPS mass
2) Manufacturabiliby
3) Foldability
4) Stowability
5) Response model fidelity

Parameter, Value:
1) Mass equivalent or less than silicone impregnated reusable ceramic ablator (SIRCA)-15
2) Demonstration of scale-up to 1m x 1m
3) Minimum fold radius 2.5 times thickness
4) Volume equivalent to acoustic blanket in shroud
5) Mean: bias error < 10%, time-to-peak error < 10%, recession to be determined.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

9.1 Aeroassist and Atmospheric Entry
9.1.2 Thermal Protection Systems for Deployable Decelerators

9.1.2.3 Flexible Thermostructural Thermal Protection System (TPS)

TECHNOLOGY

Technology Description: Lightweight carbon fabric capable of accomodating thermal heating loads and load-bearing pressures, as well as being flexible enough to be stowed during launch.

Technology Challenge: Challenges include scaling up from 1 meter and conducting repeated deployment testing.

Technology State of the Art: Flexible carbon fabric of thicknesses ~150mil with gore dimensions on the order of 1meter; 1meter scale fabric manufactured, coupon scale materials tested in combined heating and mechanical loads.

Parameter, Value:

Peak heating: 250 W/cm^2 demonstrated at coupon level.

TRL

3

Technology Performance Goal:

Gore: ~1m (required for target missions)

Peak heating: 250 W/cm^2

Heat load: > 10 kJ/cm^2

Capable of line loads ~ 600 lbs/in

Parameter, Value:

Peak heating: 250 W/cm^2

Heat load: > 10 kJ/cm^2

Capable of line loads ~ 600 lbs/in

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flexible thermostructural TPS.

Capability Description: Lightweight carbon fabric capable of accomodating thermal heating loads and aeroloading pressures, as well as being flexible enough to be stowed during launch.

Capability State of the Art: Not in current use. Supersonic Planetary Experiment Development (SPED) concept in 1960s had deployable structures but without TPS needs; conceptual studies have been conducted.

Parameter, Value:

None exists.

Capability Performance Goal: Multi-layer pure carbon fabric (IM7 fibers) capable of being folded (stowed), and scalable from 1m to 20m configurations.

Parameter, Value:

Peak heating: 250-500 W/cm^2

Heat load: > 10 kJ/cm^2

Capable of line loads ~ 600 lbs/in.

Able to survive 2 distinct heat pulses.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.2 Thermal Protection Systems for Deployable Decelerators

9.1.2.4 Textile Fabrics and Coatings for Catalycity and Thermal Resistance

TECHNOLOGY

Technology Description: Provides high-strength, high-temperature textile fabrics and coatings that can extend the thermal environment in which deployable decelerators can operate.

Technology Challenge: Challenges include identifying low catalytic chemistries that are chemically stable at temperatures up to 1650°C and can be applied to fibrous yarns and tows, and developing coating processes that can be used to deposit thin layers of non-catalytic coating refractory yarns and tows without bonding fiber filaments.

Technology State of the Art: For high-temp applications, Kevlar-29 is the material of choice due to its strength at temperature. Technora and Vectran offer better flex-crack resistance. Seam and joint strengths need to improve.

Parameter, Value:
Temperature at 50% strength for Kevlar: ~270-300º C.

TRL 3

Technology Performance Goal:
Lighter weight, higher specific heat coatings.
Better seam and joint efficiencies.
Smaller denier, higher weave count fabrics.
Better resistance to ultraviolet (UV) degradation.
Improved strength at temperature.

Parameter, Value:
Improvement in strength at temperature: 85%.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improving flexible material performance.

Capability Description: Using processing to improve the performance of flexible materials for entry, descent, and landing (EDL).

Capability State of the Art: Kevlar, Technora, Vectran: typically coated for permeability and thermal resistance with silicone or other coating. For catalycity: Current flexible systems rely on intrinsic chemical reaction layers that form a chemically stable surface chemistry, such as silica or quartz, that is both non-catalytic and oxidation resistant.

Parameter, Value:
Temperature at 50% strength for Kevlar: ~270-300º C.

Capability Performance Goal: Improved strength at temperature.
Robustness to repeated handling; packing and deployment cycles.

Parameter, Value:
Improvement in strength at temperature: 85%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.2 Thermal Protection Systems for Deployable Decelerators

9.1.2.5 Textile Fabrics and Coatings for Radiation Reflection and Resistance

TECHNOLOGY

Technology Description: Provides high-strength, high-temperature textile fabrics and coatings that can extend the radiation environment in which deployable decelerators can operate.

Technology Challenge: Challenges include identifying viable material candidates that would provide the photonic reflectance, surface adherence, chemical compatibility, and thermal stability required for a particular mission application.

Technology State of the Art: Optical coating technology used for mirrors and filters exists at Technology Readiness Level (TRL) > 8 with a solid modeling and manufacturing foundation that can be readily used to guide potential modification of the refractory textiles used for flexible thermal protection systems. Dielectric reflectance coatings consisting of one or more thin (< 0.001 mm) layers of material deposited can be used to alter photonic reflectance. Another approach can be highly reflective metallic coatings of the type used to produce mirrors.

Parameter, Value: | **TRL**: 2

Reflectivity, thermal resistance, flexibility and packability, no degradation beyond uncoated material. Specific values have not been determined at this TRL.

Technology Performance Goal:

Lighter weight, higher specific heat coatings.

Better seam and joint efficiencies.

Smaller denier, higher weave count fabrics.

Better resistance to ultraviolet (UV) degradation.

Improved strength at temperature.

Parameter, Value: | **TRL**: 6

Reflectivity increase of 50%, thermal resistance increase of 50%, no increase to mass and flexibility.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improving flexible material performance.

Capability Description: Using processing to improve the performance of flexible materials for entry, descent, and landing (EDL).

Capability State of the Art: Current reflectance capability relates to the basic principles used for mirrors and optical filters with very limited practical applications relevant to flexible thermal protection systems.

Parameter, Value:

Temperature at 50% strength Kevlar: ~270 -300ºC.

Capability Performance Goal: Improved strength at temperature.

Improved robustness.

Parameter, Value:

Improved strength at temperature: 85%.

Robustness: > 80%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.1 Sample Return Capsules

TECHNOLOGY

Technology Description: Low-mass structures, impact attenuators, and capsule systems that enable low-cost sample returns.

Technology Challenge: Challenges include developing a thermal protection system (TPS) to meet reliability needs, conducting system design and validation testing, and meeting planetary protection requirements.

Technology State of the Art: Stardust used phenolic impregnated carbon ablator (PICA) heat shield, parachutes. Genesis used carbon-carbon aeroshell with backup honeycomb structure, and parachute (crashed due to chute g-switch installation but samples were largely intact). Hayabusa used carbon-phenolic TPS.

Parameter, Value:

Stardust entry velocity is 12.8 km/s, mass is 45.8 kg, diameter is 0.83 m, and TPS mass fraction is 22%.

Genesis entry velocity is 11 km/s, mass 210 kg, and diameter is 1.5 m.

TRL

5

Technology Performance Goal: Mars Sample Return's (MSR's) reliability requirements imply no parachute, heritage TPS. Mass goal is < ~35 kg.

Parameter, Value:

Minimize system mass for returned payload.

50% cost reduction over Genesis for most missions.

Meet system reliability of 1×10^{-6} for biological samples.

TRL

3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sample return capsules.

Capability Description: Enables sample return to Earth at high speed (> 11 km/s), meeting planetary protection, sample integrity, and cost requirements.

Capability State of the Art: Stardust, Genesis, and Hayabusa.

Parameter, Value:

Stardust 0.8 m, 12.8 km/s, Discovery class, no planetary protection requirements.

Capability Performance Goal: Varies with destination; goal is to improve capsule mass and performance to enable low-cost (Discovery and New Frontiers-class) missions.

Parameter, Value:

1×10^{-6} reliability for MSR.

Return speeds > 13 km/s for comets and asteroids.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.2 Entry Vehicles with Lift/Drag (L/D) 0.4 to < 2.0

TECHNOLOGY

Technology Description: Provide entry for mission applications where g-load or targeting requirements cannot be satisfied with lower L/D, or when landing opportunity intervals motivate higher-entry trajectory cross-range performance.

Technology Challenge: Challenges include the complex vehicle design, packaging, structural/thermal protection system (TPS) mass fraction, and reliability.

Technology State of the Art: Only low L/D vehicles have been flown at other planets. Studies show Neptune aerocapture requires L/D > 0.8. Design Reference Architecture (DRA) 5.0 uses mid L/D vehicle for human Mars landing. Other in-depth studies to determine advantages for other shapes and destinations have not been performed.

Parameter, Value:

SOA L/D > 0.4 is based on Earth entry vehicles. No significant development in Mars vehicles.

TRL

3

Technology Performance Goal: Design of an entry vehicle with L/D > 0.4 that is volumetrically efficient for launch vehicles and extensible to human Mars aerocapture/entry and other planetary missions with minimal mass and dual use as a launch vehicle shroud.

Parameter, Value:

Mass- and volume-efficient configuration with hypersonic L/D > 0.4 for Mars precursors, < 10mt payloads up to 40 t for Mars human missions with launch vehicle diameter compatible with SLS < 10 meter shroud.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mid L/D entry vehicles.

Capability Description: Provide hypersonic entry for mid-to high-performance vehicles and missions.

Capability State of the Art: Guided, lifting entry vehicles with 0.4 < L/D < 2.0 are currently limited to the X-37. Multiple vehicles have flown, including lifting bodies and winged entry vehicles. These include: X-23, X-24, X-37, Space Shuttle Orbiter, Buran. Applications have been limited to Earth entry.

Parameter, Value:

g-loads: < 10

Reliability: > 0.999

Entry system mass fraction: < 30%

Capability Performance Goal: Use of guided, lifting entry vehicles at other planets of configurations that are extensible to human Mars mission aerocapture and entry.

Parameter, Value:

Guided, lifting entry vehicle with hypersonic L/D > 0.4 enabling < 100 mt mass at Mars entry with 40 mt payload to 10 km altitude at Mach < 3.5; g-loads < 4; dual heat pulse capable; dual use as launch vehicle shroud.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.3 Enhanced Aerodynamics for Slender Vehicles

TECHNOLOGY

Technology Description: Provides a vehicle with additional lift through deployable aerodynamic surfaces (chines, wings, etc.).

Technology Challenge: Challenges include packaging, heating on leading edges, complex vehicle design, and reliability.

Technology State of the Art: Flight test of a sub-scale X-24 derivative vehicle successfully demonstrated inflatable wings. Variable cant wings utilized on a foreign government vehicle. Deployable wings or moveable wings used by other U.S. government agencies.

Parameter, Value:
X-24 sub-scale demonstration increased L/D from 3 to 6 upon wing deployment.

TRL
2

Technology Performance Goal: Increase lift/drag (L/D) above that which is achievable via slender axisymmetric geometries (L/D > 0.8).

Parameter, Value:
Varies by mission and vehicle; L/D > 1.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Vehicles with advanced lifting capability.

Capability Description: Provides vehicles with several degrees of freedom for complex missions.

Capability State of the Art: No current utilization.

Parameter, Value:
L/D enhancement, center of pressure shift for trim angle of attack (AOA) alteration.

Capability Performance Goal: Increased lift and control allows higher precision landings and lower velocity touchdown.

Parameter, Value:
Mission specific; L/D > 1.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	4 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	4 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.4 Entry Vehicles with Lift/Drag (L/D) > 2.0

TECHNOLOGY

Technology Description: Enable significant downrange performance for hypersonic transport vehicles, significant plane change capability for orbital transfer vehicles, and lift sufficient to perform aerogravity turn, aerobraking, and aeroassist.

Technology Challenge: Challenges include packaging, heating on leading edges, complex vehicle design, and reliability.

Technology State of the Art: Another U.S. government agency has conducted multiple high-lift flight demonstration programs. National Aero Space Plane flight test vehicle development ended prior to flight.

Parameter, Value:

Lift/drag (L/D) > 2

TRL

6

Technology Performance Goal: Vehicle systems that can perform aerogravity assist.

Parameter, Value:

L/D > 5

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Basic research in high-temperature materials for sharp leading edges (see TA 12, Materials, Structures, Mechanical Systems, and Manufacturing).

CAPABILITY

Needed Capability: High-L/D entry vehicles.

Capability Description: Provide hypersonic entry for high-performance vehicles and missions.

Capability State of the Art: Medium- and long-range weapons delivery systems have undergone recent flight demonstrations.

Parameter, Value:

g-loads, entry system mass fraction, time of flight from launch to impact, distance from launch to impact, percent of lift generated, acceleration compared to planetary gravity, and delta-V for orbital plane change.

Capability Performance Goal: Vehicle systems that can perform aerogravity assist.

Parameter, Value:

L/D > 5

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	6 years
Planetary Flagship: Push	Enhancing	--	--	--	8 years

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.5 Aerodynamics Modulation Hardware

TECHNOLOGY

Technology Description: Hardware that allows modulation of aerodynamics (lift, drag, etc.) for enhanced maneuverability during entry, descent, and landing (EDL).

Technology Challenge: Challenges include mass, heating, complexity, power, risk, and conducting a test demonstration.

Technology State of the Art: Aerosurfaces and reaction control system (RCS) proven for entry. Trim flaps flown on high lift re-entry vehicles (Space Shuttle), but not capsules. Efforts to define approaches for deployable trim tabs have been investigated. Fluid transfer utilized on B-1 bomber for center of gravity (CG) control, deployable wings or moveable wings, deployable structures in test mode.

Parameter, Value: — **TRL** 4

Planetary blunt bodies: lift/drag (L/D) change, trim alpha (0.2 L/D increment with ~0.1 mass fraction).

Lifting vehicles: L/D change, trim alpha, plus stability and control (values are vehicle specific).

Technology Performance Goal: Modulation of aerodynamics (lift, drag, etc.) for enhanced maneuverability during EDL. This could be in the form of aerodynamics surfaces (such as trim tabs or control surfaces), or movable CG.

Parameter, Value: — **TRL** 6

Blunt bodies: L/D change, trim alpha (> 0.2 L/D increment with << 0.1 mass fraction).

Lifting vehicles: L/D change, trim alpha, plus stability and control (values are vehicle specific).

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Aerodynamics modulation hardware.

Capability Description: Hardware that allows modulation of aerodynamics (lift, drag, etc.) for enhanced maneuverability during EDL.

Capability State of the Art: For entry hypersonic environment, trim and control aerosurfaces and RCS are proven standard technology, as flown on Space Shuttle, X-37, and other vehicles. Limited CG control via discrete mass dumps was performed by MSL entry at Mars.

Parameter, Value:

Varies by vehicle and mission; in general, desire most control for least mass and complexity/risk.

Capability Performance Goal: Varies by vehicle and mission; in general, desire most control for least mass and complexity/risk.

Parameter, Value:

Affect angle of attack change of > 20 degree mass < 50% of that required by mass ejection method.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.6 Control Modulation Software

TECHNOLOGY

Technology Description: Software that commands aerodynamic control during hypersonic entry, descent, and landing (EDL) based on vehicle and environmental state data.

Technology Challenge: Challenges include system-level integration, end-to-end testing, and obtaining adequate vehicle and environment information to make the concept feasible.

Technology State of the Art: Mars Science Laboratory (MSL) Hypersonic guidance, based on Apollo entry guidance algorithm; Orion predictor corrector guidance, Shuttle entry guidance.

Parameter, Value:
Not adaptive, at this time.

TRL
9

Technology Performance Goal: Pseudo-adaptive control on an entry vehicle. Reduction of operational cost.

Parameter, Value:
Onboard calculation of controller forward gain.
30% increase in system robustness. 20% cost reduction in design development and operational phases.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Control modulation software.

Capability Description: Software that commands aerodynamic control during hypersonic EDL based on vehicle and environmental state data.

Capability State of the Art: Space Shuttle used classical control algorithms. X-38 used dynamic inversion controller for drop test vehicle. Full entry has not been demonstrated. Pseudo adaptive control has not been demonstrated for an entry vehicle.

Parameter, Value:
Pre-flight gain calculations/specification required.

Capability Performance Goal:
Onboard calculation of controller forward gain.
30% increase in system robustness.
20% cost reduction in design, development, and operational phases.

Parameter, Value:
Degree of adaptability: 100%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years

9.1 Aeroassist and Atmospheric Entry
9.1.3 Rigid Hypersonic Decelerators

9.1.3.7 Entry Guidance Software

TECHNOLOGY

Technology Description: Numerical model-based predictor-corrector entry guidance algorithms for lifting entry vehicles, which increase robustness, enhance dynamic flight constraint mitigation, and improve mission success statistics over analytic and reference-trajectory-based algorithms. (See also 9.1.4.6 Advanced Guidance and Navigation Systems.)

Technology Challenge: Going from the SOA to the performance goal is challenging because onboard numerical algorithms are more central processing unit (CPU) intensive and require increased load processing demands during dynamic flight. Improved attitude initialization error prior to entry will provide improved dispersions at supersonic phase initiation.

Technology State of the Art: Orion Exploration Flight Test (EFT)-1 with direct entry using limited numerical predictor-corrector with analytic final phase; Exploration Mission (EM) 1/2 simulation testing with full skip entry numerical predictor-corrector with analytic final phase; full skip entry and final phase with numerical predictor-corrector.

Parameter, Value: | **TRL**
Skip entry targeting to EM1/2 target. | 5

Technology Performance Goal: A robust model-based energy management algorithm (analytical or NDC) that depletes excess energy prior to transitioning to a NDC targeting algorithm utilizng full capability of the vehicle. Achieve with the targeting accuracy at parachute deploy or supersonic retropropulsion (SRP) ignition: < 5 km with dispersions and 0.27 lift/drag (L/D) robustness to in-flight dispersions.
Factor of Safety: 1.2 for all dispersions simultaneously with 0.27 L/D.

Parameter, Value: | **TRL**
20-30% increase in targeting accuracy, dispersion coverage (FOS), and flight corridor. | 6

Improved real-time adaptive trajectory control for constraints.

30% reduction in I-Load design time.

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Guidance software.

Capability Description: Algorithms for lifting entry vehicles, which increase robustness, dynamic flight constraint mitigation, and mission success statistics.

Capability State of the Art: All lifting vehicles to date for entry (Earth and Mars) have used analytic- or reference-trajectory-based guidance techniques. Orion skip entries are intending to employ a numerical model-based predictor-corrector. Apollo, Space Shuttle, Mars Science Laboratory (MSL) (used Apollo entry guidance).

Parameter, Value:
Applying MSL, Apollo, and Shuttle approaches for guidance results in: targeting accuracy at chute deploy or SRP ignition - 5 km with dispersions and 0.27 L/D; robustness to in-flight dispersions. FOS: 1.2 for all dispersions simultaneously with 0.27 L/D.

Capability Performance Goal: Fully numeric guidance based on vehicle state and environmental inputs, with accuracy required at the end of the hypersonic phase to enable pinpoint landing for humans on Mars. Guidance utilization of full vehicle capability.

Parameter, Value:
Human landing footprint: 100 m diameter 3-sigma.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.1 Inflatable Entry Systems

TECHNOLOGY

Technology Description: Deploys an inflatable rigid structure protected by a flexible thermal protection system (TPS) to increase the vehicle aerodynamic drag, thus lowering the ballistic coefficient.

Technology Challenge: Challenges include manufacturability, scaleability, aero-structural modeling, and durability.

Technology State of the Art: 2012 flight of Inflatable Reentry Vehicle Experiment 3 (IRVE-3), a stowed inflatable decelerator launched to an apogee of 476km; ground-based testing in National Full-Scale Aerodynamic Complex (NFAC) of 6 meter inflatable structure. Thermal testing of flexible TPS in Large Core Arc Tunnel (LCAT) and High-Temperature Tunnel (HTT).

Parameter, Value:

Integrated heat load: 5 kJ/cm²

Peak heating: 40 W/cm²

Inflatable structure temperature: 250-300°C

Stowed diameter: 0.47m

Deployed diameter: 3.0m

Deceleration: 20 g

TRL

5

Technology Performance Goal: Increase deployed diameter, higher temperature materials and structures, and higher performance TPS for increased heat rate and heat load.

Parameter, Value:

Peak heating: 50-100 W/cm²

Inflatable structure temperature: > 400° C Deployed diameter: > 10-25m

Payload: 5-40mt

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: 9.1.2 Thermal Protection Systems for Deployable Decelerators, 9.1.2.3 Flexible Thermostructural TPS, and 9.1.4.4 Flexible Structural Materials

CAPABILITY

Needed Capability: Hypersonic deceleration.

Capability Description: Provides hypersonic deceleration.

Capability State of the Art: IRVE-3, a 3m deployed structure, was launched to an apogee of 476km. The deployed structure had a peak deceleration of 20g's. (first generation inflatable structure and flexible TPS).

Parameter, Value:

Integrated heat load: 5 kJ/cm²

Peak heat rate: 40 w/cm²

Inflatable structure T: 250-300°C

Stowed diameter: 0.47m

Deployed diameter: 3.0m

Deceleration: 20g

Capability Performance Goal: Increase the payload mass of entry systems and enable higher elevation landing sites.

Parameter, Value:

Deliver 50 times more payload to >- 4.5 km Mars altitude, with adequate entry, descent, and landing (EDL) timeline margin.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.2 Mechanically-Deployed Entry Systems

TECHNOLOGY

Technology Description: Deploys a mechanical, rigid structure protected by a structural thermal protection system (TPS) membrane to increase the vehicle aerodynamic drag, thus lowering the ballistic coefficient. See also TA 12.1.3 Flexible Material Systems.

Technology Challenge: Challenges include fabric thermal performance, thermostructural capability, load transfer and shape management at interfaces, and deployment reliability.

Technology State of the Art: Early developmental. Current focus is component maturation. Currently working "high risk" areas, such as woven carbon cloth (TPS/aero loaded structure), and the cloth/sub-structure interface.

Parameter, Value:

2m ground test article.

Carbon fabric tested peak heating: 200W/cm^2

Heat load: 20kJ/cm^2

TRL 3

Technology Performance Goal:

1. Robotic: deliver payloads > 1 t to Venus and Mars.
2. Human Mars exploration: deliver 20-40 t to Mars.

Parameter, Value:

Robotic:

Heating: 250-500 W/cm^2

Payload: 1000 kg

Deployed diameter: up to 8m

Deceleration: 30 g

Human Mars Exploration:

Heating: 250 W/cm^2

Payload: 40,000 kg

Deployed diameter: 20-25m

Deceleration: 3 g

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: 9.1.2.3 Flexible Thermostructural TPS

CAPABILITY

Needed Capability: Hypersonic deceleration.

Capability Description: Provides hypersonic deceleration.

Capability State of the Art: Pioneer Venus rigid aeroshell.

Parameter, Value:

~5000 W/cm^2

4-6 atm pressure

0.76-1.42 m diameter

200 g deceleration

Capability Performance Goal: Increase the payload mass of entry systems, reduce g-loads, and enable higher elevation landing sites.

Parameter, Value:

~5000 W/cm^2

4-6 atm pressure

Payload up to 40,000 kg

30 g deceleration

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.3 Transformable or Morphable Entry Systems

TECHNOLOGY

Technology Description: Enable a vehicle to change shape or configuration to achieve additional functions during entry, descent, and landing, such as providing direct alpha and beta control or direct ballistic number control.

Technology Challenge: Challenges include aerothermal augmentation, structural integrity, flowfield instability, and control mechanics.

Technology State of the Art: No entry system, rigid or deployable, has controlled the flight trajectory via outer mold line (OML) morphing. Current focus is on simulation and modeling to determine feasiblilty.

Parameter, Value: Early developmental; none exists.

TRL: 1

Technology Performance Goal: Full vehicle control via shape change.

Parameter, Value: For the case of a 23 m deployed decelerator, the ability to deflect localized OML ~0.5m.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Transformable or morphable entry systems.

Capability Description: Enable a vehicle to change shape or configuration to achieve additional functions during entry, descent, and landing.

Capability State of the Art: Current deployable control limited to center of gravity (CG) modulation, as demonstrated on Inflatable Reentry Vehicle Experiment 3 (IRVE-3).

Parameter, Value: Single degree of freedom (DOF) CG modulation to examine flight handling characteristics.

Capability Performance Goal: Full deployed aeroshell morphing to achieve L/D and bank angle acceleration requirements to meet the needs of controlling the flight trajectory.

Parameter, Value: Lift/drag (L/D): ~.15-0.20 and delta-L/D acceleration of 0.005-0.008/s^2. Drag modulation of ~10:1 or larger drag ratio (if no lift modulation).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: New Frontiers 5	Enhancing	--	2029	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.4 Flexible Structural Materials

TECHNOLOGY

Technology Description: Provides flexible structures that can reduce structural mass over SOA. Upon deployment, the flexible materials provide the load-bearing aeroshell structure. See the technology roadmap for TA 12, Materials, Structures, Mechanical Systems, and Manufacturing.

Technology Challenge: Challenges include manufacturing process control and the mechanical performance of material at temperature.

Technology State of the Art: Hypersonic Inflatable Aerodynamic Decelerator (HIAD) developing and ground testing new inflatable material system: Zylon over a Teflon bladder. Adaptable, deployable entry and placement technology (ADEPT) developing high-temperature structural/TPS membrane: carbon fiber weave for operation temperature in excess of 1500° C.

Parameter, Value:

Operational temperature up to 250-300° C.

TRL

5

Technology Performance Goal: Increased operation temperature of inflatable structures for HIAD and scale of both inflatable and mechanical deployable systems.

Parameter, Value:

Operational temperature: up to 400° C for HIAD.

Scale: up to 20-25 m.

TRL

4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flexible structural materials.

Capability Description: Advanced high-temperature flexible structural materials, including bladders, ribs, and rigidizable concepts that can reduce structural mass over SOA. Upon deployment, the flexible materials provide the load-bearing aeroshell structure.

Capability State of the Art: Inflatable Reentry Vehicle Experiment (IRVE) 3: Kevlar fiber/silicone matrix with a silicon bladder inflated to 20 psi. Upon inflation, the flexible material acted as a rigid aeroshell.

Parameter, Value:

Operational temperature up to 250-300° C.

Capability Performance Goal: Need elevated operating temperatures to minimize thermal protection system (TPS) and hence system mass.

Parameter, Value:

Operational temperature; up to 400°C.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.5 Non-Propulsive Flight Control Effectors

TECHNOLOGY

Technology Description: Provides non-propulsive flight control effectors, including control surfaces and active modulation, which facilitate potential system flexibility.

Technology Challenge: Challenges include mechanical complexity, payload translation/rotation acceleration and rates; flaps on deployable structures; large-range drag modulation; deployable/inflatable system mass and volume with lift vector control system; multi-heat pulse aeroshell capability for aerocapture and entry; separation system for payload from deployable aeroshell; and supersonic retropropulsion control.

Technology State of the Art: Inflatable Reentry Vehicle Experiment (IRVE) 3 flight test of center of gravity (CG) movement to investigate vehicle response. Other methods have been demonstrated for lift and should be plausible for depoyables. Rotation of payload about two axis currently being developed by Adaptable, Deployable Entry and Placement Technology (ADEPT).

Parameter, Value:

Single-axis CG modulation.

TRL

4

Technology Performance Goal: Full lift vector control via payload modulation and/or active control system (ACS)/flap control to allow complete bank and/or angle of attack and/or sideslip angle modulation for vehicle trajectory control. Can also allow full drag modulation control, which can acheive the performance parameters necessary for aerocapture and/or entry.

Parameter, Value:

2-degree of freedom (DOF) mass CG control (rotation or translation of payload relative to aeroshell) or flap control to modulate alpha/beta.

Enabled with 2-DOF:

Lift/drag (L/D): ~.15-0.20 and delta-L/D acceleration of 0.005-0.008/s^2

Drag modulation of ~10:1 or larger drag ratio (if no lift modulation).

Traditional capsule:

L/D: .25-.30, with bank angle acceleration: 3-5°/s^2.

TRL

3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-propulsive flight control effectors.

Capability Description: Provides non-propulsive flight control effectors, including control surfaces and active CG modulation, which facilitate potential system flexibility.

Capability State of the Art: IRVE-3 single axis payload CG offset. Laterally shifted the aft portion of the centerbody, which fixed the lift vector in order to measure the effect on trajectory. Employed active control system (ACS) to dampen roll motion only. No bank or alpha/beta modulation has been tested.

Parameter, Value:

CG offset to affect L/D of at least 0.12.

Capability Performance Goal: The ability to control the trajectory of the vehicle, thus allowing higher precision landing or aeroassist/aerocapture maneuvers. Nominally CG offset should affect L/D > 0.3.

Parameter, Value:

Guidance: 3 g's nominal; 5-g's 3-sigma (for human, human system integration requirements (HSIR) constraints should be used); 5% of propulsive orbit insertion value, for 3-sigma delta-V for post-aerocapture orbit adjust; 50 m 3-sigma landing accuracy; 2 km clearance around ground assets from any jettisoned components.

Navigation: 0.1 deg 3-sigma entry flight path angle from nominal at Mars entry.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	6 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.6 Advanced Guidance and Navigation Systems

TECHNOLOGY

Technology Description: Provides advanced guidance and navigation systems that are adapted to deployable system controllers. Aerocapture and subsequent entry and landing are addressed. (See also 9.1.3.7 Entry Guidance Software).

Technology Challenge: Challenges with guidance include achieving desired performance with lower lift/drag (L/D) and lower L/D modulation capability than typical capsules used for guided flight. Challenges with navigation include achieving autonomous or onboard accurate approach navigation, achieving precise landing with hazard avoidance and miniaturizing autonomous landing and hazard avoidance technology (ALHAT) system components. Improved attitude initialization error prior to entry will provide improved dispersions at supersonic phase initiation.

Technology State of the Art: Guidance: analytical.

Navigation: Delta-differential one-way ranging (DOR) for approach.

Parameter, Value:

Mars Science Laboratory (MSL) precision; ~4 x 10 km ellipse.

TRL

2

Technology Performance Goal: Guidance: 1. Aerocapture: minimize the propulsive delta-V required to attain the desired orbit while not exceeding any vehicle or crew constraints. 2. Entry and terminal descent: achieve a safe, precise landing without violating any vehicle, ground assets, or crew constraints.

Navigation: 1. Planetary approach: autonomous navigation or onboard navigation, which achieves desired planetary approach accuracy. 2. Descent: precise terrain relative navigation and hazard avoidance.

Parameter, Value:

Guidance: 3 g's nominal; 5 g's 3-sigma (for human, human system integration requirements (HSIR) constraints should be used); 110% of nominal for 3-sigma delta-V for post-aerocapture orbit adjust; 100 m 3-sigma landing accuracy; 2 km clearance around ground assets from any jettisoned components.

Navigation: 0.1 deg 3-sigma entry flight path angle from nominal at Mars entry; 100 m 3-sigma landing accuracy.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced guidance and navigation systems.

Capability Description: Provides advanced guidance and navigation systems that are adapted to deployable system controllers. Aerocapture and subsequent entry and landing are addressed.

Capability State of the Art: Guidance: Analytic predictor correctors and analytic reference trajectory methods that use bank angle modulation (lift vector control) for both downrange and crossrange (MSL). L/D for typical deployable decelerator designs are ~0.2-0.35. Simulations show that these currently-used guidance systems perform well for deployable decelerators, assuming 3-5 deg/s^2 of bank acceleration and L/D ~0.25-0.3 (typical capsule performance).

Navigation: Approach navigation (Delta DOR) as demonstrated by MSL. Terminal navigation for precision landing and hazard avoidance as demonstrated by ALHAT.

Parameter, Value:

Guidance: Guidance is used to control trajectory loads, heating, and targeting accuracy parameters. The desired parameter values are dependent on environment and application. Currently, the deployable decelerators provide adequate performance in simulations assuming rigid body (capsule-like) stability, control, and L/D.

Navigation: Mars entry flight path with 0.1 deg. ALHAT landing accuracy knowledge within 100 meters.

Capability Performance Goal: Overall, vehicles should be designed with enough control authority (L/D and maneuvering capability) to fly out atmospheric and aerodynamic dispersions, limit g-loads as necessary for humans and other payloads, and land precisely to minimize operations time and cost. Aerocapture should achieve > 95% of the required delta-V aerodynamically.

Parameter, Value:

Landing precision: 100 m.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

9.1 Aeroassist and Atmospheric Entry
9.1.4 Deployable Hypersonic Decelerators

9.1.4.7 On-Orbit Assembled Entry Systems

TECHNOLOGY

Technology Description: Makes use of in-space assembly to create a vehicle that might not otherwise be launched without complex, automated deployment systems. Can potentially lead to low-cost re-entry systems, as well as re-entry vehicle and upper atmosphere research. Also includes in-situ manufacturing.

Technology Challenge: Challenges include thermal protection system (TPS) seams, mass fraction, and validation.

Technology State of the Art: Low-Technology Readiness Level report on in-situ manufacturing, NASA studies for assembly. Simulation studies and arc jet teseting of regolith-based heat shield produced by in-space fabrication.

Parameter, Value:	TRL
Arc jet heating to 92 W/cm^2. Displaying sufficient thermal protection on rear surface.	1

Technology Performance Goal: Reduce the launch mass required for large entry, descent, and landing (EDL) payloads by taking advantage of on-orbit assembled systems or space-manufactured structures/systems.

Parameter, Value:	TRL
Launch-to-download payload mass ratio improved over other large decelerator choices. Maximum Mars payload: 40 t.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Deployable hypersonic decelerators.

Capability Description: Provides deceleration and protection from heating, as well as aero loads during hypersonic entry.

Capability State of the Art: No current use of in-space assembled systems. All current entry systems are launched intact. Other than Inflatable Reentry Vehicle Experiment tests, they are constrained to launch vehicle shroud sizes.

Parameter, Value:

Mars Science Laboratory, 4.5 m diameter, 200 W/cm^2 heat flux capability

Capability Performance Goal: Large, mass-efficient, reliable deceleration.

Parameter, Value:

Diameter: 20-25m

Heat flux capability: 100 W/cm^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Push	Enhancing	--	--	--	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years

9.2 Descent and Targeting
9.2.1 Attached Deployable Decelerators

9.2.1.1 Supersonic Inflatable Aerodynamic Decelerator (SIAD)

TECHNOLOGY

Technology Description: An inflatable, deployable decelerator that provides aerodynamic (drag, lift/drag (L/D), or stability) augmentation in the high supersonic Mach number range (2-5+) for higher altitude deceleration, increased timeline, and staging.

Technology Challenge: Challenges include end-to-end testing and reliability.

Technology State of the Art: NASA flight test of 6 meter SIAD at Mach 4 in June 2014.

Parameter, Value:

Diameter: 6 m.

TRL 5

Technology Performance Goal: Larger devices in the range of 8 - 12m+ diameter.

Parameter, Value:

Diameter: 8 -12 m

C_D: > 1.0

TRL 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Aerodynamic deceleration through the supersonic flight regime.

Capability Description: Provides aerodynamic (drag, L/D, or stability) augmentation in the high supersonic Mach number range (2-5+) for higher altitude deceleration, increased timeline, and staging.

Capability State of the Art: Munitions deceleration and stabilization at supersonic Mach numbers.

Parameter, Value:

Diameter: ~ 1m.

Capability Performance Goal: Larger devices in the range of 8 - 12m+ diameter.

Parameter, Value:

Diameter: 8 -12 m

C_D: > 1.0

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.1 Attached Deployable Decelerators

9.2.1.2 Mechanically Deployed Decelerators and Methods of Active Control

TECHNOLOGY

Technology Description: Provide descent deceleration using rigid, actuated deployable decelerators with or without a rigid skeleton and textile membrane.

Technology Challenge: Challenges include testing, modeling, and validating the technology.

Technology State of the Art: Adaptable, Deployable Entry and Placement Technology (ADEPT) represents the SOA, which includes conceptual studies, system design, benchtop component prototypes, and aerothermal materials testing.

Parameter, Value: 2 meter, not actuated, deployed in laboratory.

TRL 2

Technology Performance Goal: Provide reliable, lightweight, rigid deployable decelerators with active control allowing guided entry.

Parameter, Value: Human Mars: 40 t landed payload.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reliable, lightweight, high-drag decelerator.

Capability Description: Requirement for lightweight drag device that can be stowed in a launch faring and deployed to significantly increase drag area and reduce entry, descent, and landing (EDL) system mass fraction.

Capability State of the Art: No current use, low Technology Readiness Level; proposed for large-scale Mars landers (10-40 t).

Parameter, Value: None exists.

Capability Performance Goal: Current Design Reference Architectures (DRAs) require as much as 40 t payload mass delivery.

Parameter, Value: 40 t landed payload mass.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.1 Attached Deployable Decelerators

9.2.1.3 Steerable and Guided Deployable Decelerators

TECHNOLOGY

Technology Description: Allow control of a drag device to a precise landing location.

Technology Challenge: Challenges include testing, modeling, and validating large, possibly flexible systems undergoing fluid-structure interaction.

Technology State of the Art: Technology currently exists as a conceptual design.

Parameter, Value:	TRL
None exists	2

Technology Performance Goal: Provide reliable, lightweight, deployable decelerators with active control allowing guided entry.

Parameter, Value:	TRL
Bank angle rate of 20°/s and bank angle acceleration 5°/s^2	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Precision landing with deployable decelerators.

Capability Description: Enable landing payloads successfully within 100 m footprint.

Capability State of the Art: Subsonically-dropped payloads, landing tests (1990s), and recreational parafoils. Military airdrop < 100m precision on Earth.

Parameter, Value:
Pinpoint landing achievable on Earth from aircraft altitudes.

Capability Performance Goal: Human Mars: landing footprint < 100 m.

Parameter, Value:
Footprint: < 100 m.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	7 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.1 Attached Deployable Decelerators

9.2.1.4 Dual-Mode Attached Decelerator Systems

TECHNOLOGY

Technology Description: A decelerator that deploys supersonically, then could operate through the subsonic regime, perhaps by changing shape or attachment geometry (for example, an attached isotensoid that when cutaway becomes a parachute).

Technology Challenge: Challenges include testing, modeling, and validating large, possibly felxible systems undergoing fluid-structure interaction.

Technology State of the Art: Largely conceptual studies, including Adaptable, Deployable Entry and Placement Technology (ADEPT) landing leg concept ("test" concept).

Parameter, Value: None exists.

TRL: 2

Technology Performance Goal: Robust flight through multiple flight regimes with a single system.

Parameter, Value: Entry, descent, and landing (EDL) system mass fraction: < 30%.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Dual mode attached decelerator systems.

Capability Description: Dual mode attached decelerator systems that are optimized for supersonic and subsonic flight.

Capability State of the Art: None exists.

Parameter, Value: None exists.

Capability Performance Goal: Robust flight through multiple flight regimes with a single system.

Parameter, Value: EDL mass fraction: < 30%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	7 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.2 Trailing Deployable Decelerators

9.2.2.1 Supersonic Parachutes

TECHNOLOGY

Technology Description: Provides more capable supersonic parachutes and large subsonic and supersonic parachutes for low-density use, including multi-stage reefing.

Technology Challenge: Challenges include validating system performance.

Technology State of the Art: Mars Science Laboratory (MSL) 21.5 m supersonic disk gap band (DGB) parachute is the SOA. NASA is maturing a 30.5 m supersonic parachute for Mach ~2.5.

Parameter, Value: 21.5 m, Mach 2.1, no reefing, single chute (actual deploy at Mach 1.75).

TRL: 9

Technology Performance Goal: Larger nominal diameter, higher Mach at deploy, supersonic reefing and clustering, improved drag area/mass.

Parameter, Value: > 30 m, Mach 2.5+, > 50% load reduction via reefing, clustering to 3+ chutes.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Supersonic parachutes for deceleration at Mars, Venus, and other Solar System bodies.

Capability Description: Provides low-mass supersonic deceleration at Solar System bodies with significant atmospheres.

Capability State of the Art: MSL disk-gap-band parachute.

Parameter, Value: Nominal diameter: 21.5 m (supersonic).

Capability Performance Goal: Improve Mars landed mass, altitude. Enable landed missions at Venus.

Parameter, Value: Landed mass, 2x MSL; altitude, > -2 km Mars Orbiter Laser Altimeter (MOLA).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.2 Trailing Deployable Decelerators

9.2.2.2 Trailing Inflatable Aerodynamic Decelerators (Ballutes)

TECHNOLOGY

Technology Description: Provides a drag-only method of deceleration that trails the main vehicle for easy release. Also allows pilot to deploy large parachutes.

Technology Challenge: Challenges include manufacturing, system-level testing, modeling, and the ability to control the system.

Technology State of the Art: NASA successfully demonstrated a 4.4 m ballute for use as a supersonic pilot device at Mach 2.7; has also been studied in the hypersonic regime for aerocapture.		**Technology Performance Goal:** Larger diameter; higher Mach deployment for larger payloads, Mars deceleration.	
Parameter, Value:	**TRL**	**Parameter, Value:**	**TRL**
Diameter: 4.4 m Speed: Mach 10	4	Diameter: 5 m+ Speed: Mach 3+	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Trailing decelerators.

Capability Description: Provides a drag-only method of deceleration that trails the main vehicle for easy release.

Capability State of the Art: Limited current use on Earth; successfully deployed ballutes ~5 ft in diameter at Mach numbers of up to 9.7	**Capability Performance Goal:** Higher deceleration in the descent regime.
Parameter, Value:	**Parameter, Value:**
Diameter: 5 ft Deploy Mach: 10	Diameter: 5 m+ Speed: Mach 3+

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	5 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.2 Trailing Deployable Decelerators

9.2.2.3 Autonomous Parachute Disreef

TECHNOLOGY

Technology Description: Provides informed disreef command to a parachute based on vehicle state.

Technology Challenge: Challenges include demonstrating the required reliability in a system that cannot be modeled effectively and the need to conduct repeated tests.

Technology State of the Art: Chemical pyro cutters based on timers; parachute deploy imparts undesired loads to vehicle if not in nominal attitude.

Parameter, Value:
Reliability: 99+% for Earth-based subsonic disreef.

TRL 3

Technology Performance Goal: Provide disreef based on vehicle state with high reliability.

Parameter, Value:
Reliability: 99+% on autonomous system.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Staging mechanisms or systems for phased drag deployment.

Capability Description: Provide methods to deploy drag devices in a controlled manner.

Capability State of the Art: Chemical pyros based on timers. Industry has a patent on wireless system, tested once in a helicopter drop test.

Parameter, Value:
Reliability; not yet established.

Capability Performance Goal: Provide drag device deployment based on vehicle state with 99+% reliability.

Parameter, Value:
Reliability: 99+%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	4 years

9.2 Descent and Targeting
9.2.2 Trailing Deployable Decelerators

9.2.2.4 Lightweight, High-Strength Broadcloth (Scrim)

TECHNOLOGY

Technology Description: Develop multi-directional, laminated, lightweight, high-strength material for supersonic and subsonic parachutes for mass efficiency.

Technology Challenge: Challenges include manufacturing and joining the material, fabric crimp, and packing.

Technology State of the Art		Technology Performance Goal	
Technology State of the Art: Orion Capsule Parachute Assembly System (CPAS) nylon broadcloth.		**Technology Performance Goal:** Higher strength-to-weight ratio than conventional parachute material.	
Parameter, Value:	**TRL**	**Parameter, Value:**	**TRL**
1.1 oz/yd^2	6	0.7-0.9 oz/yd^2	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Supersonic parachutes for Mars deceleration.

Capability Description: Provide decelerator mass and volume savings for planetary deceleration, particularly Earth and Mars.

Capability State of the Art: Orion parachutes (CPAS), a polyconical design, quarter spherical ringsail; also Mars Science Laboratory (MSL) parachute, 21.5 m disk-gap-band.

Parameter, Value:

CPAS parachute diameter: 116 ft

CPAS maximum dynamic pressure: ~55 psf

Capability Performance Goal: Lower packing volume, larger main parachutes, direct deployment of main parachutes, and reduced overall mass of the parachute system.

Parameter, Value:

Earth subsonic parachute diameter: > 116 ft

Earth subsonic maximum dynamic pressure: > 55 psf

Reduce volume by 10-20%

Reduce mass by > 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	4 years

9.2 Descent and Targeting
9.2.3 Supersonic Retropropulsion

9.2.3.1 Advanced Algorithms and Sensors for Supersonic Retropropulsion (SRP)

TECHNOLOGY

Technology Description: Control and stabilize entry vehicles in the presence of complex fluid dynamic interactions.

Technology Challenge: The potential for destabilizing forces and torques on vehicle due to rocket plume interaction with flow field during supersonic retropropulsion, particularly at engine start, may require advanced attitude control sensors and algorithms.

Technology State of the Art: 3 degree of freedom (DOF) trajectory simulations of human-scale SRP descent at Mars. Re-light of Falcon 9 first stage provides technology demonstration of vehicle control while undergoing SRP.

Parameter, Value: No current documented values with assessment of scalability to Mars.

TRL: 3

Technology Performance Goal: Acceptable vehicle attitude control during SRP engine ignition and throttle up, and through transonic flight to subsonic powered descent.

Parameter, Value: Attitude rate (per axis): < 10°/s

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced algorithms and sensors.

Capability Description: Control and stabilize entry vehicles in the presence of complex fluid dynamic interactions.

Capability State of the Art: Falcon 9 first stage SRP at Earth.

Parameter, Value: Falcon 9 first stage appears to fly in a stable manner; no specific value determined at this time.

Capability Performance Goal: Acceptable vehicle attitude control during SRP engine ignition and throttle up, and through transonic flight to subsonic powered descent. Provides acceptable attitude behavior for terrain relative navigation (TRN) and hazard detection and avoidance (HDA) sensing.

Parameter, Value: Attitude rate (per axis): < 10°/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years

9.2 Descent and Targeting
9.2.3 Supersonic Retropropulsion

9.2.3.2 Deep-Throttling, High Thrust Engines for Mars Descent

TECHNOLOGY

Technology Description: Provides both supersonic retropropulsion (SRP) and terminal descent and touchdown thrust requirements (see also TA 2.1.2, Liquid Cryogenics).

Technology Challenge: Challenges include scaling up and testing in a relevant environment over a range of operating conditions.

Technology State of the Art: Engine/tank conceptual design for human-scale Mars entry, descent, and landing (EDL) systems. Commercial demonstration of Earth-based SRP via Falcon 9 first stage re-light with unknown throttling capability. 10:1 throttling demonstrated with the Propulsion and Cryogenics Advanced Development (PCAD) Deep Throttle Engine Project with a 18,000lbf liquid oxygen/liquid hydrogen engine. Apollo Lunar Module Descent Engine used bipropellant hypergolic propellants; Mars Terminal Descent retro-thrusters are steady-state as in Mars Science Laboratory (MSL) mission.

Parameter, Value:

No current documented value.

TRL

2

Technology Performance Goal: Deep throttling for landing large payloads at maximum fuel efficiency.

Parameter, Value:

Throttling: 10:1

Thrust: 100s of kN

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Engines for Mars descent; possibly of shared design required for Mars ascent, and possibly of shared design for lunar descent.

Capability Description: Provides both SRP and terminal descent/touchdown thrust requirements.

Capability State of the Art: Falcon 9 first stage re-light is only demonstrated SRP capability. Demonstrated throttling level is unknown at this time. MSL Sky Crane (1 t landed) is SOA for Mars.

Parameter, Value:

Mars Lander engine thrust: 3 kN

Throttle: 400:3060 N

Capability Performance Goal: Safe landing of 40 mt payloads on Mars.

Parameter, Value:

Throttle range: 10-100% for human missions, 5-100% for robotic (could be achieved at the system level by turning off engines).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years

9.2 Descent and Targeting
9.2.6 Large Divert Guidance

9.2.6.1 Convex Optimization Problem Solving

TECHNOLOGY

Technology Description: Research into computationally-efficient methods of solving convex optimization problems. These methods are used for real-time solving of the fuel-optimal solution for large diverts.

Technology Challenge: Challenges include developing methods to solve convex optimizations, which are executable on flight-class computational environments.

Technology State of the Art: Demonstrated in small-scale rocket free-flyers in the Autonomous Descent and Ascent Powered-flight Testbed (ADAPT) program.

Parameter, Value:

Divert 800 m

Solve < 0.3 s

TRL 5

Technology Performance Goal: Develop guidance algorithms that can divert a distance at least twice the height at powered descent start, while respecting all spacecraft constraints and minimizing fuel, and that can run in a space-qualified processor in less than in 0.1 s.

Parameter, Value:

Divert 1-10 km

Solve < 0.1 s

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fuel-optimal divert for pinpoint landing.

Capability Description: Quickly and robustly find a constrained, optimal divert during powered descent for hazard avoidance and pinpoint landing next to surface assets and science targets.

Capability State of the Art: No large divert capability currently exists. Previous small divert capability demonstrated by Apollo/MSL polynomial guidance and Viking/Phoenix gravity turn.

Parameter, Value:

Mars Science Laboratory (MSL) 300 meter divert starting powered descent at 1600 meters.

Capability Performance Goal: Solve a guidance trajectory in flight environment in < 0.1 s, resulting in 1-10 km divert with landing accuracy within 100 m.

Parameter, Value:

Divert 1-10 km

Solve < 0.1 s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.6 Large Divert Guidance

9.2.6.2 Guidance for Large Divert on Flight Computer

TECHNOLOGY

Technology Description: Demonstrate large divert guidance algorithm running on a flight testbed, such as the Mars Science Laboratory (MSL) testbed. This will demonstrate the algorithms operating in a flight-identical computational environment.

Technology Challenge: Challenges include testing in relevant computational environment.

Technology State of the Art: Demonstrated in small-scale rocket free-flyers in the Autonomous Descent and Ascent Powered-flight Testbed (ADAPT) program.

Parameter, Value:
Divert 800 m
Solve < 0.3 s

TRL
5

Technology Performance Goal: Demonstrate operating in flight-identical computer in flight-identical computational environment.

Parameter, Value:
Divert 1-10 km
Solve < ~0.1 s

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fuel-optimal divert for pinpoint landing.

Capability Description: Quickly and robustly find a constrained, optimal divert during powered descent for hazard avoidance and pinpoint landing next to surface assets and science targets.

Capability State of the Art: No large divert capability currently exists. Past divert capability problem-solving was provided by human-in-the-loop (Apollo). MSL backshell avoidance divert is the largest current divert capability demonstrated.

Parameter, Value:
Divert size: 300 m
Solution time: < 0.1 s

Capability Performance Goal: Demonstrate operating in flight-identical computer in flight-identical computational environment.

Parameter, Value:
Divert 1-10 km
Solve < 0.1 s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.6 Large Divert Guidance

9.2.6.3 Guidance for Large Divert Flight Testbed

TECHNOLOGY

Technology Description: Demonstrate large divert guidance operating on a free-flying vehicle in flight-like conditions, performing flight-scale diverts.

Technology Challenge: Challenges include executing a flight test in flight-like conditions and at flight scale diverts.

Technology State of the Art: Demonstrated in small-scale rocket free-flyers in the Autonomous Descent and Ascent Powered-flight Testbed (ADAPT) program.

Parameter, Value:
Divert: 800 m

TRL: 5

Technology Performance Goal: Demonstrate operating in flight-identical computer in flight-identical computational environment.

Parameter, Value:
Divert: 1-10 km

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Testbed to demonstrate fuel-optimal divert for pinpoint landing.

Capability Description: Quickly and robustly find a constrained, optimal divert during powered descent for hazard avoidance and pinpoint landing next to surface assets and science targets.

Capability State of the Art: Demonstrated in small-scale rocket free-flyer testbeds, including ADAPT.

Parameter, Value:
Divert: 600 - 800 m

Capability Performance Goal: Demonstrate operating in flight-like conditions in flight-scale diverts.

Parameter, Value:
Divert: 1-10 km

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2019	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.7 Terrain Relative Sensing and Characterization

9.2.7.1 Advanced Sensors for Spacecraft Velocimetry and Altimetry

TECHNOLOGY

Technology Description: Provide low-cost, long-range, high-precision, high-rate measurements of spacecraft altitude and three-dimensional (3D) velocity to improve navigation accuracy and vehicle control performance. Precise knowledge of altitude and velocity can also be used to trigger events, such as backshell separation and parachute deployment, which help reduce landing site dispersion.

Technology Challenge: Challenges include reducing volume, mass, and power while improving performance (such as maximum operating range), as well as qualifying sensors in space.

Technology State of the Art: Terminal Descent System (TDS), Autonomous Landing and Hazard Avoidance Technology (ALHAT) Doppler LIDAR, ALHAT Laser Altimeter.

Parameter, Value:

25 kg (Mars Science Laboratory (MSL) TDS)
30 W (MSL TDS)
~$35M recurring cost (MSL TDS)
32 kg (ALHAT Doppler LIDAR (DL))
145 W (ALHAT DL)
11 kg (ALHAT laser altimeter (LA))
70 W (ALHAT LA)

TRL 5

Technology Performance Goal: Sensor technology that will enable any spacecraft to land anywhere.

Parameter, Value:

Mass: 1kg
Power: 10W
Recurring cost: < $5M

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Accuracy (cm/s/cm-level), range (6km), insensitivity to dust.

Capability Description: The sensor needs to initiate landing events, such as deployment of parachute. Also, the sensor suite is needed to land with insignificant horizontal velocity.

Capability State of the Art: Current capability is the TDS system for the MSL mission or the ALHAT technology demonstrated on the Morpheus vehicle.

Parameter, Value:

TDS (10 km range with 2% range accuracy, 0.2 m/s + 0.75% magnitude velocity accuracy), ALHAT DL (3000 m range, 10 cm range accuracy, 0.2 cm/s velocity accuracy).

TDS (25 kg, 100W, ~1 m x 0.2 m x 0.2 m volume).

Capability Performance Goal: High maximum operating range with accurate range and velocity performance with low mass, volume, and power.

Parameter, Value:

6 km range, 2% range accuracy, 2 cm/sec + 0.75% of spacecraft velocity accuracy, and a recurring cost of < $5M.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.7 Terrain Relative Sensing and Characterization

9.2.7.2 Advanced Sensors for Real-Time Three-Dimensional (3D) Terrain Mapping

TECHNOLOGY

Technology Description: Provide high-rate, high-precision 3D measurements of the terrain shape for onboard map creation and hazard detection.

Technology Challenge: Challenges include mass, power, accuracy, maximum operating range, and space qualification. Additionally, there is a need for compact lasers with more powerful pulses than are currently available, as well as advanced Readout Integrated Circuits (ROICs).

Technology State of the Art: Scanning/Flash LIDAR, stereo vision, phased array radar.

Parameter, Value:	TRL
Mass: 10 kg Power: 30 W	5

Technology Performance Goal: Light-weight, low-power sensor able to generate high-resolution 3D maps from orbit under all weather/lighting conditions.

Parameter, Value:	TRL
Mass: 10 kg Power: 30 W	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: 2cm 3-sigma intra-image precision and adjustable resolution as a function of range (e.g., 1million pixels per sec @ 100 meters), 0.1 million pixels per sec @ 1000 meters, and 100 pixels per sec @ 10 km.

Capability Description: The sensor needs to be able to identify safe landing spots on the surface.

Capability State of the Art: An example of SOA is Autonomous Landing and Hazard Avoidance Technology (ALHAT) technology, Sensor Test for Orion Relative-Navigation Risk Mitigation (STORRM) LIDAR.

Parameter, Value:

ALHAT Flash LIDAR 128x128 pixel, 20 Hz, 8cm 1-sigma, at 1500m.

Capability Performance Goal: Deep-space qualified instruments with characteristics suitable for Discovery class and performance to support Comet Surface Sample Return (CSSR), Asteroid Redirect Robotic Mission (ARRM), and human Mars pinpoint landing.

Parameter, Value:

512 x 512 pixels, 50 Hz, < = 5cm 1-sigma at > 2500 m.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	3 years
New Frontiers: New Frontiers Program 4 (NF4/~2017 AO Release)	Enhancing	--	2024	2016	2 years
New Frontiers: New Frontiers 5 (NF5 / ~2022 AO Release)	Enhancing	--	2029	2021	4 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.7 Terrain Relative Sensing and Characterization

9.2.7.3 Advanced Sensors for Terrain Imaging and Surface and Subsurface Characterization

TECHNOLOGY

Technology Description: Provide data for localization, science target identification, or hazard detection at different wavelengths.

Technology Challenge: Challenges include range, resolution, shutter speed/image transfer rate, field of field, and distortion.

Technology State of the Art: Mars Descent Imager (MARDI) instrument on Mars Science Laboratory (MSL).

Parameter, Value:	TRL
70° x 55° FOV ~4 frames per second 50-80:1 nominal SNR	9

Technology Performance Goal: Wide field of view, high resolution, low noise, fast transfer time.

Parameter, Value:	TRL
90° field of view (FOV) < 30 ms transfer time High signal-to-noise ratio (SNR)	4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Large FOV, low-noise, high-rate, low-distortion sensors.

Capability Description: Large FOV, low-noise, high-rate, low-distortion sensors will enable imaging/characterization in support of localization, hazard detection and avoidance, and autonomous science target detection.

Capability State of the Art: MARDI instrument on MSL.

Parameter, Value:
1600x1200 pixel, 3.8 frames/s, 70° x 55° FOV, visible spectrum.

Capability Performance Goal: Wide field of view, high resolution, low noise, fast transfer time.

Parameter, Value:
90° FOV, < 30 ms transfer time, high SNR.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enabling	--	2020	2017	2 years

9.2 Descent and Targeting
9.2.7 Terrain Relative Sensing and Characterization

9.2.7.4 High-Fidelity Sensor Modeling and Simulation Tools

TECHNOLOGY

Technology Description: Provide advanced, integrated models and simulation tools for active and passive terrain sensors, including effects of dust and plume interactions.

Technology Challenge: Challenges include integrating complex optical, radio-frequency, thermal, mechanical, and atmospheric models and adapting and implementing them for high-fidelity and real-time simulations.

Technology State of the Art: Mars Science Laboratory (MSL) Terminal Descent System (TDS) physics-based models, dust accumulation modeling for small body navigation.

Parameter, Value:	**TRL**
MSL TDS Sulcata tool (specific to MSL TDS application).	9

Technology Performance Goal: High-fidelity simulations of sensor performance close to the surface when retro rockets blow up dust.

Parameter, Value:	**TRL**
Ability to generate simulated return from radar or LIDAR altimeter / velocimeter, or images looking though exhaust plume and blown up dust with intensity accuracy better than 1%.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-fidelity physics-based models for non-TDS (ka-band) frequency, dust, plume interaction models.

Capability Description: Ability to generate simulated images looking though exhaust plume and airborne dust.

Capability State of the Art: Ability to generate Mars images with high-rise camera. However, images does not include rocket plume or blown up dust. Dust accumulation on sensor for asteroid navigation under performance-based navigation (PBN).

Parameter, Value:

No current value.

Capability Performance Goal: Generation of images with intensity accuracy better than 1%.

Parameter, Value:

Pixel intensity better than 1%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enabling	--	2020	2017	3 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enhancing	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.1 Terrain/Map Absolute Localization

TECHNOLOGY

Technology Description: Enables pinpoint and multi-point landing with < 100 m position error relative to an onboard map generated from a priori sensing data.

Technology Challenge: Challenges include developing robust algorithms for performing map matching in a range of potential environmental and vehicle conditions (e.g. terrain types, season, dust, illumination, vehicle dynamics, etc.).

Technology State of the Art: Lander Vision System (LVS) and Descent Image Motion Estimation System (DIMES) (Mars Exploration Rover, or MER) use passive imagery to allow feature-relative navigation. LVS terrestrial field testing has demonstrated map localization over a wide range of Mars-like terrain.

Parameter, Value:

Position accuracy: 40 m (3 sigma)

Solution time: 10 s

Probability of solution: 99%

TRL 5

Technology Performance Goal: Demonstrated localization over wide range of terrain types, sensing conditions, etc.

Parameter, Value:

Position accuracy: 20 m (3 sigma)

Solution time: 1 s

Probability of solution: > 99%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ability to determine absolute location of the spacecraft in a small body (asteroid, comet) fixed frame with an accuracy of better than 10m 3-sigma under variable illumination conditions; small body size and shape; and robust to a dusty atmosphere.

Capability Description: Localize vehicle position relative to an onboard map in a variety of potential vehicle and environmental conditions.

Capability State of the Art: None

Parameter, Value:

None exists.

Capability Performance Goal: Demonstrated localization over wide range of terrain types, sensing conditions, etc.

Parameter, Value:

Position accuracy: 20 m (3 sigma)

Solution time: 1 s

Probability of solution: > 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enabling	--	2020	2017	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.2 Terrain/Terrain Relative Location

TECHNOLOGY

Technology Description: Enables terrain feature identification and tracking using passive and/or active imaging for navigation and targeting purposes.

Technology Challenge: Challenges include identifying terrain features during descent using a variety of potential sensors and tracking the features from sensor measurement to sensor measurement. Features may vary widely in size, contrast, etc.

Technology State of the Art: Autonomous Landing and Hazard Avoidance Technology (ALHAT), Descent Image Motion Estimation System (DIMES), and Lander Vision System (LVS) have demonstrated some amount of success in feature tracking.

Parameter, Value:

Number of features identified: ~100

Velocity accuracy: < 2 m/s (3 sigma)

Probability of solution: 99%

TRL 5

Technology Performance Goal: Robust identification and tracking of features across a wide variety of terrain types, environmental conditions, and vehicle states.

Parameter, Value:

Number of features identified: ~100

Velocity accuracy: < 1 m/s (3 sigma)

Probability of solution: > 99%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Robust identification and tracking of features.

Capability Description: Robust identification and tracking of features across a wide variety of terrain types, environmental conditions, and vehicle conditions.

Capability State of the Art: DIMES, 2 features.

Parameter, Value:

Number of features identified: ~100

Velocity accuracy: < 3.7 m/s (3 sigma)

Probability of solution: 71%

Capability Performance Goal: > 100 features

Parameter, Value:

Number of features identified: ~100

Velocity accuracy: < 1 m/s

Probability of solution: > 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enabling	--	2020	2017	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.3 Autonomous Digital Elevation Map Generation

TECHNOLOGY

Technology Description: Creates digital elevation maps autonomously during descent. Digital elevation maps need to be localized and oriented correctly relative to the rest of the target body, be high resolution, and be relatively free of noise.

Technology Challenge: Onboard digital elevation map (DEM) generation without human-in-the-loop checking is a challenge. Eliminating noise created by autonomously-generated DEMs and minimizing true terrain features filtered are also challenges.

Technology State of the Art: Autonomous Landing and Hazard Avoidance Technology (ALHAT) creates DEMs in-flight using flash LIDAR. Current ALHAT requirement is data acquisition and DEM generation in 5s or less.

Parameter, Value:

DEM generation time: < 5 s

TRL 5

Technology Performance Goal: Develop DEM generation processes that work for a variety of potential sensors, environmental conditions, and vehicle states.

Parameter, Value:

DEM generation time: 1 s

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomously generate high-resolution digital elevation maps.

Capability Description: Generate DEMs of sufficient resolution to identify landing hazards of a size that is dependent on mission destination and mission objectives.

Capability State of the Art: ALHAT tests generating 60m x 60m mosaic DEM.

Parameter, Value:

DEM generation time: < 5 s

Capability Performance Goal: Robustly and rapidly generate high-fidelity digital elevation maps.

Parameter, Value:

DEM generation time: < 1 s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.4 Autonomous Hazard Detection and Avoidance

TECHNOLOGY

Technology Description: Enables the identification and location determination of landing hazards using just-acquired passive and/or active imaging. Also predicts and corrects landing location errors relative to a changing target from the position and hazard detection components.

Technology Challenge: Challenges include the need to detect and identify a wide variety of potential landing hazards, such as slopes and rocks, autonomously during descent, and in the presence of dust.

Technology State of the Art: Mars Science Laboratory (MSL) Terminal Descent sensor; terrain-relative localization using Lander Vision System (LVS); Autonomous Landing and Hazard Avoidance Technology (ALHAT).

Parameter, Value:	TRL
Object detection: < 1 m range accuracy Velocity accuracy: 0.1 m/s	5

Technology Performance Goal: Demonstration of robust hazard detection and avoidance over a large variety of potential hazards.

Parameter, Value:	TRL
Object detection: 2 cm range accuracy Velocity accuracy: 1 cm/sec	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomously and robustly detect landing hazards.

Capability Description: Enables terrain-relative precision landing and hazard avoidance.

Capability State of the Art: MSL Terminal Descent Sensor (radar) for altimetry and velocimetry only. No demonstrated hazard detection on flight missions other than human-in-the-loop for Apollo.

Parameter, Value:

Object detection: < 1 m range accuracy

Velocity accuracy: 0.1 m/s

Capability Performance Goal: Radar and optical techniques for ranging and velocimetry and terrain, hazard, and science target recognition.

Parameter, Value:

Object detection: 2 cm range accuracy

Velocity accuracy: 1 cm/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Europa	Enhancing	--	2022*	2020	5 years
Strategic MIssions: Mars 2020	Enhancing	--	2020	2017	5 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.5 Autonomous Science Target Acquisition

TECHNOLOGY

Technology Description: Identifies high-value science targets autonomously onboard a spacecraft during descent using available sensors.

Technology Challenge: Given sensor information, need to autonomously identify science targets so that the spacecraft can access the targets.

Technology State of the Art: Autonomous targeting of instruments has been demonstrated on the surface by rovers, but no knowledge of this occurring during a critical event like entry, descent, and landing (EDL).

Parameter, Value: None exists.

TRL: 2

Technology Performance Goal: Demonstrate the ability to identify science targets during descent or on approach to a small body.

Parameter, Value: Detect targets with diameter < 20 cm

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Detection of science targets autonomously during descent.

Capability Description: Detect, identify, and track science targets during descent under a wide range of environmental and spacecraft conditions.

Capability State of the Art: Autonomous targeting of instruments has been demonstrated on the surface by rovers, but no knowledge of this occurring during a critical event like EDL.

Parameter, Value: None exists.

Capability Performance Goal: In-flight detection and tracking of science targets.

Parameter, Value: Target diameter, 20 cm

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	2 years
Planetary Flagship: Push	Enhancing	--	--	--	5 years

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.6 Offline Reference Map Generation, Validation and Verification

TECHNOLOGY

Technology Description: Provides ability to generate high-quality, high-resolution, low-noise, and registered terrain and digital elevation reference maps.

Technology Challenge: Map generation challenges include filtering out map generation noise without eliminating true terrain features and registering maps and terrain features without ground truth. Map products need to be translatable and usable by vehicles during descent.

Technology State of the Art: Generating Digital Elevation Map (DEMs) and Earth and Mars verified by some amount of ground truth.

Parameter, Value:
~1 meter resolution.
DEMs registered to within ~100 meters.

TRL: 9

Technology Performance Goal: Generate 1 meter or better resolution DEMs rapidly with minimal noise for unknown targets with minimal or no ground truth.

Parameter, Value:
Better than 1 meter resolution.
DEMs registered to within 5 meters.

TRL: 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fundamental sensor data.

CAPABILITY

Needed Capability: Ability to generate high-fidelity reference maps.

Capability Description: Generate high-fidelity, registered terrain and digital elevation map from data collected.

Capability State of the Art: Terrain data products for Mars, Earth as used for Mars Science Laboratory (MSL) landing site selection.

Parameter, Value:
1 meter resolution.
DEMs registered to within ~100 meters ("map tie" error).

Capability Performance Goal: High-quality, high-resolution, low-noise, and registered terrain and digital elevation reference maps.

Parameter, Value:
Better than 1 meter resolution.
DEMs registered to within 5 meters.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.7 Onboard Dedicated Compute Elements

TECHNOLOGY

Technology Description: High-performance, low-power-consumption computing is required for processing sensor data and executing computationally-intensive tasks, such as localization, terrain tracking, autonomous hazard detection and avoidance, autonomous science target identification, and autonomous guidance/trajectory optimization and design.

Technology Challenge: Space-qualified computers typically have the computing power equivalent to commercial desktop computers from 20 years ago. The computation required for the tasks identified cannot be accommodated in current spacecraft computers that are responsible for other critical tasks. As a result, a dedicated high-performance computer is required to support the new functions identified.

Technology State of the Art: High-performance, space-qualified computers are currently in development (example, SpaceCube 2.0). Current standard computers (e.g. RAD750) have limited power.

Parameter, Value:	TRL
RAD750b: 300	9

Technology Performance Goal: Dedicated high-performance computer with low power consumption, adaptable to a variety of sensors and computing applications.

Parameter, Value:	TRL
Millions of instructions per second (MiPS): 6000	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-performance compute elements for computationally-intensive tasks.

Capability Description: Provide high-performance computing capability to enable tasks such as localization, terrain tracking, and autonomous hazard detection and avoidance.

Capability State of the Art: Mars Science Laboratory (MSL)/Mars Reconnaissance Orbiter (MRO) compute element.

Parameter, Value:
MiPS: 300

Capability Performance Goal: Dedicated compute element.

Parameter, Value:
MiPS: 6000

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.2 Descent and Targeting
9.2.8 Autonomous Targeting

9.2.8.8 Small Body Proximity Operations

TECHNOLOGY

Technology Description: Develop small body specific approaches for proximity operations and targeting.

Technology Challenge: Small bodies present specific challenges, such as variable and uncertain geometry and low gravity.

Technology State of the Art: A foreign space agency's Rosetta mission is performing proximity operations and identifying touchdown location for lander; Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) planning asteroid proximity operations and landing.

Parameter, Value:

Low-gravity operations (milli-g)
Low-gravity touchdown (milli-g)
Small body targeting to < 5 m

TRL 6

Technology Performance Goal: Architecture and operations strategy for small body proximity operations, landing site targeting, touchdown, and ascent. Low-gravity navigation and terrain-relative sensing.

Parameter, Value:

Low-gravity operations (milli-g)
Low-gravity touchdown (milli-g)
Small body targeting to < 3 m

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Architecture and operations strategy for small body proximity operations, landing site targeting, touchdown, and ascent.

Capability Description: Small body specific approaches for proximity operations and targeting, including low gravity guidance, navigation, and control.

Capability State of the Art: A foreign space agency's Rosetta mission is performing proximity operations and identifying touchdown location for lander.

Parameter, Value:

Mapping from 25 km or less.
Landing at < 1 m/s.

Capability Performance Goal: Architecture and operations strategy for small body proximity operations, landing site targeting, touchdown, and ascent.

Low-gravity navigation and terrain-relative sensing.

Parameter, Value:

Requirements dependent on science objectives.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years

9.3 Landing
9.3.1 Propulsion and Touchdown Systems

9.3.1.1 Penetrators and Spike Anchors

TECHNOLOGY

Technology Description: Provide a means of retaining hold on a treacherous body.

Technology Challenge: Targets like comets or asteroids have low gravity, making it difficult to land or attach to the target and stay attached through events like contact science or drilling–spike anchors and micro-spines can help with this situation. Penetrators can embed in targets to stay attached.

Technology State of the Art: Champollion anchoring system; Deep Space 2

micro-spine grippers.

Parameter, Value: Anchor 76 kg lander with impact velocity of 4 m/s vertical and 1 m/s horizontal to a micro-gravity body.

TRL 2

Technology Performance Goal: Anchor reliably to the surface of small bodies for extended close-proximity operations.

Parameter, Value: Retention load capability: > 1 Earth g

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Penetration systems and retention devices for maintaining contact with a target body.

Capability Description: Hardware that goes subsurface during entry, descent, and landing (EDL) or grips the target surface.

Capability State of the Art: A foreign space agency's Rosetta-Philae harpoons (nitrocellulose system did not fire).

Parameter, Value: Anchor a 100-kg spacecraft to a comet post-landing.

Capability Performance Goal: Anchor spacecraft reliably to the surface of small bodies for extended close-proximity operations.

Parameter, Value: Anchor 100 kg lander with retention load capability: > 1 Earth g

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	8 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.3 Landing
9.3.1 Propulsion and Touchdown Systems

9.3.1.2 Active Landing Gear

TECHNOLOGY

Technology Description: Active landing gear for greater performance on rocks and slopes.

Technology Challenge: Challenges include applying emerging terrestrial robotic technology for space application to radically improve touchdown system capability in extreme environments.

Technology State of the Art: No current landings use truly active gear (Rosetta legs can rotate, lift, and tilt spacecraft after damping landing forces).

Parameter, Value:	TRL
Land 100 kg on a comet and adjust it to upright.	7

Technology Performance Goal: Landing on any surface condition for moderate power and mass fraction.

Parameter, Value:	TRL
Robustness: 3x improvement	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Active landing gear.

Capability Description: Enables landing on various moons of outer planets, gas giants, and treacherous terrains.

Capability State of the Art: Terrestrial, commercial robots (SandFlea, Atlas, Big Dog).

Parameter, Value:

Robots of tens to a couple hundred kilograms can walk, run, jump, and maneuver slopes and hazards on Earth.

Capability Performance Goal: Landing on any surface condition for moderate power and mass fraction.

Parameter, Value:

Land on slopes > 20 deg, rocks > 10 cm without damage.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	7 years

9.3 Landing
9.3.1 Propulsion and Touchdown Systems

9.3.1.3 Mid-Air Retrieval (MAR)

TECHNOLOGY

Technology Description: Enables the soft touchdown of descending vehicles by capturing the payload parachute via helicopter or aircraft. During the final stages of descent a carrier air vehicle locates and matches the trajectory of the payload with the parachute deployed. The air vehicle then captures the parachute and transports the payload to the final destination.

Technology Challenge: Coordination of final re-entry location and retrieval aircraft, atmospheric condition prediction, parachute/parafoil reliability.

Technology State of the Art: Heritage systems use helicopters to recover payloads with round parachutes.

Parameter, Value:
Gross recovery payload weight less than 4,000 lbm.

TRL 8

Technology Performance Goal: High-reliability systems and lower capture "shock load" enabled through the use of high-glide ram-air-inflated parafoils to increase cross range performance and trajectory control.

Parameter, Value:
Near term: gross recovery payload weight up to 10,000 lbm.
Long term: gross recovery payload weight up to 22,000 lbm.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Airborne recovery of payloads entering Earth's atmosphere.

Capability Description: This capability recovers objects in Earth's atmosphere, before they impact the ground. Uses include: sensitive payloads that cannot survive a shock impact; payloads that must be kept secure; items that need to be returned to a specific location more quickly than they can be located, accessed, and transported after landing; and high-value hardware that can be reused with minimal refurbishment, to save costs.

Capability State of the Art: MAR has been used extensively by the Department of Defense through the 1980's. Heritage systems utilize round parachute designs which limit descent cross range and control.

Parameter, Value:
Gross recovery payload weight less than 4,000 lbm.

Capability Performance Goal:
Increased recovered payload weight. Mission specific to meet the needs of target re-entry system or launch asset.

Parameter, Value:
Near term: gross recovery payload weight up to 10,000 lbm.
Long term: gross recovery payload weight up to 22,000 lbm.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Suborbital: Earth Venture Suborbital	Enhancing	--	On-going	--	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.1 Multi-Disciplinary Coupled Analysis Tools

TECHNOLOGY

Technology Description: Development of validated, multi-disciplinary coupled analysis tools (bridging aerosciences, flight mechanics, material response, and structural and thermal analysis), particularly for high-reliability and extreme-environment applications. Includes models for fluid structure interaction that are capable of predicting and mitigating aeroelastic and aerothermoelastic effects, including buckling, on material and system performance.

Technology Challenge: Validation at flight-relevant conditions is the main challenge. Software and model development is difficult but tractable. A secondary challenge is computational efficiency; resulting code(s) need to be sufficiently fast to be usable for engineering design.

Technology State of the Art: Discipline-level tools are reasonably mature for many applications. Efforts are underway to demonstrate tight coupling between computational fluid dynamics (CFD) and flowfield radiation, and between CFD and material response. Tightly-coupled, mid-fidelity mission analysis tools (e.g. Multi-Mission System Analysis for Planetary Entry (M-SAPE)) are also in developmental stages. Improvements to fluid structure interaction (FSI) capability are currently being considered for further development.

Parameter, Value:	TRL
Coupling level: loose. Defined as running several single-discipline codes and using some combination of external scripts or manual interface to connect them.	3

Technology Performance Goal: Tight coupling demonstrated for aero/radiation/material response and thermo/structural/aero (FSI). Tight coupling at mid-fidelity demonstrated and validated for full entry, descent, and landing (EDL) simulation.

Parameter, Value:	TRL
Coupling level: tight. Defined as either a single multi-disciplinary tool, or automated data transfer routines between single discipline codes.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Multi-disciplinary coupled analysis tools.

Capability Description: Coupled tools for high reliability and extreme environment applications.

Capability State of the Art: Primarily uncoupled or loosely-coupled analysis remains standard practice. Aerothermal analysis is performed uncoupled to material response and/or shock layer radiation. Some loosely-coupled capabilities have been developed and applied, particularly for CFD and flowfield radiation models. Thermostructural analysis typically is not coupled to CFD. Flight dynamics analysis includes empirical models to enable low-fidelity coupling as required. Fluid structure interaction capability exists, but is not at high Technology Readiness Level for EDL problems, and is not currently coupled to aeroheating.

Parameter, Value:

Simulation time: 1 week or more.

Validation level: low.

Capability Performance Goal:

Fully-coupled analysis.

Solution time sufficient for engineering design.

Simulations fully validated with ground and flight data.

Parameter, Value:

Coupling level: 100%

Total simulation time: < 1 day

Validation: full

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.2 Aerothermodynamics Modeling

TECHNOLOGY

Technology Description: Models for aerothermodynamics, including shock layer radiation and high-enthalpy ionized turbulent and separated flows, across the continuum and non-continuum flight regimes, with particular emphasis on flight-relevant experimental validation.

Technology Challenge: Validation at flight relevant conditions is the main challenge. Software and model development is difficult but tractable.

Technology State of the Art: Full three-dimensional (3D) nonequilibrium flow analysis using parallel algorithms/computers on structured meshes. One-dimensional (1D) shock-layer radiation transport. Large uncertainties in required surface radiation rates for high-velocity and non-Earth entry. Limited flight data for validation of current or developmental models. 3D Direct Simulation Monte Carlo (DSMC) with some parallelism and limited non-equilibrium chemistry models.

Parameter, Value:

Attached, steady: mostly validated.

Separated, steady: partially validated.

Separated, unsteady: unvalidated.

Radiation: partially validated.

DSMC: partially validated.

TRL: 3

Technology Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptible limits. Key models are validated with a mix of ground and flight data.

Parameter, Value:

Validated simulation capability for separated unsteady flows and shock layer radiation for continuum and non-continuum regimes.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Aerothermodynamics modeling.

Capability Description: Models for aerothermodynamics with minimum uncertainties to allow robust vehicle designs.

Capability State of the Art: Full 3D nonequilibrium computational fluid dynamics (CFD) models, typically uncoupled shock layer radiation models. Large, and sometimes unquantified, uncertainties remain in various aspects of simulation, particularly for high enthalpy flows, separated wakes, and flows with significant coupling.

Parameter, Value:

Convective heating uncertainty (%): low-Earth orbit (LEO) return (15%), lunar return (25%), Mars return (40%), robotic Mars (30%), human Mars (45%), Venus (40%), Titan (25%), giant planet (100%).

Radiation uncertainty: higher in all cases, mission-specific.

Capability Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptible limits. Key models are validated with a mix of ground and flight data.

Parameter, Value:

Convective heating uncertainty (%): 25% for robotic missions, 15% for crewed missions.

Shock layer radiation surface heating uncertainty: mission specific requirements.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.3 Ablative Material Response Models

TECHNOLOGY

Technology Description: Models for thermal response of thermal protection system (TPS) materials, including physics-based modeling of ablation, internal radiation, pyrolyzation, recession, multilayer materials, gas-surface interactions, and conductivity. Models acreage and details, including attachments and damage.

Technology Challenge: Validation at flight relevant conditions is the main challenge. Software and model development is difficult but tractable.

Technology State of the Art: Primarily one-dimensional (1D) simulation using equilibrium models and semi-empirical formulations. Models designed to ensure conservatism over accuracy. No models for some effects (such as melt flow and spallation). Minimal use of two-dimensional (2D) and three-dimensional (3D) methodologies. Primary shortfall is availability of material-specific property data and appropriate validation data.

Parameter, Value:

Component validation: minimal

Model validation: arc jet data

Dimensionality: 1+

Physical models: equilibrium

Numerical scheme: structured finite difference.

TRL

7

Technology Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptible limits. Key models are validated with a mix of ground and flight data. Establish relevant physical models for micro-spallation and melt flow.

Parameter, Value:

Component validation: full

Model validation: ground test, flight data

Dimensionality: 3

Physical models: non-equilibrium

Numerical scheme: unstructured finite element or finite volume.

TRL

7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ablative material response models.

Capability Description: Models for ablative TPS thermal response in all environments with minimum uncertainties to allow robust vehicle designs.

Capability State of the Art: Primary application is 1D using NASA-developed tools. Simple, primarily equilibrium models for thermo-chemical processes. Limited use of 3D simulation. Reliance on semi-empirical methodology makes extrapolation to flight enivronment very difficult, leading to large design margins.

Parameter, Value:

Bondline temperature: 20%

Time to peak temperature: 25%

Total recession: 35%+

Some dependence on entry atmosphere and conditions (Venus, Outer planet entries have higher uncertainty).

Capability Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptible limits. Key models are validated with a mix of ground and flight data.

Parameter, Value:

Bondline temperature: 10%

Time to peak temperature: 15%

Total recession: 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.4 Non-Ablative Material Response Models

TECHNOLOGY

Technology Description: Models for thermal response of thermal protection system (TPS) materials, including physics-based modeling of internal radiation, pyrolyzation, multilayer materials, gas-surface interactions, and conductivity. Models acreage and details, including attachments and damage.

Technology Challenge: Validation at flight relevant conditions is the main challenge here. Software and model development is difficult but tractable.

Technology State of the Art: Primarily three-dimensional (3D) simulation using commercial tools (e.g. ComSol). Primary shortfall is availability of material-specific property data and appropriate validation data.

Parameter, Value:

Component validation: minimal.

Model validation: arc jet data.

Physical models: equilibrium.

TRL

7

Technology Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptable limits. Key models are validated with a mix of ground and flight data.

Parameter, Value:

Component validation: full.

Model validation: ground test, flight data.

Physical models: non-equilibrium.

TRL

7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-ablative material response models.

Capability Description: Models for non-ablative TPS thermal response in all environments with minimum uncertainties to allow robust vehicle designs.

Capability State of the Art: 3D simulation using commercial software is commonplace.

Parameter, Value:

Surface temperature prediction: 20%

Bondline temperature prediction: 20%

Time to peak temperature: 25%

Some dependence on entry atmosphere and conditions (Venus, Outer planet entries have higher uncertainty).

Capability Performance Goal: All relevant uncertainties are quantified and within (mission risk profile specific) acceptible limits. Key models are validated with a mix of ground and flight data.

Parameter, Value:

Surface temperature: 10%

Bondline temperature: 10%

Time to peak temperature: 15%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	3 years
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.5 Thermal Protection System (TPS) Quantification Models and Processes

TECHNOLOGY

Technology Description: Quantifies TPS margin and system reliability using statistical analysis, test design techniques, and archive storage of Agency thermal test data, as required for Commerical Orbital Transportation Services and NASA crewed vehicles, as well as high-reliability sample return missions. See also TA 12.3.6 Certification Methods.

Technology Challenge: Validation at flight-relevant conditions is the main challenge. Software and model development is difficult but tractable.

Technology State of the Art: Mix of Monte-Carlo statistical and semi-empirical root of sum squares (RSS) or stacked uncertainties. Minimal validation of the methodology leads to concerns about validity and use of conservative estimation techniques.

Parameter, Value:
Method: mixed fidelity
Validation: minimal
Reliability estimate: 50% confidence
Margin estimate: 50% confidence

TRL
5

Technology Performance Goal: Validated probabalistic physics based model to predict n-σ dispersions in bondline temperature performance, recession performance, and overall reliability with credibility.

Parameter, Value:
Method: fully probabalistic
Validation: full (ground and flight)
Reliability estimate: 95% confidence
Margin estimate: 95% confidence

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Thermal protection system (TPS) margin and reliability quantification.

Capability Description: Numerical analysis to determine required TPS margin to meet missions requirements and overall design reliability.

Capability State of the Art: Capability in transition from empirically-determined RSS'ed margin components to a statistical Monte-Carlo methodology for margin and reliability. Current capability remains a hybrid of the two.

Parameter, Value:
n-σ bondline temperature dispersion: 25%
n-σ surface recession dispersion: 50%

Capability Performance Goal: Physics-based probabilistic model with sufficient accuracy to predict n-σ dispersions in bondline temperature performance, recession performance, and overall reliability with credibility.

Parameter, Value:
n-σ bondline temperature dispersion: 10%
n-σ surface recession dispersion: 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.6 Numerical Methodologies and Techniques

TECHNOLOGY

Technology Description: Provides improved numerical methodologies and techniques, taking advantage of expected computer architecture and hardware improvements.

Technology Challenge: Challenges include robustly capturing strong shocks in nonequilibrium flow, computational efficiency, adapability to nonequilibrium flow models, and amenability to multi-disciplinary analysis.

Technology State of the Art: Full three-dimensional (3D) simulations using structured meshes are efficient for simple geometries, but become overwhelmingly complex for detailed geometries. Newer approaches are very immature and not well validated. Work is in progress to update severeral disciplines to a more modern numerical architecture.

Parameter, Value:
Methodology: structured.
Solution time (varies, hours to weeks).

TRL
2

Technology Performance Goal: Reliable unstructured hypersonic computational fluid dynamics (CFD) with high parallel efficiency and time accurate dynamic simulation capability. Parallel algorithms in all disciplines that make use of modern supercomputers (which is a moving target – latest advance is graphical processing units (GPUs), which no entry codes are optimized for).

Parameter, Value:
Methodology: unstructured.
Solution time: factor of 2 improvement.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Numerical methodologies and techniques.

Capability Description: Provides improved numerical methodologies and techniques, taking advantage of expected computer architecture and hardware improvements.

Capability State of the Art: Parallel distributed memory finite volume methodologies on structured meshes dominate hypersonic CFD world. Steady-state calculations are the norm; unsteady interactions are largely ignored. Shock layer radiation uses one-dimensional (1D) transport. Direct Simulation Monte Carlo (DSMC) methods use parallelism, but have simplistic physical models for high enthalpy gases. Material response is typically 1D and based on numerical approaches developed in the 1960s.

Parameter, Value:
Computational efficiency and numerical accuracy are the primary metrics for performance; values are hugely application dependent.

Capability Performance Goal: Validation of new numerical methods to reproduce prior results when same physical models employed. Validation of new physical models with ground and flight data.

Parameter, Value:
New numerical methods validated to within 3% of old results.
Efficiency: factor of 2 improvement.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Push	Enhancing	--	--	--	2 years
New Frontiers: Push	Enhancing	--	--	--	2 years
Planetary Flagship: Push	Enhancing	--	--	--	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.7 Autonomous Aerobraking

TECHNOLOGY

Technology Description: Provides autonomous control methods that can reduce "human-in-the-loop" costs and the risk of planetary aerobraking.

Technology Challenge: Challenges include qualifying without putting a mission at risk.

Technology State of the Art: Periapsis timing is a level of autonomy used in previous missions. Control authority has been developed by NASA Engineering and Safety Center (NESC) but not employed on aerobraking orbiter.

Parameter, Value:

Staff time: 75-150 days.

TRL

5

Technology Performance Goal: Reduce staff hours and Deep Space Network (DSN) coverage while safely maintaining aerobraking orbit control parameters within designed limits.

Parameter, Value:

Mission dependent. Mission operations support cost: 50% less than SOA.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced aerobraking concepts.

Capability Description: Provides advanced aerobraking concepts to reduce mass, risk, or cost.

Capability State of the Art: Periapsis Timing Estimator flown on Mars Reconnaissance Orbiter (MRO), Autonomous Aerobraking corridor control maintenance logic developed by NESC.

Parameter, Value:

Staff hours: Odyssey required 77 days with 7-day/week operations; MRO required 145 days with 7-day/week operations.

Capability Performance Goal: Reduce staff time without increasing risk.

Parameter, Value:

Staff time: 50% reduction

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Push	Enhancing	--	--	--	2 years
New Frontiers: Push	Enhancing	--	--	--	2 years
Planetary Flagship: Push	Enhancing	--	--	--	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.8 Orbital Debris Entry and Breakup Modeling

TECHNOLOGY

Technology Description: Models and techniques for predicting breakup of human-made spacecraft upon entry into Earth's atmosphere.

Technology Challenge: Challenges include developing a coupling structure failure model to 6 degrees of freedome (DOF) trajectory simulation tool and tracking debris of various sizes.

Technology State of the Art: Tools are of engineering fidelity at best. Extensive use of correlations, and not entirely physics-based. Higher-fidelity models have not been validated.

Parameter, Value:

Validation: minimal

Methodology: semi-emprical

TRL

3

Technology Performance Goal: Prediction of breakup of International Space Station (ISS) upon its eventual de-orbit upon end of mission life. Prediction of breakup of de-orbited satellites – a capability that would prove useful to small sat/CubeSat operators.

Parameter, Value:

Validation: full (software Technology Readiness Level (TRL) of 6+)

Methodology: coupled high fidelity

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Planetary defense against orbital debris.

Capability Description: Simulation capability to predict demise of (planned or unplanned) de-orbited space assets. Simulation capability includes determination of number and size of pieces (from thermal/mechanical failure), and their eventual ground track.

Capability State of the Art: (a) Engineering-fidelity tools for entry break up. Tools assume idealized shapes for compnents (debris) with rudimentary trajectory tools (b) Simulation tool, CART3D, has been used to investigate Soyuz TMA-10 and 11 entry anomalies. 6DOF trajectories using pre-computed aerodynamics database, equilibrium aerothermodynamics to determine thermal loads, supplemented with structural failure models. Debris tracking capability, developed for Columbia accident investigation, has been anchored to ballistic range experiments.

Parameter, Value:

Probability of survival: 50% confidence

Landing footprint: 50% confidence

Solution time: days

Capability Performance Goal: Integrated multi-disciplinary modeling capability, based on and anchored by high-fidelity tools developed for entry, descent, and landing (EDL). Ability to predict entry trajectory, rate of mass loss, likelihood of breakup, probability of survival to ground, and landing footprint.

Parameter, Value:

Probability of survival: 90% confidence

Landing footprint: 90% confidence

Solution time: < 1 day

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	3 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.9 Meteor Entry and Breakup Modeling

TECHNOLOGY

Technology Description: Models and techniques for predicting breakup of extraterrestrial objects (asteroids/meteors, comets) entering Earth's atmosphere.

Technology Challenge: Challenges include coupling of flow, radiation, materials, and trajectory models; resolution of length scales ranging from 1 cm to 10-100 km; thermal and/or structural response to imposed high-pressure on porous medium (for Si or C-based meteors) and melting material (for Fe, Ni-based meteors); and aerothermal simulation of very high speed entry to Earth (physics much more complex than for NASA entries).

Technology State of the Art: Limited to rudimentary model developed for meteors/bolides, with correlation of parameters (explosive energy) to luminosity. Since models are tuned to particular meteor entries, breadth of applicability is not completely known.

Parameter, Value:

Validation: almost none

Methodology: semi-emprical

Physical model maturity: low

TRL: 1

Technology Performance Goal: Upgrade thermodynamic models in current simulation tools to include multi-stage ionization of species. Upgrade governing equations with models that include long-range (Coulombic) forces and solid phase (particle laden flow), and liquid phase, if necessary. Predict aerothermal environments up to entry velocities of 30 km/s for ballistic coefficients ranging from 100 to 300 kg/m^2.

Parameter, Value:

Validation: full

Methodology: physics-based

Physical model maturity: high

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Planetary defense and early warning system against asteroids.

Capability Description: Simulation capability (perhaps an integrated set of tools): (1) to predict the break up and associated energy release of extraterrestrial objects (asteroids/meteors, comets) upon entry into Earth's atmosphere, (2) assess risk and magnitude of strike/damage to populated areas, and (3) develop an early warning system.

Capability State of the Art: Models are essentially non-predictive outside of the class.

Parameter, Value:

Probability of survival: 0% confidence

Landing footprint: 0% confidence

Solution time: days

Capability Performance Goal: Integrated multi-disciplinary modeling capability, based on and anchored by high-fidelity tools developed for EDL. Ability to predict entry trajectory, rate of mass loss, likelihood of breakup, probability of survival to ground, and landing footprint.

Parameter, Value:

Probability of survival: 75% confidence

Landing footprint: 75% confidence

Solution time: 1 day

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	5 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.10 Fluid Structure Interaction (FSI) Tools

TECHNOLOGY

Technology Description: Enables static and dynamic assessment of flexible decelerators, including acquisition of data sets useful for FSI validation efforts at relevant aerodynamic and aerothermodynamic environments. For subsonic chutes, this is needed for multi-chute interaction. For both subsonic and supersonic, wake closure is relevant.

Technology Challenge: Material models and experimental verification and validatoin (V&V) remain a technology challenge.

Technology State of the Art: High transient structural response models are poorly validated with experimental data sets. Explicit FSI solution sets can be benchmarked with experimental results, but predictive capability is highly uncertain.

Parameter, Value:	**TRL**
Essentially no SOA for problems of interest to the planetary entry, descent, and landing (EDL) community.	3

Technology Performance Goal: Quasi static (low transient loading) has practical applications for deployable decelerators. Large deflection deployment (e.g. parachute) FSI would be most useful as a predictor of design change impacts. Ideally, FSI tools accurately model performance of the parachute inflation and flight characteristics under subsonic and supersonic conditions. It also models the contributions of the air mass of the canopy the coupled motion.

Parameter, Value:	**TRL**
Validation, high transient: medium Validation, quasi-static: high Validation, large deflection: medium	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fluid structure interaction (FSI) tools.

Capability Description: Computational fluid dunamics (CFD) tools that accurately predict the deployment and performance of a descent decelerator.

Capability State of the Art: Strongly coupled FSI solver in US3D handles high transient response problems. A commercially-available software capability, can handle quasi-static problems. Large deflection problems (such as parachute deploy) are currently university research products with no validated SOA.

Parameter, Value:

Essentially no SOA for problems of interest to EDL community.

Capability Performance Goal: Validation of simulation capability for problems of interest based on ground test and flight data. More robust parachute design with reduced margin resulting in lower system mass. Provide the ability to assess vendor designs with reduced number of costly drop tests.

Parameter, Value:

Agreement between prediction and flight test

Total deflection: 10%

Frequency: 20%

Pressure peak: 10%

Heating peak: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Push	Enhancing	--	--	--	5 years
Discovery: Push	Enhancing	--	--	--	5 years
Planetary Flagship: Push	Enhancing	--	--	--	5 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.11 Supersonic Retropropulsion (SRP) Modeling Tools

TECHNOLOGY

Technology Description: Develop validated SRP modeling tools to reduce risk and improve efficiency.

Technology Challenge: Challenges include aero/propulsive interactions and convective and radiative heating.

Technology State of the Art: Navier-Stokes computational fluid dynamics (CFD) codes compared to cold-gas wind tunnel data for one or multiple nozzles. Primarily structured grids.

Parameter, Value:	TRL
Structured grid static simulation. Validation: minimal, wind tunnel.	2

Technology Performance Goal: Ground hot-fire test and flight databases with aero/propulsive force and moment and aerothermal data. Tools validated against databases. Identification of modes that cause large-scale unsteadiness.

Parameter, Value:	TRL
Unstructured grid dynamic simulation. Validation: full with ground/flight data.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Propulsive descent modeling and simulation.

Capability Description: Provides high-fidelity computational tools for the descent phase of the mission.

Capability State of the Art: Minimal validation with cold-gas tunnel data. Models are minimally predictive of untested configurations, particularly with multiple nozzles.

Parameter, Value:

Prediction capability for all parameters: ±100%.

Capability Performance Goal: Full validation with ground and flight data, including hot-fire data. Demonstrated ability to use tools in a predictive manner.

Parameter, Value:

Prediction capability:

Net thrust: 10%

Pressure peak: 10%

Heating peak: 20%

Unsteadiness frequency: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	13 years

9.4 Vehicle Systems
9.4.5 Modeling and Simulation

9.4.5.12 Aerodynamic Modeling Tools

TECHNOLOGY

Technology Description: Models to compute steady and dynamic aerodynamics, with an emphasis on aftbody and wake interaction flows, including reaction control system (RCS) interaction and plume impingement dynamics.

Technology Challenge: Properly capturing wake physics (specifically, pressure recovery) behind blunt supersonic vehicles, with and without RCS interaction. Sting effects in wind tunnel testing may be prohibitive to validation of predictive models.

Technology State of the Art: Structured Navier-Stokes computational fluid dynamics (CFD) codes with limited ability for dynamic simulation. Ballistic range and spin tunnels for dynamic aerodynamics.

Parameter, Value:

Fidelity: static Reynolds Averaged Navier-Stokes (RANS).

Capability unvalidated.

Solution time: days

TRL 3

Technology Performance Goal: Unstructured, fully dynamic CFD simulation capability. Predict supersonic drag to reduce landing ellipse error. Demonstrate validated predictive capability for vehicle dynamics. Demonstrate validated predictive capability for RCS interaction effects.

Parameter, Value:

Fidelity: dynamic Detatched Eddy Simulation (DES)/ Large Eddy Simulation (LES)/direct numerical simulation (DNS).

Capability validated with ground/flight data.

Solution time: < 1 day

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Aerodynamic modeling tools.

Capability Description: Models entry, descent, and landing (EDL) aerodynamics, with an emphasis on of aftbody and wake interaction flows.

Capability State of the Art: RANS, LES, DES CFD. Base pressure correction based on flight data.

Parameter, Value:

Uncertainty in prediction tools: mission-dependent, but can be > 30% or higher in wake region, even compared to static or average values.

Capability Performance Goal: Static models validated with ground and flight data. Dynamic simulation capability developed and validated. RCS interaction validated with ground test data. Ubiquitous use of LES/DES/DNS models for turbulence. Unstructured grids for complex geometries.

Parameter, Value:

Landing ellipse: 100 m accuracy

Uncertainty in prediction tools on:

Pressure: < 10% static

Heating: < 15% dynamic

Frequency: < 20% (RCS Interaction)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Mars 2020	Enhancing	--	2020	2017	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.1 Thermal Protection System (TPS) Instrumentation

TECHNOLOGY

Technology Description: Measures performance of entry vehicle TPS, as well as atmosphere and flight dynamics parameters, to improve design for future missions. Includes in-depth and surface temperature, surface pressure, TPS recession, and surface heat flux and catalycity measurements.

Technology Challenge: Challenges include meeting mass, volume, power, cost, and data-rate constraints on small missions; developing an extreme environment capability; calibration; and testing and qualifying on the ground. Will require modularity to achive “plug-and-play” capability.

Technology State of the Art: The MSL Entry, Descent, and Landing Instrumentation (MEDLI) sensor suite flown on Mars Science Laboratory (MSL) provided in-depth temperatures and pressure measurements at 7 locations on the heat shield, including an isotherm-tracking sensor. The Exploration Flight Test (EFT)-1 flight test expanded upon this instrumentation suite with more thermal plugs, pressure measurement systems, and in-depth thermocouples on both the heat shield and afterbody, as well as 2 radiometers on the heat shield.

Parameter, Value:

System mass: 13 kg

Cost: > $20M (Flagship-class)

TRL

3

Technology Performance Goal:

Need systems to provide pressure (P), temperature (T), recession, and radiation information on Discovery-class missions. Cost: < $5M.

50% mass improvement.

Negligible volume and power.

Parameter, Value:

Temperature: < 30° C (during max heating)

Pressure: 0.01 psi (forebody) Recession: < 0.5 mm

Heat flux: < 1 W/cm^2

Spectrometer that includes ultraviolet to infrared spectral range.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intrusive entry instrumentation.

Capability Description: Obtain performance and environment data in situ during entry.

Capability State of the Art: A suite of TPS thermocouples, isotherm sensors, heat flux gauges, flush air data systems (pressure), and radiometer are available for use in moderate (MSL, EFT-1) entry environments. Galileo had recession sensors. Catalycity has not been measured.

Parameter, Value:

Thermocouples and pressure sensors are at high Technology Readiness Level, and can be deployed in flight tests and large robotic missions.

Capability Performance Goal: Forebody and backshell systems small enough to be included on Discovery-class missions.

Parameter, Value:

Mass: 50% MEDLI

Volume: minimal

Cost: 10% MEDLI

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.2 Radiometers and Spectrometers for Entry Vehicle Heat Shields

TECHNOLOGY

Technology Description: Obtain radiative shock layer energy and/or constituent/electron number density information during entry.

Technology Challenge: Challenges include meeting mass, volume, power, cost, and data-rate constraints on small missions (packaging and qualification); providing extreme environment capability; and calibration.

Technology State of the Art: Apollo-era test flight included radiometers; Exploration Flight Test (EFT)-1 flight test has 2 radiometers on the heat shield. Pyrometers used regularly in ground test facilities.

Parameter, Value:
Radiation predictive model uncertainty: 40-100%

TRL
3

Technology Performance Goal: Obtain flowfield energy and chemistry measurements suitable for validating tools.

Parameter, Value:
Model uncertainty: < 20%

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intrusive entry instrumentation.

Capability Description: Obtain radiative shock layer energy and/or constituent information during entry to improve model uncertainty

Capability State of the Art: Apollo flight tests, EFT-1 radiometer.

Parameter, Value:
Radiation prediction uncertainty currently > 100% depending on mission.

Capability Performance Goal: Obtain measurements suitable for validating tools.

Parameter, Value:
Model uncertainty: < 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.3 Distributed Instrumentation

TECHNOLOGY

Technology Description: Measures performance of entry vehicle and its sub elements with distributed sensor networks to improve design for future missions (includes Integrated System Health Monitoring (ISHM), micrometeoroid orbital debris (MMOD), shape change).

Technology Challenge: Challenges include meeting mass, volume, power, cost, and data-rate constraints on small (Discovery-class) missions; extreme environment capability; calibration; and testing and qualifying on the ground. Will require modularity to achive "plug-n-play" capability.

Technology State of the Art: Distributed systems exist on aircraft, other terrestrial vehicles.

Parameter, Value:
Not available for space vehicles.

TRL: 2

Technology Performance Goal: Need systems to provide ISHM, MMOD, and shape information on Discovery-class missions.

Cost: < $5M.

50% mass improvement.

Negligible volume and power.

Parameter, Value:
Structural load to within 10%; structural shape: mm for rigid, cm for flexible; MMOD strike of 1 cm x 1 cm.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intrusive entry instrumentation.

Capability Description: Obtain performance and environment data in situ during entry.

Capability State of the Art: Discrete locations of thermal protection system (TPS) thermocouples, isotherm sensors, heat flux gauges, flush air data systems (pressure), and radiometers are available for use in moderate (Mars Science Laboratory (MSL), Exploration Flight Test (EFT-1)) entry environments.

Parameter, Value:
Thermocouples and pressure sensors are at high Technology Readiness Level, and can be deployed in flight tests. Material stresses are not measured in rigids; strap loads are measured on inflatable decelerator tests.

Capability Performance Goal: Systems small enough to be included on Discovery-class missions.

Parameter, Value:
Mass: 50% MSL Entry, Descent, and Landing Instrumentation (MEDLI)

Volume: 30% MEDLI

Cost: 10% MEDLI

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enabling	--	2023	2020	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.4 Miniaturized, Micro Electro Mechanical Systems (MEMS)-Based Sensors for Entry Vehicles

TECHNOLOGY

Technology Description: Provide pressure, temperature, recession, shape, and other parameters in forebody and aftbody entry environments, for minimal mass, power, and volume.

Technology Challenge: Challenges include developing an extreme environment capability; calibration; testing and qualifying on the ground; and packaging. Will require modularity to achive "plug-and-play" capability.

Technology State of the Art: Diaphragm-based transducers, no working MEMS sensors in flight on entry vehicles.

Parameter, Value:

Mass: roughly 15 kg.

TRL 3

Technology Performance Goal: Radically reduced mass and cost over SOA.

Parameter, Value:

Mass: 10x reduction

Cost: 10x reduction

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intrusive entry instrumentation.

Capability Description: Obtain performance and environment data in situ during entry.

Capability State of the Art: Apollo, Mars Viking, MSL Entry, Descent, and Landing Instrumentation (MEDLI); and Exploration Flight Test (EFT)-1; COMARS+ European instrument.

Parameter, Value:

Mass on order of 15 kg for entire system (MEDLI).

Capability Performance Goal: Systems small enough to be included on Discovery-class missions.

Parameter, Value:

Mass: 50% MEDLI

Cost: 10% MEDLI

Accuracy at least as good as historical/SOA.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.5 Semi- or Non-Intrusive Instrumentation Concepts

TECHNOLOGY

Technology Description: Obtain heating, pressure, and/or shape information on entry vehicles, using semi- or non-intrusive instrumentation concepts, including wireless (data and power), electromagnetic, visual, and acoustic systems.

Technology Challenge: Challenges include developing an extreme environment capability; calibration; testing and qualifying on the ground; and packaging. Will require modularity to achive “plug-and-play” capability.

Technology State of the Art: Wireless sensors in terrestrial applications (airplanes), cameras used for decelerator drop tests, etc.

Parameter, Value:

None exists for planetary entry vehicles.

TRL 2

Technology Performance Goal: Radically reduced mass and cost over SOA; improved flight validation data for decelerator deployment, shape.

Parameter, Value:

Mass: 10x reduction

Cost: 10x reduction from discrete methods.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-intrusive entry instrumentation.

Capability Description: Provides performance and environment data during entry, without active onboard instruments.

Capability State of the Art: No known use in relevant environment.

Parameter, Value:

Mass on order of 15 kg for entire system (MSL Entry, Descent, and Landing Instrumentation, or MEDLI).

Capability Performance Goal: Systems small enough to be included on Discovery-class missions.

Parameter, Value:

Mass: 50% MEDLI

Cost: 10% MEDLI

Accuracy at least as good as historical/SOA.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enabling	--	2020	2017	3 years
Discovery: Discovery 14	Enabling	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

9.4 Vehicle Systems
9.4.6 Instrumentation and Health Monitoring

9.4.6.6 Remote Observation Platforms for Earth Entries

TECHNOLOGY

Technology Description: Provides multiple diagnostics on incoming Earth entry vehicles. See the technology roadmap for TA 12.2.3 Reliability and Sustainment.

Technology Challenge: Challenges include demonstrating sensor-directed flight on a unmanned aerial system (UAS) and pointing stability of tracking systems. There are also limitations with spectral instrumentation for measurements pertaining to ablation/radiation physics associated with hypervelocity reentry qualification of thermal protection system (TPS) doped with tracer elements.

Technology State of the Art: A flight test and evaluation and imaging-based scientific measurement capability is virtually nonexistent. Terrestrial range electro-optical infrastructure suffers major shortfalls in ability to provide scientific/engineering-quality data. Current airborne measurement capability requires experienced crew and sensor operators and the sensor technology provides limited instrument flexibility. Existing crewed aerial platforms are vulnerable to local weather, present schedule/priority constraints, and are often cost prohibitive. The technology includes obtaining new information through heat shield seeding and other passive methods.

Parameter, Value:

Image platforms: large crewed aircraft.

Observation location and loiter time: constrained by lower service ceiling and consumables (fuel). Target acquisition/tracking: high-risk manual process.

Sensor configuration: best practices, increased risk of data loss.

TRL 3

Technology Performance Goal: Autonomy, improved reliability and data quality, and reduced mission costs.

Parameter, Value:

Inches per pixel: 2

Frame rate: 1kHz

Pointing stability: 1 microrad

Large aperture: > 10 –in

Long focal length: > 10 ft

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-intrusive entry instrumentation.

Capability Description: Provides performance and environment data during entry, without active onboard instruments.

Capability State of the Art: Government or commercial imaging platforms and optical systems (current capability): Stardust (spectral); Jules Verne Automated Transfer Vehicle (ATV) (spectral); Hayabusa (spectral); Shuttle (thermal); NASA Engineering and Safety Center (NESC) MLAS (visual-thermal); Dragon (thermal); Falcon 9 (visual-thermal); Falcon 9 stage 1 (visual/thermal).

Parameter, Value:

Platform: large crewed aircraft using high-risk manual process for flight and sensor operations. Typical observation campaign cost with existing technology under current logistical model: $1 million. Typical spatial resolution in infrared wavebands with existing technology: 15-20 in per pixel at 30 NM standoff distances; 3-120 Hz framing rates. Spectrally resolved shock layer measurements: emphasis in the ultraviolet band.

Operations range: 2000 NM, several hours on station.

Capability Performance Goal: High Altitude Long Endurance (HALE) UAS with intelligent sensor suite for optimized sensor configuration, and payload-directed autonomous flight to provide performance, model validation, and environmental data on entry, descent, and landing (EDL) entry systems at 20-30% of the cost of existing imaging platforms.

Parameter, Value:

Cost per observation campaign: $200-300K. Autonomous flight and sensor operations: no crew.

Global reach capability: 10-15 days on station.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 13	Enhancing	--	2020	2017	3 years
Discovery: Discovery 14	Enhancing	--	2023	2020	3 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)