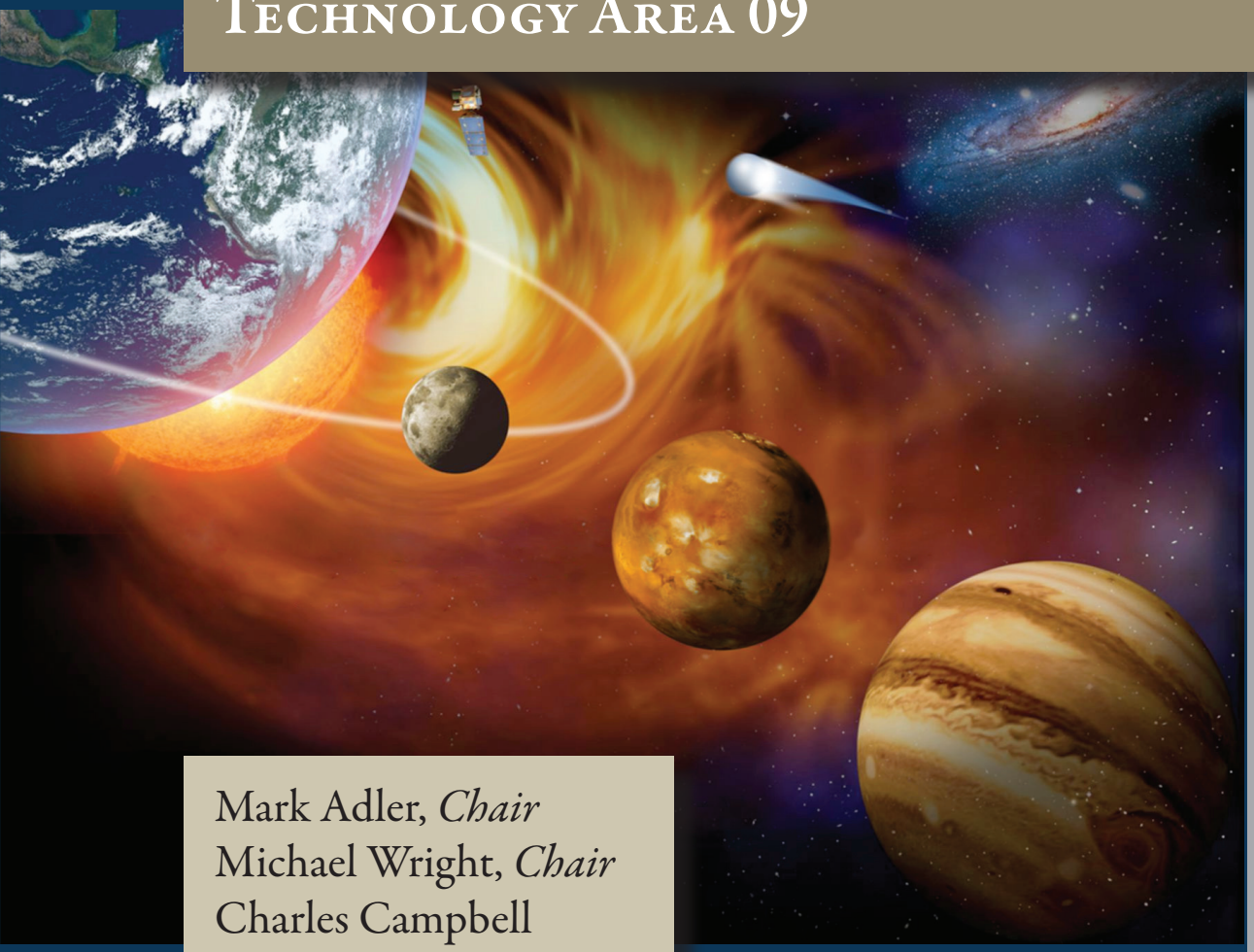
National Aeronautics and Space Administration

Entry, Descent, and Landing Roadmap

Technology Area 09



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 09 input: Entry, Descent, and Landing. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

For the purposes of this 20-year technology roadmap, shown in Figure 1, entry, descent and landing (EDL) is defined to encompass the 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 (just "E"), landing on small or large bodies with no substantial atmosphere (just "L"), and missions that end in the atmosphere, such as probes, or that deploy aircraft into the atmosphere ("ED"). This roadmap does not address aircraft or aircraft technologies, such as for balloons or powered airplanes (see TA04), nor does it address in-space propulsion preceding atmosphere entry (see TA02).

EDL is an emergent behavior of a system arising from the combination of hardware, software, trajectory, operations (including site selection), and the natural environments being encountered. The components of the behavior are highly interdependent and can only be validated in the context of the sequence of events. However the end-to-end sequence and associated environments are difficult or impossible to test as a whole before launch, and so qualification of EDL systems and operations depend strongly on computer simulations of the entire sequence. These simulations need to be grounded in component tests, analyses, and modeling. As a result, EDL technology developments must also be defined and executed within the context of expected technology applications, and careful consideration given to the qualification approach that will be used by the mission that first infuses the technology. Furthermore, different EDL technology developments may interact strongly with each other in their applications, and so as a technology matures, the interacting technologies and their requirements must be reevaluated.

These interactions are most evident for the development and evolution of human class EDL for Mars. The approach that will be used to land tens of metric tons of payload on Mars is not known today, and cannot be known purely through paper studies. Only through technology development can the large uncertainties that exist today be reduced in the design of such a mission in order to begin to converge on the most cost effective and reliable combination of systems. Even though such a mission may be three decades away, there will need to be several flight tests in Earth's atmosphere and possibly at Mars in order to gain sufficient confidence in these systems before relying on them for a human expedition. Tracing back the schedule from human landing on Mars, assuming reasonable development times for the flight tests, and allowing for an occasional failure, it becomes clear that we need to begin such technology developments within the next few years in order to enable an early 2040 decade pathway to human landings on Mars. Alternate pathways should also be pursued for revolutionary capabilities, with downselects occurring along the way.

New EDL technologies, both revolutionary and evolutionary, will also enable future robotic missions to other solar system destinations, including asteroids, comets, Venus, Mercury, Mars, icy moons, the gas giant planets, Titan, and others. Decadal Survey planning teams have previously identified and are currently in the process of updating the set of high priority science goals. These goals will include missions that enter the Venus atmosphere and deliver long lived surface landers, Mars surface penetrator and network lander concepts, Saturn probes, Titan airships and landers. They will also include new missions that enter the Gas Giants at high velocities, resulting in radiative and convective heating rates that exceed current TPS material capabilities. Strategic EDL technology investments, 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.

A continuous backdrop of system design and analyses 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, that 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.

Earth testing on the ground and in flight is the foundation of EDL technology development and qualification. However, due to the expense of these developmental tests, EDL missions to date have relied heavily on the technology developed and qualified in the 1960's and 1970's with very

few new developments. We have reached the limits of those technologies, and in some cases, have stretched their qualification limits. In order to move forward, we will need to invest in a vigorous program of ground and flight testing as was common in the 1960's and 1970's.

In addition to Earth testing, the science robotic, precursor robotic, and human missions to the Moon, Mars, and asteroids in addition to 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.

The key performance characteristics that EDL technology developments will target are delivery/performance reliability, cost, delivered mass, landing site access, and landing precision. Like EDL subsystems, these characteristics interact with each other. Reliability is manifested in the completeness of the tests and analyses of component technologies, such as thermal protection systems, deployable decelerators, landing hazard tolerance, and separation systems. Reliability is also realized with increased timeline to complete events as a result of larger drag devices applied earlier, 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. Low cost is enabled by improved simulation and ground-to-flight extrapolation, and by incorporating high-G landed systems into mission architectures. Delivered mass can be increased or enabled through the use of more capable TPS for the more difficult environments presented by larger entry vehicles, larger drag devices applied at higher speeds, descent-phase (supersonic) retropropulsion, and more efficient terminal descent propulsion. Landing site access can be increased through TPS that permits higher entry speeds (allowing a wider range of targets), small body proximity operations, increased altitude performance, again by virtue of higher drag earlier than can be provided currently, and higher precision allowing a wider range of safe sites. Greater control authority 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 of the natural environments.

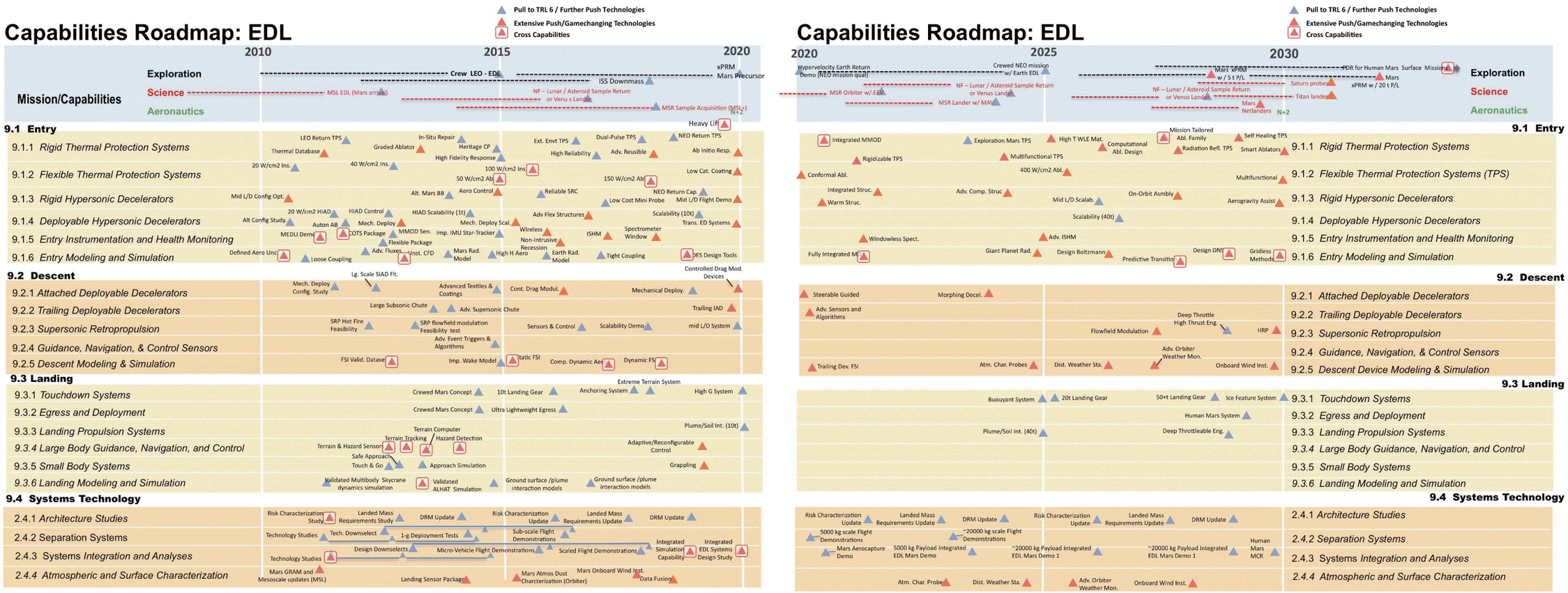
The key recommended areas of technology development (in no particular order) are then:

- Low mass TPS for higher entry speeds, and qualification over a wider range of conditions
- Resilience to and monitoring of TPS MMOD and radiation damage
- Deployed rigid or flexible drag devices for both the entry and descent phases, including flexible TPS development for entry and high-strength, high-temperature fabrics for descent, and supersonic and subsonic parachutes
- Lightweight, high-temperature structures for entry vehicles
- Improved entry and descent control authority through higher L/D, control surfaces, C.G. modulation, and controllable descent decelerators
- Supersonic retropropulsion systems
- Deep-throttling terminal descent engines
- Landing gear for very large payloads, and for small payloads on extremely hazardous terrain
- High-G landed avionics, power systems, and sensors
- Mitigation of surface modification and hazard creation by terminal descent propulsion
- Advanced sensing (terrain tracking and hazard detection) and guidance for terminal descent
- Small body descent, touch, hover, ascent, fault protection, and sustained contact methods
- Staging systems for deployment, separation, and recontact avoidance specific to each component, and the development of advanced pyrotechnic initiation devices
- Flight instrumentation of key performance aspects of EDL systems to guide subsequent applications and technology developments
- Improved modeling of all EDL systems to reduce the number of parallel technology paths, project qualification costs, reduce margins, and increase reliability
- Increased knowledge and improved models of the atmospheric and surface environments, both a priori and during EDL (using instruments on the vehicle or on leading probes)

In order to support these technology developments, we will need:

- More refined design concepts and architectures for large scale exploration missions to provide a framework for related technology developments
- Maintenance and enhancement of key ground

Figure 1: *Entry, Descent, and Landing Technology Area Strategic Roadmap (TASR)*



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test facilities in NASA and other government Agencies, and the development of new test capabilities at low and high altitudes and speeds in Earth's atmosphere

- A steady pace of EDL technology developments and flight tests as well as missions employing EDL segments to develop and grow the experienced workforce that will be needed to successfully land humans on Mars and other destinations beyond LEO
- A robust STEM student outreach program that attracts America's youth and engages them actively in EDL technology development

This roadmap's most direct impact will be on efforts initiated in the next five years, and it is anticipated that the roadmap will be regularly reviewed/revised to reflect changing agency priorities. Section 3 of this document lists a set of recommended immediate actions.

Benefits and Impacts

NASA investments in fundamental atmospheric flight and AEDL technologies in the 1960's and 1970's have enabled many of our current EDL capabilities of today. For example, the current state of the art for human scale Earth entry is defined by the Shuttle Orbiter (1970's). 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 (1970's) and utilized in large part on all of the robotic Mars landers since. TPS technologies developed for Apollo and the Space Shuttle in that same timeframe are being recycled or requalified today for current human spacecraft concepts. NASA's pioneering entry missions to Venus (Pioneer) and the Giant Planets (Galileo Jupiter) were also designed in the 1970's, and current SMD proposal concepts are largely reliant on derivative technologies from those missions for current mission planning. Currently, advances in EDL capabilities are generally driven by individual mission performance requirements, constrained budgets, and near-term schedule demands, and often require high TRL, low-risk technologies for mission infusion. There is a large reliance on heritage technology, even to the point where technology limitations are effectively constraining science objectives for many SMD missions.

The Mars Science Laboratory (MSL), NASA's flagship Mars mission scheduled to launch in 2011, defines the current SOA for Mars EDL systems. MSL is using much of the same Viking-derived EDL technologies and architecture, augmented by the SkyCrane touchdown delivery system, and will 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, without significant investments in new technologies. Human scale Mars missions, the ultimate goal in NASA's human space exploration plans, will require 20-60 t of landed payload mass *[1]*. This represents more than an order of magnitude increase in mass compared to MSL derived capabilities, an increase in capability on the order of the jump between Apollo and the Space Shuttle Orbiter. Human Mars missions of 20-60 t of landed payload mass would necessitate Mars arrival masses on order of 50-150 t. If NASA wants to send humans to the surface of Mars, sustained and coordinated investments 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.

Mission enabling EDL technology requirements are not limited to human or Mars exploration. Large-scale Earth return from hyperbolic velocities will require thermal protection materials well beyond those under development for Orion. Hyperbolic velocities may exceed 13 km/s for some NEO and Mars return opportunities, and will include significant radiative and convective heating. The availability of suitable TPS materials has limited robotic mission planning for Giant Planet probes (due to high heating and pressure encountered) and Mars Sample Return (due to planetary protection reliability requirements). Autonomous landing operations at or near the surface of small bodies with low gravity (asteroids and comets) will require advanced capabilities in terrain recognition, guidance and surface anchoring, particularly for small bodies where the surface may be icy or highly fractured. Human lunar or NEO exploration will require hazard avoidance, precision landing, deep throttle descent propulsion and lightweight landing attenuation systems. Giant planet (and possibly Venus) exploration will require, at a minimum, requalification of out-of-production TPS materials. New classes of advanced science missions, including long-lived Venus landers, robotic airships or airplanes at Mars, Venus, or Titan, new missions that enter and explore the atmospheres

of the gas giants, and Europa landers, may be enabled by coordinated and strategic investments in "push" technologies. Key push technologies include dramatic reductions in TPS mass (Giant Planet), and low ballistic coefficient deployable decelerators (all destinations). Revolutionary advances in propulsion (e.g. nanoenergetic fuels) may enable new EDL concepts to augment aerodynamic drag, and potentially to harvest drag energy during entry.

In general the benefits of focused EDL technology activities include:

- Increased mass delivery to a planet surface (or deployment altitude),
- Increased planet surface access (both higher elevation and latitudes),
- Increased delivery precision to the planet's surface,
- 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,
- Human safety during return from missions beyond LEO, and
- Sample return reliability and planetary protection.

Low TRL EDL technology advancements, from the laboratory through development, qualification and flight test, also provide fertile training ground for young systems engineers and technical workforce. In the 1950's and 1960's, the plethora of aircraft and aerospace flight projects served to develop a cadre of engineering and technical talent that largely enabled the successful Apollo program to land men on the Moon. In addition, other nations are making strategic and concerted investments in EDL technologies which will diminish our technological advantage without focused NASA investment. For our nation to continue to lead, future human solar system exploration and EDL systems capabilities will require investment in and development of the young technical workforce, many of whom may only be in grade school today.

Mission Pull

The following missions (shown in Table 1) relevant to EDL and associated dates were assumed for this roadmap. They were derived from the Agency Mission Planning Manifest *[2]* a Human Exploration Framework Team briefing *[3]*, other agency planning documents, the current SMD decadal survey *[4]*, and other sources. SMD is in the process of updating their decadal survey now; this roadmap will be amended once those data become available.

Technology Area Breakdown Structure (TABS)

The Technology Breakdown Structure is shown in Figure 2.

1. DETAILED PORTFOLIO DISCUSSION

The recommended technology investment portfolio is discussed by TABS element, including a brief assessment of the current SOA and recommended mission pull and technology push investments. Push investments are highlighted in blue.

1.1. Aerobraking, Aerocapture, and Entry Systems (AAES)

AAES are defined as the intra-atmospheric technologies that decelerate a spacecraft from hyperbolic arrival through the hypersonic phase of entry. Over the next 20+ years, NASA mission objectives will require significant advances to the state-of-the-art in AAES in the following areas: higher entry speeds (crew/sample return from beyond 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 low cost COTS access to space. The unique challenges of entering large systems (>1 t) payloads at Mars will require revolutionary changes to the current SOA. Other mission classes will benefit, or in some cases be enabled, by evolutionary or revolutionary improvements to the current SOA. In order to support the required advances in this area, the team has identified six key technology investment areas (product lines) in AAES. Each product line will be discussed below.

Major challenges for all AAES technologies include a wide range of mission requirements that necessitate multiple parallel investments. These include the availability and suitability of ground facilities for testing and model validation, our ability to human rate the developed systems, long term retention of critical EDL-unique skills (particularly for ablative TPS) in the NASA workforce, and the requirement of system level validation of many technologies via flight test. Flight demonstration of aerocapture may facilitate adoption by mission planners, but was not considered to be a major technical challenge. Aerobraking, while a critical capability for some NASA missions, was not determined to have significant technical capability

Table 1. *Potential missions related to EDL technologies and capabilities*

Mission	Launch	Critical EDL Capabilities	Comments
Crewed orbital velocity return	2015	Large-scale Earth EDL	NASA and/or commercial vehicles
Lunar sample return	Competed opportunities in 2017/2022/2027	Lunar landing / Earth EDL of sample	New Frontiers
Asteroid sample return	Competed opportunities in 2017/2022/2027	Asteroid touch and go, proximity operations / Earth EDL of sample	New Frontiers
Venus lander	Competed opportunities in 2017/2022/2027	Extreme environment TPS	New Frontiers
Saturn probes	Competed opportunities in 2017/2022/2027	Low Mass Extreme environment TPS	New Frontiers
Mars sample return sample acquisition	2018	1-2 t class Mars EDL	Advanced from MSL
ISS down-mass capability	2018	Low cost TPS, deployable decelerators	HIAD testing and application
Crewed high-velocity Earth return	2020	Low mass TPS	From HEO in preparation for asteroid mission
Mars sample return orbiter	2022	High reliability TPS and SRC (planetary protection)	Planetary protection requirements
Mars sample return surface rendezvous	2024	Precision landing, deployable decelerators	Meets up with sample cache left on surface
Crewed asteroid rendezvous and return	2025	High-q low mass reliable TPS	Low gravity proximity ops, hover, touch, land
Mars network	2029	Guidance, small low cost SRC	Seismology
Titan aerial vehicle, landers/ splashers	2032	Titan entry, descent and deploy, Titan EDL	Flagship mission
Crewed Mars orbiter	2035	Aerocapture, possible crewed Phobos landing: Mid L/D or Large Deployable Decelerator for Aerocapture	
Crewed Mars surface	2041	Mars large EDL: SRP, Mid L/D or large Deployable Decelerator	~30 metric tons lander
Icy moon lander	2042	Icy moon EDL	e.g., Europa, Enceladus

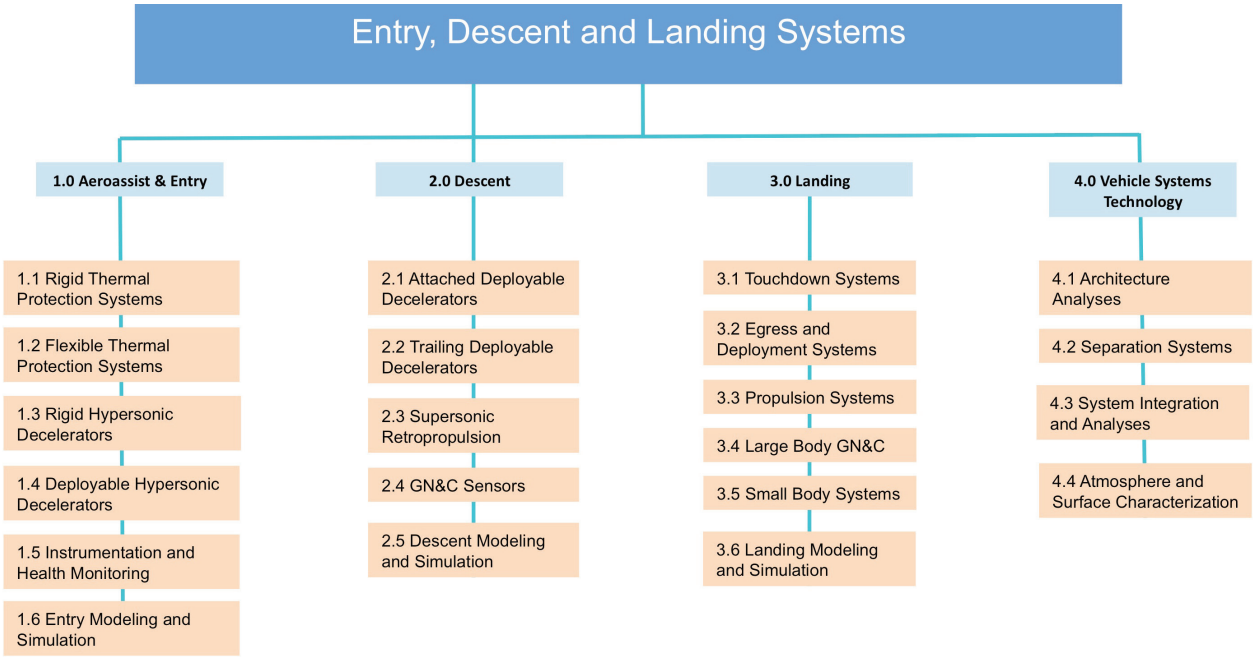

Figure 2. *Entry, Descent, and Landing Systems Technology Breakdown Structure*

gaps other than higher temperature capable solar panels, an advance carried in the In-Space Power (TA02) roadmap. A roadmap has been developed which will overcome most challenges through sustained investment in the technology area, with time-phased milestones to support mission drivers, as well as development of key push technologies that may significantly enhance future NASA mission capabilities or enable new mission classes. The limitations of existing ground test capabilities can only be addressed by the extension of current arc-jet capabilities for Venus, Giant Planet, and human hyperbolic return capability. Technical challenges specific to each AAES investment area will be discussed below.

Finally, it should be noted that TPS technology is also integral to Thermal Management Systems. Entry TPS technologies identified under this TA are consistent with key technologies identified during the Thermal Management (TA05) technology roadmapping process and have been fully coordinated with that team. Several cross-cutting technology areas, including reusable acreage and WLE TPS, heat pipes, in-space repair, self-healing TPS, and multifunctional combined thermal and integrated load bearing structural TPS are discussed in detail in the Thermal Management Roadmap, while the core Entry technologies of rigid and flexible TPS are discussed in both roadmaps.

1.1.1. Rigid Thermal Protection Systems (TPS) (cross cutting with TA05-Thermal Management)

Previous vehicles used TPS installed on a rigid aeroshell/structure, ranging from the reusable tiles on the Orbiter to ablative systems employed for planetary entry and Earth return from beyond LEO. For many exploration missions, such as near-Earth asteroid and Mars missions, ablative materials are an enabling technology needed for dual heat pulse reentries and for high velocity entries (>8 km/s). However, the current selection of high TRL rigid TPS materials is inadequate for future mission objectives, due to either insufficient thermal performance or high areal mass. Only a limited number of materials, PICA (Stardust, MSL), Avcoat (Apollo, Orion), Carbon Phenolic (Pioneer Venus, Galileo), SLA-561V (MER, Phoenix) and ACC (Genesis), have been used for previous or upcoming, exploration missions. The U.S. no longer possesses the capability to manufacture the flight qualified Carbon Phenolic TPS material used for the Pioneer-Venus and Galileo missions as a result of a lack of suppliers for the critical precursor Rayon materials and the absence of a U.S. based carbonization processing capability that is required to produce the entry grade TPS. Advances are required to significantly lower the areal mass of TPS concepts, demonstrate extreme environment capability, demonstrate high reliability, demonstrate improved manufacturing consistency and lower cost, 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. Experience has shown that a large fraction of aeroshell risk and DDT&E costs are due to integration and closeout issues. However, these issues are implementation-specific engineering problems, not technologies per se. Therefore, while very important, they are not included in this roadmap. Current agency investments include ablative materials development within ARMD (Hypersonics) and ESMD (Orion & ETDD), primarily in support of crewed return from the Moon and Exploration missions to Mars. Investments in SMD (In-Space Propulsion) advanced the TRL of several new ablators to 3-4 and are beginning to explore the challenges of Carbon Phenolic redevelopment. These investments have already demonstrated the potential to reduce TPS areal mass by ~40% for these applications via dual-layer or graded design *[5]*. Larger mass savings may be possible via push investment in tailored materials that reject a component of incident heating (radiation or catalysis), tailor material properties as a function of depth, or employ new reinforcement or impregnant concepts. However, there is currently minimal investment in materials concepts for other mission classes and highly innovative multifunctional materials. Notably, as a result of the lack of Carbon Phenolic material supply chain issues noted above, missions that involve Earth return of crew from beyond the Moon, or robotic entry to Venus or the Giant Planets, have no available qualified TPS solution at this time. Further exploration of Jupiter will require significant reduction in areal mass over Carbon Phenolic in order to avoid entering probes with a TPS mass fraction approaching 1.0. Other mission classes must resort to capable, but extremely heavy, TPS solutions. Entry to Titan, robotic entry to Mars, and LEO return missions can be accomplished with existing high TRL TPS, although evolutionary advances may have mission benefit. Push technol-

ogies, such as TPS materials that reflect incident shock layer 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. Recent efforts under Constellation have revived ablation analysis capabilities. TPS development efforts should be expanded to include material response/flow field coupling codes (for both engineering calculations and high-fidelity solutions), integration of ablation models into standard 3-dimensional thermal modeling codes, and ground testing to generate data for code correlation and validation. The parallel development of high-fidelity material response models is particularly important for entry TPS, where a "test as you fly" approach to system validation cannot be applied, and therefore the designer is dependent on simulation capability in order to define the baseline system as well as the necessary margin in order to meet reliability requirements. There is some TPS investment within other government Agencies and industry, with a primary focus is on reusable systems to support hypersonic cruise. Major technical challenges include the development of fundamentally new material concepts, fidelity of current response models, availability of suitable ground test facilities, ground to flight traceability, high uncertainties in input aerothermal environments (covered in Section 1.1.6) 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 level flight test. Primary areas of recommended NASA investment are summarized below:

- Advanced Ablator materials
  - » Mid-density ablators for Earth return from beyond LEO, Venus, and Mars entry missions, including dual heat pulse capable materials with at least 40 percent lower areal mass than the current SOA (overlap with Thermal Management, Materials & Structures).
  - » Extreme environment ($q > 2$ kW/cm^2, $p > 1$ atm) materials, including redevelopment of extremely high-reliability (using heritage Rayon) Carbon-Phenolic for Mars Sample Return, and alternate materials for future missions to Venus and the Giant Planets.
  - » Development of radiation reflective and smart or self-healing ablator systems
- Multifunctional materials designed for thermal protection as well as improved MMOD and radiation protection (covered in the Thermal Management Roadmap)
- Improved thermal response models, including high fidelity ab initio in-depth ablation response, gas-surface interactions, and computational materials design capability. (overlap with Materials & Structures)
- Improved processes for quantification of TPS margin and system reliability, including statistical analysis, testing techniques, and archival storage of agency thermal test data, as required for COTS and NASA crewed vehicles as well as high reliability sample return missions.
- Improved manufacturing and inspection processes, which should include the use of automated, robotic systems especially for coating/primer application and material installation on structure.

1.1.2. Flexible Thermal Protection Systems (cross cutting with TA05-Thermal Management)

System studies have shown that large entry decelerators provide a potentially enabling means to increase landed mass on the Martian surface, as well as the consideration of a whole new class of missions. Flexible TPS is an enabling component for deployable entry systems (Section 1.1.4). In addition, current research *[5]* indicates that high performance flexible materials may provide strongly enhancing benefits for rigid systems as well (in terms of reduced life cycle cost and ease of manufacturing, as evidenced by Orbiter LCC data). In addition, flexible TPS applied to rigid aeroshell structure should significantly mitigate design issues such as cracking, thermostructural performance, bond verification, and scalability to large aeroshells. These advances may provide game-changing benefits to multiple current and future NASA missions, as well as COTS Cargo and/or Crew return concepts. The current SOA is the AFRSI blankets employed on the leeward side of the Orbiter, which are reusable systems designed for ~5 W/cm^2 of maximum heating. Future deployable entry systems will require TPS concepts that can be stowed for months in space and then deployed into an entry configuration that can withstand 20-150 W/cm^2 of heating at Mars or Earth. These are envisioned as single or dual (entry plus aerocapture) use systems. Both non-ablating and ablating concepts may be

suitable, where the key trade is TPS development complexity versus system scalability and controllability. 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 fiber weaving techniques can be employed to tailor material properties for given mission requirements. The current NASA portfolio includes small investments in q<40 W/cm^2 non-ablative materials (ARMD Hypersonics), and q<150 W/cm^2 ablative materials (ESMD ETDD). All of these materials are low TRL at this time, although a TRL 4 insulative 20+ W/cm^2 system is planned to be flight tested in 2012 on IRVE-3. As a push technology, the extension of flexible 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 and or shock layer radiation, which may provide strongly enhancing mass savings for all NASA missions. 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. Areas of recommended NASA investment are summarized below:

- Non-ablative (insulative or transpiration cooled) concepts with high flexibility & stowability,
- Ablative concepts, including systems that rigidize in-space or during entry. Includes high-heat flux semi-flexibles (q > 150 W/cm^2) for low-cost application to rigid aeroshells,
- Multifunctional materials that provide MMOD/radiation protection and/or carry structural loads,
- Non-catalytic coatings to reduce aeroheating environments and additives to reflect radiant heat,
- Improved thermal response and reliability quantification models.

1.1.3. Rigid Aeroshells

All NASA entry vehicles to date have employed rigid aeroshells, with almost all concepts in one of two classes: low-L/D, and mid-L/D (Orbiter). The current SOA is the classic sphere-cone (70° at Mars, 60° at Earth, 45° at Venus and Giant Planets) and the truncated sphere (Apollo and Orion). Typically these aeroshells are either metallic or composite, with the TPS bonded to the structure via an adhesive. The carrier structure is designed to bear all aerodynamic loading (without reliance on the TPS). Control of these vehicles has been effected via Reaction Control Thrusters in most cases (aerodynamic control surfaces are of course employed on the Orbiter). There has been very little effort within NASA to develop new entry aeroshells or aeroshell technologies beyond the conceptual stage, primarily due to the lack of a mission driver. However, one class of mission, 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. Current NASA investment in alternate aeroshell designs is minimal beyond the conceptual stage, and includes an Apollo derived aeroshell for Mars 2018, and a stable parachuteless capsule for Mars Sample Return (SMD – ISPT). Previous studies included mid lift/drag (L/D) (biconic or ellipsled) designs for Mars entry and Neptune aerocapture, 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 current state of the art in several supporting disciplines, notably aerothermodynamics, has large uncertainties leading to large design margins and mass-inefficient entry systems (covered in Section 1.1.6). Non-NASA investment in such systems has been restricted to slender cones for RV applications and mid to high lift hypersonic cruise vehicles, which are minimally applicable to proposed NASA missions. Major technical challenges include developing lightweight structures, effecting non-propulsive control for low to mid L/D bodies, and the development of high fidelity aero/aerothermal databases, including dynamic stability. In addition, push investment in advanced guidance algorithms (such as numerical predictor/corrector) is required for aerocapture and could enable precision landing of entry vehicles, including optimal divert for proximity operations of multiple landed assets. Concept maturation to TRL 6 will require a mix of ground and subscale system level flight tests. Areas of recommended NASA investment include:

- Highly reliable sample return capsules that meet planetary protection requirements, low cost aeroshells (50% reduction over SOA), and performance optimized low lift aeroshell designs,
- Performance optimized lifting bodies (L/D ~ 0.6) for high mass entry and aerocapture,
- High lift (L/D > 2.0) maneuverable bodies for aerogravity assist,
- Dual use launch shroud/payload fairings and entry aeroshell systems
- Advanced lightweight structures, including warm/hot structures/adhesives and integrated structural/ TPS systems that reduce total aeroshell mass by at least 40% over current SOA for multiple mission classes (overlap with Materials & Structures),
- Non-propulsive flight control effectors, including control surfaces and active c.g. modulation,
- Advanced guidance and navigation systems for aerocapture and entry, including precision guidance for multi-probe missions.

1.1.4. Deployable Aeroshells

Deployable entry systems provide a means by which the ballistic coefficient at entry is relatively unconstrained by launch shroud limitations. 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 and COTS missions ranging from International Space Station (ISS) downmass to crewed Earth return from beyond LEO. No truly deployable entry system has been tested at flight-relevant scale (other than for aerobraking, which is performed using deployed solar panels), but multiple small-scale flight tests have been conducted (most recently IRVE-II in 2009) with varying degrees of success. NASA has significant investment plans in this technology area, including IRVE and supporting materials and analysis research (ARMD Hypersonics & ESMD ETDD) and a "fast-start" hypersonic inflatable aerodynamic decelerator program sponsored by OCT. Similar investments have been sponsored by other government Agencies and industry for applications such as payload recovery and stage separation, although primarily in the supersonic regime. However, the only deployable entry concept that has seen significant development to date is inflatables; investment in mechanically deployed systems lags significantly despite having been identified as attractive in multiple system analysis studies. Major technical challenges include scalability, reliable deployment, aeroelastic and aerothermoelastic effects, 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. Primary areas of recommended NASA investment include:

- Attached or towed inflatable entry systems employing advanced flexible TPS technology,
- Mechanically deployed and/or on-orbit assembled entry systems,
- Transformable or morphable entry systems for use during descent and or landing,
- Advanced high temperature flexible structural materials, including bladders, ribs, and rigidizable concepts that can reduce structural mass over current SOA (overlap with materials & structures),
- Non-propulsive flight control effectors, including control surfaces and active c.g., modulation; methods must account for and be consistent with potential system flexibility,
- Advanced guidance and navigation systems adapted to deployable system controllers,
- Advanced fluid structure interaction modeling sufficient to predict and mitigate aeroelastic and aerothermoelastic effects, including dynamic buckling, on material and system performance, and
- Advanced aerobraking concepts including autonomous control methods that can greatly reduce "human in the loop" costs and reduce the risk of planetary aerobraking.

1.1.5. Entry Instrumentation and Health Monitoring

Entry instrumentation for both engineering data and vehicle health monitoring provides a critical link between predicted and observed performance of the AAES system, and is crucial for improving the design of current systems, and for ensuring sufficient system reliability prior to deployment or use. In addition, 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. The current SOA consists of thermocouples, recession sensors, and pressure ports embedded into the TPS material (such as will fly on MSL in 2011), and acoustic impact detection systems used on the Shuttle wing leading edge. There is little current NASA investment in this area other than through a few research grants within ARMD/FAP. In addition, there is some development of wireless systems within Constellation (CUIP), but that is slated to end in 2011. Recent investments in the SMD ISPT led to the development of advanced recession sensors that will fly on MSL in 2011. Major technical challenges in entry instrumentation include 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. Primary areas of recommended NASA investment include:

- Sustained investment in improved intrusive entry instrumentation (e.g., faster response times, higher thermal capability, compact low mass pressure measurements, direct measurements of heat flux, catalycity), and development of systems for the measurement of shock layer radiation,
- In-situ instrumentation for flexible/deployable TPS systems,
- Semi or non-intrusive instrumentation concepts, including wireless (data and power), electromagnetic, and acoustic based systems,
- Advanced distributed systems for MMOD detection,
- Advanced ISHM systems, including multifunctional response and the ability for closed-loop initiation and monitoring of *in situ* repairs, and
- Remote observation platforms for Earth entries.

1.1.6. Entry Modeling and Simulation

Often overlooked in technology roadmaps, modeling and simulation capabilities, including experimental validation, are a lynchpin of modern AAES design. Ground test limitations preclude a "test as you fly" approach to AAES, and flight tests are prohibitively expensive for most missions. As a consequence, validated high-fidelity models are used to extrapolate ground test results to predict flight performance. The current NASA SOA in entry system modeling ranges from good (flight mechanics and 6-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 validation of these codes at flight-like conditions (e.g., high enthalpy, high Reynolds number, correct gas composition). Well designed ground tests are a critical component of simulation validation. NASA currently supports some core investment in modeling and simulation (primarily in the Aerosciences) in ARMD (Hypersonics) and ESMD (Orion and ETDD), as well as some validation activities in the NASA Engineering and Safety Center (NESC) (RCS-aero interactions). Flight missions, such as MSL, typically invest in the development of mission-specific databases, but do not support investment in advances to the state of the art. Modeling and simulation, and its validation, is an area where a sustained investment in core technical disciplines is essential to maintaining cutting-edge design practices for future missions. In the Aerosciences, specific advances are required in the area of higher order turbulence modeling (such as DNS 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. These phenomena must be modeled in the context of a hypersonic chemically reacting environment, which places additional constraints on the methods employed. Many improvements to the state of the art 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. Note that atmosphere modeling is included in Section 1.4.5. Primary areas of recommended NASA investment include:

- Development of validated multi-disciplinary coupled analysis tools (bridging aerosciences, flight mechanics, structural, and thermal

analysis), particularly for high reliability and extreme environment applications,

- Sustained investment in improvements in aerodynamics and aerothermodynamics modeling, including shock layer radiation and high enthalpy ionized turbulent and separated flows, across the continuum and non-continuum flight regimes. Includes a strong focus on flight relevant experimental validation,
- Sustained investment in the underlying numerical methodologies and techniques, taking advantage of expected computer architecture and hardware improvements (*overlap with Modeling & Simulation*).

1.2. Descent

Descent 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 a terminal descent propulsion system or landing. Historically, the descent phase of flight has focused on simply providing sufficient deceleration to stage to a particular landing system, and thus the primary technology for this phase of EDL has been the parachute. As planetary missions move towards larger payloads with greater emphasis on targeted landings, the SOA in descent technology will require major advances. These advances primarily focus 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 provide benefits to a variety of mission concepts at other planets as well, particularly as larger and larger landed masses are desired. As with AAES, the team has identified five focused technology investment areas and each is discussed below.

Although each of the descent technology areas identified has a unique set of challenges associated with it, the issue of scalability impacts nearly all of them. That is, 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 appreciable scales but also develop strategies for flight programs to qualify the technology at larger sizes and more stringent test conditions.

1.2.1. 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 (Section 1.1.4) in that they are deployed endo-atmospherically after the peak heating and peak deceleration phases of flight. As a result, the thermal and structural environments are considerably less severe, although with the added complexity of a dynamic deployment event. Attached decelerators can provide order of magnitude increases in drag area at Mach numbers and dynamic pressures considerably higher than current supersonic decelerators, which in turn enables increased timeline margin and/or increased mass delivery to higher elevation landing sites. The primary application of attached deployable decelerators may be at Mars due to its tenuous atmosphere, but other applications, including ISS downmass and the landing of large payloads on other atmosphere bearing bodies, are possible. Attached decelerators can be further categorized as flexible (e.g. SIADs) 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 prior development on 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, has continued over the past five years within ARMD/FAP. More recently, SIADs have been identified by OCT and SMD as the target of a fast paced

development and flight test program aimed at achieving TRL 6 in 2013. Development of mechanically deployed or rigid attached decelerators is largely non-existent except in conceptual studies. Most envisioned attached deployable decelerators are purely drag devices, but a push investment in lifting deployables (such as guidable or steerable systems) could have game-changing impact in terms of landing precision. Major technical challenges include scalability, deployment methodology (for non-inflatable designs), dynamic stability, and controllability. Primary areas of recommended NASA investment include:

- Progression of SIAD development into large scale atmospheric flight testing,
- High strength, high temperature textile fabrics and coatings that can extend the thermal environment in which deployable decelerators can operate,
- Staging mechanisms or systems for phased drag deployment,
- Mechanically deployed decelerators and methods of active (e.g. drag modulation) control,
- Steerable and guided deployable decelerators, and
- Dual mode attached decelerator systems that are optimized for supersonic and subsonic flight.

1.2.2. 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. The SOA in subsonic trailing decelerator technology are ribbon and ringsail parachutes, used individually or in clusters, such as employed on Pioneer Venus Large Probe, Galileo, Apollo, and planned for Orion. The SOA in trailing decelerator technology for supersonic use is the DGB parachute developed through the PEPP, SPED, SHAPE, and BLDT flight test programs of the 1960's and 1970's *[9]*. These parachutes have been the primary deployable decelerator for planetary robotic missions for the past 40 years. The qualification limits in size and deployment conditions for these parachutes hinder the ability to land missions beyond the size of MSL. Supersonic parachutes larger and more efficient than the 21.5 m DGB used by MSL will enable larger Mars robotic missions and will likely be used as staging devices for larger human class missions. In addition, the ability to deploy such chutes at higher Mach number, which requires technology advances in textile strength and thermal performance, may provide significant timeline benefit for some missions. The amount of heritage in subsonic parachutes for other planetary applications is much larger than with supersonic chutes, though not always in a relevant environment (e.g., temperature and density). Entries to Venus and the Giant planets can use traditional subsonic parachutes with good efficacy, although investment in higher temperature capability textiles is warranted for those applications. Additional investment in evolutionary concepts, like parachute clusters and multi-stage reefing, is warranted, but is not considered a significant advance to the state of the art over, for example, Apollo. Investment in lifting trailing decelerators (such as paragliders) as descent systems does not seem warranted given proposed mission requirements. NASA investment in parachute technology has been nearly non-existent since the Viking BLDT program with the exception of three high-altitude subsonic drop tests of a 33.5 m ringsail. IADs 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. Primary areas of recommended NASA investment include:

- Large (> 30 m) subsonic and supersonic parachutes for low density use, including multi-stage reefing,
- More capable supersonic parachutes (larger diameter, > Mach 2.2, 800 Pa dynamic pressure deployments),
- High strength, high temperature textile fabrics and coatings that can extend the thermal environment in which trailing decelerators can operate,
- Trailing inflatable aerodynamic decelerators (ballutes), and
- Embedded wireless sensors and algorithms for smart feedback.

1.2.3. Supersonic Retropropulsion (SRP)

As Mars missions approach human class entry masses, the required size of supersonic deployable aerodynamic decelerators renders them impractical due to the tenuous atmosphere *[6]*. As a result, initiation of propulsive deceleration must occur earlier in the descent phase while the vehicle is traveling at supersonic velocities. Thus, SRP becomes an enabling technology for human class Mars missions *[6]*. Smaller-scale SRP systems may

have enhancing benefits to other mission classes as well. The SOA in SRP is limited to primarily Viking era wind tunnel testing of a limited number of notional configurations using perfect gas jets *[7]*. No engine development specifically for supersonic decelerator applications has been funded. NASA investment in the fundamental physics of SRP has been reinvigorated recently through funding by ARMD FAP and ESMD ETDP *[8]*. Current systems analysis is focused on cryogenic LOX/Methane systems (to take advantage of in-situ propellant generation), but exploration of alternate fuels should be undertaken as well. Primary areas of recommended NASA investment include:

- Advanced algorithms and sensors to dynamically control and stabilize the entry vehicle in the presence of complex fluid dynamic interactions,
- SRP configurations and packaging studies for high-mass entry vehicles,
- Flowfield modulation through the use of SRP,
- Deep-throttling (10:1), high thrust (100s of kN) engines for Mars descent,
- Sustained investment in computational tool V&V efforts (particularly fluid mechanics), and
- Expansion of the SRP initiation envelope into hypersonic regimes.

1.2.4. Guidance, Navigation, & Control Sensors

GN&C during the descent phase is typically non-unique and utilizes common instrumentation with the entry phase. A major exception is in the area of the triggers used to initiate events such as parachute deployment and heatshield jettison. Timers or inertial based velocity/altitude triggers represent the SOA in descent-phase event timing. More advanced event trigger capabilities, based on new sensor technologies and advanced on board computing power will enable greater landing and targeting precision, and more robust EDL systems in general. New sensor capabilities for event triggers may include real time atmospheric density and wind measurements via flush air data systems, optical terrain relative navigation, "smart parachute" deployment, and real time load measurements and heath monitoring. Investments in alternate event trigger mechanisms have largely been in the area of conceptual studies, although industries outside of NASA have developed sensors with potential application to future planetary missions. The primary area of recommended NASA investment is:

- Development of advanced event trigger sensors and algorithms to reduce dispersions.

1.2.5. Descent Device Modeling & Simulation

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, typically 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 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 current 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 investment in low dissipation flux methods and high spatial and temporal accuracy CFD solvers with high-order turbulence closure is certainly required. NASA support in maturing FSI and SRP modeling capabilities has been through the ARMD FAP and recent ESMD EDTP technology development tasks. Primary areas of recommended NASA investment include:

- Sustained development of FSI tools for static and dynamic assessment of flexible decelerators, Including acquisition of data sets useful for FSI validation efforts at relevant aerodynamic and aerothermodynamic environments,
- Sustained development of SRP modeling tools, and
- Sustained investments in improved aerodynamic modeling of aftbody and wake interaction flows.

1.3. Landing

The landing phase begins with the sensing of the surface and the operation of a terminal descent propulsion system (if present) 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. In the case of aerial vehicles, landing refers to the transition from deceleration to aerial free flight. The landing event may also include an egress/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. Environmental characterization of the atmosphere and surface is covered in Section 1.4.5.

1.3.1. Touchdown Systems

Small Robotic Landers (<100 kg): This category covers a wide range of potential architectures from legged systems to airbags and high G survivable systems (>5000 Gs). 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 such as DS-2 at Mars, 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. The lack of Agency/industry experience in designing and qualifying ruggedized instruments and electronic and power systems is generally their key limitation to broader adoption. Extensive ruggedization experience exists within the defense sector, which in many cases could be adapted for space flight. 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 selection prior to arrival requires these systems to be designed for more extreme surface 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 capability such as attempted by the Japanese Hayabusa probe. These technologies are discussed in more detail in Section 1.3.5. Technology investments 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.

Large Robotic Landers (100-1500 kg): This category covers robotic exploration of the Moon and Mars, as well as landing systems for Venus and Titan. Touchdown system landing performance is a major factor in landing site selection. Local topography and mechanical properties of desired landing sites will dictate the complexity of the touchdown systems employed, conversely, the limitations of the touchdown systems imposes restrictions on the sites that can be targeted. Large robotic missions will likely entail surface mobility and /or sample return systems. 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 (1500-45000 kg): This category covers not only human exploration of the Moon, NEO's, and Mars, but also large-scale robotic precursor missions. 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 com-

patible 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 in turn 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 to more clearly identify technology gaps which will in turn create more options for designers.

1.3.2. Egress and Deployment

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, leveling devices. The MSL SkyCrane system is an example in which the spacecraft configuration was designed specifically to eliminate egress. As mobile systems become large, 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.

1.3.3. Landing Propulsion

Technology advances in rocket propulsion technology (such as nano-energetic fuels and high-thrust LOX/Methane engines) could provide significant benefits to EDL. However, such advances are not directly considered within this roadmap, but are rather captured within TA-02. Regardless of the propulsion system employed, rocket plumes pose four major hazards during the landing event; soil erosion also referred to as trenching, dust cloud generation which can obfuscate sensors and leave deposits on surfaces, generation of high velocity debris which can damage nearby surface assets, and ground effects interactions with the flight system which generate destabilizing forces on the lander. Mitigation, prediction, protection are the three main ways of addressing plume effects.

- Mitigation techniques such as rocket motor design (Viking shower-head nozzle) and vehicle architecture (MSL SkyCrane) are the current SOA. Alternate mitigation techniques could include *in situ* landing site preparation, hard landers, or other concepts. Apollo did not need to do anything specific to mitigate plume effects primarily because the lunar regolith has very high inherent strength and did not erode significantly under plume forces. Mitigation techniques will be required for Human class landers targeting Mars where the regolith mechanical properties are not as robust as those on the moon, and plume forces and size are significantly larger than robotic class vehicles.
- Prediction techniques are largely CFD-based and in their early phase of development. Plume effects modeling is needed to ensure that vehicle configuration, landing site topography and flight system control system and control authority are compatible with the predicted levels of interaction. Continued investment in CFD-based plume interaction (including multi-phase continuum flow modeling) is needed. Methods of predicting soil erosion/trenching are also needed.
- Plume accelerated debris protection techniques are required for mission architectures which have surface elements landing within less than ~1 km from each other.

1.3.4. Landing Guidance, Navigation, and Control for Large Bodies

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 had only that). 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). 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 the efficient use of propellant in the redirection of the terminal descent to the desired targets and in avoiding hazards. The challenges in meeting these needs are:

- Robust algorithms for terrain tracking using passive and/or active imaging and on-board maps derived from orbital data, compensating for variations in distance, orientation, lighting, and visibility (also enabling for small bodies — see Section 1.3.5, and potentially enabling for lower cost altitude and velocity sensors to replace existing radars when terrain tracking is not needed),
- Robust algorithms for the identification and location determination of landing hazards using just-acquired passive and/or active imaging, with a low probability of false positive or negative indications,
- Passive and/or active visible or near-IR imaging sensors to provide the data for terrain tracking and hazard detection, and that are compact and low-power,
- Algorithms that predict and correct landing location errors relative to a changing target from the position and hazard detection components, and do so with optimal fuel usage,
- Adaptive or reconfigurable control algorithms to react to failed systems or components, and
- Highly capable and low power on-board dedicated compute elements to support terrain tracking, hazard detection, and possibly trajectory optimization at rates suitable for use in terminal descent on large bodies.

A worthy goal would be development of an integrated Terrain Tracker assembly, that would incorporate the sensors, compute elements, algorithms, and maps all into a single, small box with a simple interface, much like modern Star Trackers. Hazard detection algorithms could be hosted on the device as well.

1.3.5. Small Body Systems

The SOA for NASA in small-body proximity maneuvering was achieved by NEAR, which approached and landed on Eros in an end-of-mission experiment. This demonstrated the ability to navigate a descent, but did not demonstrate the capabilities needed for small-body *in situ* exploration, sample acquisition, or crewed operations. Japan's Hayabusa spacecraft attempted proximity operations at Itokawa, but was damaged by uncontrolled contact with the surface *[10]*. Proximity maneuvering around and on small bodies such as near-Earth asteroids and comets is a terminal descent guidance and landing problem. It differs from large-body terminal descent in that several new modes are added such as ascent, hover, and touch, all in concert with fault protection responses, and it differs in that the time scales for knowledge and control are longer. Future robotic and crewed missions to small bodies will require terrain-relative guided flight around and in contact with the small body, precision targeting to avoid hazards and apply tools between them, guidance laws and fault protection integrated together to assure only controlled contact with the body, and the ability to remain contact with the body either actively or passively and apply normal force to the body with surface sampling and measurement tools. The challenges in meeting these needs are:

- Terrain tracking as in Section 1.3.4,
- Guidance that targets tool contact with the body using terrain tracking, and that robustly reacts to unforeseeable forces from contact, controlling both attitude and position to avoid inadvertent contact by other portions of the spacecraft,
- State machines to control descent, touch, land, hover, and ascent modes in the presence of faults,
- Touchdown and anchoring/grappling systems to enable the application of order 100N normal forces to surface material by end-effector tools for periods of time from seconds to hours depending on the application, and
- A physics-based end-to-end simulation capability with hardware in the loop for the qualification of terrain tracking and proximity operations during project development.

1.4. Vehicle Systems Technology

A comprehensive understanding of component, subsystem, and system level performance is inherent to all successful entry vehicle systems. Prior to having sufficient flight test and operational experience, which validates a design and identifies anomalies, design verification is provided via large scale ground tests, flight tests and evaluation of design margins compared to the environmental factors that stress a system's capability. In addition, systems technology capabilities perform a key role

of identifying, characterizing and maturing system level integration and design. EDL systems are by their nature an integrated framework of technologies that necessitate system level efforts for robust maturation. At the entry vehicle level, systems are defined by their payload mass class as well as the means by which the vehicle transitions from one stage or configuration to another. In addition, architectural studies provide a strategic and critical function to define a path forward that aligns with national goals and objectives and enable informed technology investment decisions. Within this context, there are several core technology fundamentals that must be addressed to enable this decision making process. This roadmap atempts to identify those technologies that, will have the most significance in shaping such capabilities. As a distinction from individual component or subsystem level technologies, certain EDL technology frameworks encompass many aspects of a vehicle and will be captured in the context of a system technology. Vehicle Systems Technology will thus be segmented into three areas that have implications across the entire EDL architecture: Separation Systems, Vehicle Technologies, and Atmospheric Modeling & Surface Characterization. Major challenges exist to mature advanced technologies for micro payloads (<100 kg), science robotic payloads (< ~1500 kg), large payloads (<~3000 kg) and human class payloads (>~3000 kg) which would eventually lead to human class capabilities. Identification of system technologies that enable a wide range of payload mass is essential. The likely need to accomplish technology development with reduced ground infrastructure will also drive modeling and simulation to provide integrated physical modeling environments. These integrated modeling capabilities must be grounded in physics, and coupled in a manner that addresses the gap between what can be tested on the ground and the actual flight environment. As a separate consideration from payload mass class, the technology to successfully stage, transition, and avoid recontact of vehicle components during exo-atmospheric, hypersonic, supersonic, terminal descent or touchdown phases will always encompass some of the most challenging vehicle technology issues covered by EDL. As a necessary subset of vehicle reconfiguration, the technologies that enable a transition from one configuration or stage to another are critical. Vehicle transition and staging technologies ultimately determine which technologies can be successfully integrated together. In addition technologies oriented around payload mass and configuration staging, EDL for atmospheric bodies will require atmosphere characterization to a higher degree than currently achieved. Given the current state of atmospheric models for potential planetary entries to Mars, Venus or some of the moons within our solar system, additional technologies are needed to characterize the altitude and seasonal variations. Application of these technologies would provide a framework of scientific data to support development of variational models for day-of-entry assessments and weather pattern prediction and modeling.

1.4.1. Separation Systems

EDL traverses flight segments usually involving essentially static vehicle configurations, punctuated by transitions between these configurations. The time scales of vehicle reconfiguration vary significantly between exo-atmospheric conditions, where there are no aerodynamic forces to contend with, down and through aerodynamic loading associated with hypersonic, supersonic, and subsonic conditions for atmospheric entries. Many of the component level technologies associated with Separation Systems are mentioned in previous sections. However, it is essential that particular attention be given to the technology involved with integrating component level technologies for staging and separation into flight demonstrated systems. Within the context of this roadmap, this is considered to be of sufficient criticality that specific characterization of the SOA and push technologies will be included. A brief characterization of each EDL flight phase, in addition to several other key areas, is included below. Due to the difficulty in successfully and reliably accomplishing vehicle staging and reconfiguration, sustained investment in establishing integrated technology solutions for each of these flight phases will be necessary and will ultimately define what combinations of entry systems are possible. Component and subsystem technologies must be integrated and flight demonstrated due to the high risk and single point failure modes that are critical to successful vehicle staging and separation. Flight testing wrings out the inadequacies in such integrated systems, and is a necessary component of technology maturation. A vehicle transition example for the system level framework can be appreciated by considering possible re-contact after an initially successful separation. All the component technologies leading up to separation can be successful, but the integrated approach must reliably and successfully

lead to complete separation of the vehicle components without recontact.

- **Exoatmospheric.** The current SOA includes shroud separation, vehicle rendezvous and docking, and in-space construction (e.g., ISS). Push technologies include on-orbit component robotic construction, mechanical or inflatable deployment of staged systems, or rigidizable aeroshell sub-systems.
- **Hypersonic-Supersonic.** The current SOA includes aerodynamic control surfaces and trailing vehicle separation/disposal by propulsive, pyrotechnic or mechanically assisted components. Push technologies include mechanical or inflatable deployment of staged hypersonic aeroshell separation, or propulsive based hypersonic stage separation.
- **Supersonic-Subsonic.** The current SOA includes aerodynamic control surfaces, payload bay door opening/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. Push technologies include mechanical or inflatable deployment of staged systems, supersonic aeroshell and entry shroud separation, or propulsive-based stage separation.
- **Terminal Descent – Touchdown.** The current SOA includes parachute, mortar, or landing gear deployment, or shroud separation assisted by propulsive, pyrotechnic or mechanically assisted components. Push technologies include larger scale tethering devices for SkyCrane 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/debris with large propulsive system plumes suggests that technology investments should be considered for preparing a landing zone prior to touchdown. Risks associated with plume-soil interaction are discussed in landing Section 1.3.3. The current SOA is at a very low TRL and includes push technologies such as microwave conversion of soil to sintered surfaces or other soil processing methods to prepare a 'landing pad'.
- **Component Technologies.** Several component level technologies have been mentioned in the discussion above that are crosscutting and enabling for vehicle transition and staging. 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 (see Sections 1.2 & 1.3).

1.4.2. Vehicle Technology

EDL systems naturally separate themselves into categories driven by external factors. At the entry vehicle level, payload mass is one of the primary characteristics that drives the option space for technology utilization. Systems that are viable for one class of mass are not appropriate for other classes. With this factor in mind, EDL vehicles are separated here into four payload mass categories that require technology development and tailoring to suit the needs of each vehicle scale. Focusing effort into categories will enable the technology solutions that are appropriate for different mass ranges to be distinguished as such, and pursued separately. In addition to this, one of the principle techniques to facilitate investigations of integrated design solutions and flight test performance is the use of integrated mission simulations. For this reason there is a strong dependency on the technologies identified earlier, in addition to probabilistic design technologies identified in the TA12 (Materials and Structures) and integrated modeling approaches such as the digital vehicle concept identified in TA11 (Modeling and Simulation). Ultimately, the basis of these simulation capabilities in concert with ground and flight testing will provide a foundation for down select decisions on technology suites and certification analyses for the robotic, robotic-precursor and human spaceflight missions of the future. Such simulation capabilities provide the only means to evaluate how sub-scale flight tests performed to validate system technology approaches will be applicable to full scale. It is thus imperative that higher fidelity simulation and testing capabilities be integrated into the fabric of early technology development efforts, and that conscious and strategic emphasis is placed on developing these technologies to support and enable Vehicle Technology. To enable this process, additional perspective on the vehicle payload mass classes and integrated simulation are provided below. This perspective is defined in order to capture a framework that will enable component and systems level technologies to be pursued within an approach that directly recognizes that technologies will be best suited to a limited payload mass range.

- **Micro Payloads.** This class of payload mass is targeted to less than approximately 100 kg. The current SOA is characterized by the unsuccessful Deep Space-2 and Beagle 2 Mars entry vehicles. The high visibility and success of the NASA micro-satellite activities presents a compelling case for this model to be extended to micro-entry vehicles. The low entry price for this weight class of vehicle makes it an ideal candidate to promote STEM efforts that will enable and engage a skilled workforce for the future. Push technologies could include high-g self-guided navigation aids/beacons or sub-surface investigators, collaborative nano-satellite/micro-payload systems for return of biological or material samples from orbit, or low-power/mass MEMS based accelerometers or IMUs.
- **Science Robotic Payloads.** This class of payload mass is targeted to less than approximately 1500 kg. Current SOA is characterized by the Mars robotic vehicles, which utilize the Viking aeroshell configuration, reaction control systems for high-speed control, DGB supersonic parachutes, and a variety of terminal descent systems. These terminal descent systems include the use of airbags, sub-sonic retropropulsion, or the SkyCrane. Push technologies include the use of non-Viking entry configurations (The NASA 2018 Mars "Max-C" mission is planning an Apollo-derived entry configuration), inflatable/deployable aeroshells, higher L/D configurations, precision or pinpoint landing capabilities, high-G capabilities for landing that enable different design approaches, aerocapture, aerobraking, SRP, etc.
- **Exploration Precursor Payloads.** This class of payload mass is targeted to less than ~3000 kg. It is expected that initial robotic precursor missions will be limited to the current upper limit of landed mass afforded by the Delta IV-H (2-3 t). This class is intended to encompass more than the current upper limit for payload mass to Mars. Smaller mass requirements for intermediate payload mass technologies will increase the magnitude of technology jump to reach human scale missions. A larger robotic precursor upper end mass requirement, coupled with increasingly larger entry vehicles would allow confidence building before performing a human scale precursor mission. Exploration Precursors would thus provide a natural framework for development of technologies suited to a range of potential large mass entry systems. Current SOA is undefined – no high fidelity vehicle designs exist for greater than 1000 kg. Push technologies include the use of inflatable/deployable aeroshells, higher L/D configurations, precision or pinpoint landing capabilities, high-G capabilities for landing that enable different design approaches, aerocapture, aerobraking, more capable supersonic parachutes, SRP, utilization of terrain relative navigation or navigation aids/beacons, novel combinations of these technologies, etc.
- **Human Scale Payloads.** This class of payload mass is targeted to approximately 30 to 60 t. A significant impediment to the development of technologies for this scale is the cost of launch vehicles. Technology developments achieved in payload mass ranges for previous, lower mass, categories may or may not be applicable to such large entry masses for atmospheric entry. Technologies not required for atmospheric entry are likely to be much more relevant. It is assumed that there would be at least one human precursor mission without a crew and at a reduced scale before an actual crewed mission. This mission would serve as a final robotic precursor, potentially preposition assets necessary to support a crewed mission, and demonstrate all the EDL system level technologies and their integration prior to a crewed mission.
- **Integrated Mission Simulation and Risk/ Reliability Characterization.** The importance of integrated mission simulations of the entry profile and design performance is often underestimated. Modeling capabilities that are inter-disciplinary, incorporate the appropriate physical models, and are robust are necessary to address ground to flight scaling, flight test anomaly resolution, risk mitigation, appropriately evaluate and manage risk for flight demonstrations and establish certification for the human missions. The cost of performing many, or even several, flight tests to validate designs is assumed to be prohibitive and is a motivation for high fidelity modeling capabilities which are validated by ground and sub-scale, sub-system level flight testing. High fidelity integrated simulation capabilities will be necessary As pointed out earlier, the ground testing and simulation capabilities that are developed during initial TRL advancement, in addition to DDT&E, will form the foundation

for TRL advancement to 6 and beyond. In order to declare that a given ground or flight test is relevant to flight requires modeling that demonstrates applicability of the TRL 6 test to the ultimate flight scale or environment. Current SOA is much higher for individual technical disciplines than for such integrated analyses. To facilitate such analyses and risk characterization, the application of well accepted frameworks involving statistical methods, Monte Carlo assessment, uncertainty quantification, Probabalistic Design, etc. are necessary. These technologies have not been implemented for hypersonic atmospheric entry simulations and will potentially require new techniques to integrate EDL simulation capabilities into effective multi-physics capabilities. The process of TRL advancement provides the progression of activities that are necessary to motivate and execute the development of calibrated and validated high fidelity integrated analyses. A plan for technology development of integrated EDL systems should include a cyclical application of increasingly higher fidelity and validated integrated analyses to guide the selection of technologies, technology combinations and architectures appropriate for each landed mass class. These technologies must be developed for EDL if they are to be in a position to support this need.

- **Game Changing Technologies.** Clearly, there are new technologies, many of which are unknown today, which could change the entire way we approach the EDL phases of any particular mission. For example, if nuclear thermal propulsion (NTP) or other high energy density propulsion systems are realized then many of the significant EDL challenges associated with hyperbolic entry velocities could be greatly relieved and solved propulsively with significantly reduced mass and improved operational flexibilities. Other non-aerodynamic drag options for decelerating systems might include gravitational or electromagnetic repulsion systems, revolutionary energetics for retro energy, or ingestion and reuse of mass during atmospheric traversal to greatly enhance propulsive efficiencies. In the past, very little emphasis has been placed on the more far out technology opportunities and the mission architecture impacts, beyond just vehicle components or subsystems. Funding and mechanisms to encourage revolutionary and out of the box technology thinking and game changing architectural level impacts on mission systems must be encouraged and supported.

1.4.3. Atmospheric Modeling 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. Additionally, uncertainty in atmosphere density is typically handled at the expense of performance via conservatively sized decelerator systems. Improved understanding of the general magnitude of atmospheric variations would directly improve landed mass performance and facilitate guidance algorithm development, selection and tuning while real-time measurement would directly enable increased landing precision. Characterization of the dust environment at Mars and the potential impact for entry systems will be critical for human Mars missions. Terrain tracking will require onboard maps of the surface for use 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. 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. 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 investments 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 CO_2 measurements could be extended to Mars orbiters for CO_2 atmospheric density and wind profiling). NASA's investment in 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. Primary areas of recommended future investments include:

- Distributed short and long duration surface weather measurements at Mars,
- Development of orbiter instruments for wind and atmospheric property characterization at multiple altitudes including those relevant for aerocapture and aerobraking,
- Development of automated data fusion for distinct orbital data types (visible stereo imagery, multi-spectral, and altimetry) and its conversion to onboard topography and albedo surface maps suitable for use by a terrain tracker,
- Development of a low-impact standard atmospheric data package for all Mars landed missions to benefit future Mars landers with surface pressure and upward looking wind measurements,
- "Scout" Probes designed for measuring atmospheric properties and entered ahead of a primary entry vehicle, and
- Vehicle based sensors and instrumentation for making real-time assessments of local and far-field atmospheric properties.

2. INFRASTRUCTURE

EDL technology development, qualification, and certification in flight systems will require access to numerous ground test facilities and laboratories around the country. Many of these facilities require unique and highly specialized resident engineering talent that has been honed over many decades of practice. NASA and the U.S. space industries that are developing new EDL capabilities should also strive to take advantage of the capabilities of international partners, ITAR issues notwithstanding. Maintenance and stewardship of facilities through sporadic periods of utilization is essential to NASA's ability to conduct EDL missions. Advancements in computational modeling and simulation will most certainly be relied upon to a much greater extent than in the past for engineering design and ground to flight traceability, but advancements in analytical tools and physics based models still require verification and validation data, which are typically obtained either through ground based component testing or subscale flight testing. Flight testing, in relevant environments at sub- or full-scale, is often the final step in full system qualification. It is the combination of the three (ground test, simulation, and flight test) that is ultimately required to develop new EDL technologies and architectures for human and robotic exploration.

Entry - No single ground-based facility exactly replicates high-energy flight conditions associated with hypervelocity entry into atmospheres surrounding planetary bodies. Instead, individual facilities have been developed that replicate a particular aspect of high speed flight, and when combined with analysis and flight test capabilities (e.g., suborbital sounding rockets, high altitude rocket assisted balloon launch, Earth based reentry flight tests), these ground-based facilities serve to anchor component EDL technology development and flight system qualification.

Ground-based wind tunnels, with operating conditions from subsonic through hypersonic velocities, achieve fluid dynamic similarity to flight, generally at subscale conditions. These facilities are required to obtain vehicle aerodynamics across a large range of relevant Mach numbers, component aerodynamic loads, control effector and aero/jet interactions, acreage heating patterns on the vehicle surface, and estimates of configuration specific turbulent transition and heating effects for the specific vehicle shapes.

Arc-jets are required to understand thermal protection system response at moderate and high heat flux during hypersonic entry. These facilities achieve flight-like heating environments, i.e., heat rate, temperature, heat load, and shear to TPS test specimen samples. In this manner, the thermal response of flight hardware can be determined. Upgraded capability over that currently available will likely be required to achieve conditions needed to simulate full radiative and convective heating conditions associated with human scale Earth entry vehicles from beyond LEO (e.g., direct entries from NEO or Mars return trajectories. The Giant Planet Facility, a leg on the Ames Research Center (ARC) arc-jet complex, was used to test thermal protection material in a radiative/ convective H/He environment in the 1970's. This portion of the Ames test complex is no longer operational, but a similar testing capability is likely required for TPS development of future probe missions to the gas giants.

Shock tubes are used to understand the high temperature atomic, chemical kinetic, and gas dynamic behavior of the atmospheric gases at high temperature, which is essential for nonequilibrium chemistry and shock layer radiation modeling. This information is used to develop detailed physical models required for aerothermodynamic

flight prediction.

Indoor and free flight ballistic range facilities are often utilized to determine dynamic aerodynamic force coefficients, which are of significance for aerostability assessment, particularly in the transonic and supersonic regimes. These facilities can also be used to obtain stagnation-point heating and noise-free transition data.

Descent - Test requirements frequently demand access to low-density environments at high speed, often near or at full scale. Such access is typically made possible through high-altitude Earth based flight testing. NASA's Balloon Program supports high altitude Earth payloads up to 8,000 pounds. Payloads released from the high altitude balloons can then be accelerated to relevant test conditions either through simple gravity assist (subsonic) or via rocket propelled kick stages (supersonic), similar to the approach utilized in the Viking supersonic parachute qualification effort. Full-scale tests that exceed the capacity of existing balloons will require either the development of new balloon systems or specialized ground launched rocket systems. Continued access to large-scale wind tunnel facilities is also critical to testing and qualifying aerodynamic decelerators.

Landing – Terminal descent, including maneuvering, hazard detection and avoidance, integrated in-situ sensor performance and GN&C algorithm testing, and performance assessments of high and low gravity body touchdown systems, will require capabilities to test at the component and integrated system level. These capabilities may range from simple drop tests (crane or large gantry facilities with suspension systems to simulate low-G gravitational environments) to helicopter, aircraft or low-altitude rocket systems for sensor testing.

It is recommended that NASA form a test facilities team to develop a uniform cost basis and long-term utilization requirements for these facilities. Because of the critical nature of the test facilities and the resident expertise, this cost and utilization information is vital for planning EDL and other technology and system-level capability development.

In addition to facilities, the "human infrastructure" component is also a critical part of EDL technology. Because of the specialized NASA-unique nature of many of the necessary technical skills within the discipline, it is critical that NASA accelerate its development of STEM and early career opportunities for the next generation of experts in key EDL technologies.

3. IMMEDIATE ACTIONS

Given the current state of NASA investments, the authors recommend the following immediate actions that are not currently receiving adequate attention:

- Conduct advanced architectural level studies for human and large robotic Mars surface missions that are developed to a Phase-A level of design detail to drive out critical EDL technology needs and schedules.
- Develop a NASA policy for required EDL instrumentation and data acquisition in order to advance and build confidence in models that are essential to EDL system qualification.
- Implement a plan for instrumenting the Mars 2018 mission with a system at least as capable as the MEDLI system on MSL.
- Requalify heritage Carbon Phenolic TPS to support MSR earth entry reliability and Venus entries. Requires immediate carbonization of the NASA stockpile of heritage Rayon before domestic carbonization capability is mothballed.
- Investigate deployable entry systems that would be an alternative to inflatable approaches (currently being investigated) in order to not be dependent on a single path.
- Investigate alternative high mass deceleration approaches to SRP (currently being investigated) in order to not be dependent on a single path.
- Flight-qualify large subsonic or supersonic parachutes and more capable higher-Mach supersonic drag devices to support MSR surface payloads.
- Develop a supersonic Earth atmosphere test capability to support decelerator and retro-propulsion developments for high mass systems.
- Develop terrain tracking and hazard detection technology to support Mars 2018 and MSR-class missions as well as robotic and human asteroid missions.
- Advance the state of NASA pyrotechnic initiator technology to take advantage of significant advances in initiator performance and reliability in the defense sector.
- Form a NASA EDL Test Facilities Team to periodically assess and prioritize the needs and future utilization of existing and new test capabilities for EDL systems, in order to provide a reviewed and accepted source of

information for NASA and other government Agency facilities investments planning.

4. NATIONAL RESEARCH COUNCIL REPORTS

The earlier sections of this document were completed and issued publicly in December, 2010. NASA subsequently tasked the Aeronautics and Space Engineering Board of the National Research Council of the National Academies to perform the following tasks:

- **Criteria:** Establish a set of criteria to enable prioritization of technologies within each and among all of the technology areas that the NASA technology roadmaps should satisfy;
- **Technologies:** Consider technologies that address the needs of NASA's exploration systems, Earth and space science, and space operations mission areas, as well as those that contribute to critical national and commercial needs in space technology;
- **Integration:** Integrate the outputs to identify key common threads and issues and to summarize findings and recommendations; and
- **Prioritization:** Prioritize the highest-priority technologies from all 14 roadmaps.

In addition to a final report that addressed these tasks, NASA also tasked the NRC/ASEB with providing a brief interim report that "addresses high-level issues associated with the roadmaps, such as the advisability of modifying the number or technical focus of the draft NASA roadmaps."

In August, 2011, the NRC/ASEB delivered "An Interim Report on NASA's Draft Space Technology Roadmaps" which, among other things, verified the adequacy of the fourteen Technology Areas as a top-level taxonomy, proposed changes in the technology area breakdown structure (TABS) within many of the TA's, and addressed gaps in the draft roadmaps that go beyond the existing technology area breakdown structure.

On February, 1, 2012, the NRC/ASEB delivered the final report entitled "NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space". The report prioritizes (e.g., high, medium, low) the technologies **within** each of the 14 Technology Areas, and also prioritizes **across** all 14 roadmaps [highest of the high technologies].

The remainder of this section summarizes:

- The changes that the NRC recommended to the TABS presented earlier in this document
- The NRC prioritization of the technologies in this TA, as well as highlights any of this TA's technologies that the NRC ranked as a 'highest of high' technology.
- Salient comments and context, quoted verbatim, from the NRC report that provide important context for understanding their prioritization, findings, or recommendations.

4.1. NRC Recommended Revisions to the TABS

The NRC recommended minor changes to the proposed TABS, notably collecting such items such as GN&C, modeling and simulation, and instrumentation into new elements within 9.4 Vehicle Systems Technology. Below is the NRC recommended TA-09 TABS, with deleted elements lined out and added elements shown in red.

- 9.1. Aeroassist and Atmospheric Entry
- 9.1.1. Rigid Thermal Protection Systems
- 9.1.2. Flexible Thermal Protection Systems
- 9.1.3. Rigid Hypersonic Decelerators
- 9.1.4. Deployable Hypersonic Decelerators
- ~~9.1.5, 9.1.6~~

- 9.2. Descent
- 9.2.1. Attached Deployable Decelerators
- 9.2.2. Trailing Deployable Decelerators
- 9.2.3. Supersonic Retropropulsion
- ~~9.2.4, 9.2.5~~

- 9.3.Landing
- 9.3.1. Touchdown Systems
- 9.3.2. Egress and Deployment Systems
- 9.3.3. Propulsion Systems
- ~~9.3.4~~
- 9.3.5. Small Body Systems
- ~~9.3.6~~

- 9.4. Vehicle Systems Technology
- ~~9.4.1~~
- 9.4.2. Separation Systems
- 9.4.3. System Integration and Analyses
- 9.4.4. Atmosphere and Surface Characterization
- 9.4.5. EDL Modeling and Simulation
- 9.4.6. Instrumentation and Health Monitoring
- 9.4.7. GN&C Sensors and Systems

4.2. NRC Prioritization

The EDL technologies are presented here in ranked priority order based on the QFD scoring system used by the NRC.

High Priority:

- 9.4.7. GN&C Sensors and Systems (Combined with 4.6.2 and 5.4.3)
- 9.1.1. Rigid Thermal Protection Systems (Combined with 9.1.2 and 14.3.1)
- 9.1.2. Flexible Thermal Protection Systems (Combined with 9.1.1 and 14.3.1)
- 9.1.4. Deployable Hypersonic Decelerators
- 9.4.5. EDL Modeling and Simulation
- 9.4.6. Instrumentation and Health Monitoring
- 9.4.4. Atmosphere and Surface Characterization
- 9.4.3. System Integration and Analyses

Medium Priority:

- 9.2.2. Trailing Deployable Decelerators
- 9.2.1. Attached Deployable Decelerators
- 9.1.3. Rigid Hypersonic Decelerators
- 9.3.1. Touchdown Systems
- 9.3.5. Small Body Systems
- 9.3.3. Propulsion Systems

Low Priority:

- 9.4.2. Separation Systems
- 9.2.3. Supersonic Retropropulsion
- 9.3.2. Egress and Deployment Systems

Of the 8 high priority technologies identified by the NRC, the last four were promoted to high priority despite their QFD scoring because "investments in these technologies will support a wide range of expected future EDL missions." The top three scoring technologies (GN&C, rigid and flexible TPS) were grouped with technologies from other TA's into unified GN&C and TPS technology areas, and all were selected as part of the top 16 cross-cutting agency priorities for investment in the next five years. These technologies were noted to have broad, potentially game changing benefit across a wide range of technology challenge areas.

Of the low scoring EDL technologies, 9.4.2 and 9.3.2 were considered to be primarily engineering developments, and 9.2.3 was considered to be extremely technically challenging and applicable only to human Mars missions. 9.3.5 fell to medium primarily because it "was judged to have a low benefit because of its very limited mission applicability. This technology may actually fit better in the roadmap for TA04, because it is essentially a rendezvous and docking problem."

4.3. Additional / Salient Comments from the NRC Reports

To place the priorities, findings and recommendations in context for this TA, the following quotes from the NRC reports are noteworthy:

- TA-09 Top Technical Challenges: Mass to Surface, Surface Access, Precision Landing, Surface Hazard Detection and Avoidance, Safety and Mission Assurance, Affordability. (2-38)
- The committee consensus is that low-TRL, NASA Innovative Advanced Concepts-like funding should be on the order of 10 percent of the total. (3-17)
- NASA's Office of the Chief Technologist (OCT) should use disciplined system analysis for the ongoing management and decision support of the space technology portfolio, particularly with regard to understanding technology alternatives, relationships, priorities, timing, availability, down-selection, maturation, investment needs, system engineering considerations, and cost-to-benefit ratios; to examine "what-if" scenarios; and to facilitate multidisciplinary assessment, coordination, and integration of the roadmaps as a whole. OCT should give early attention to improving systems analysis and modeling tools, if necessary to accomplish this recommendation. (4-2)
- OCT should reestablish a discipline-oriented technology base program that pursues both evolutionary and revolutionary advances in technological capabilities and that draws upon the expertise of NASA centers and laboratories, other federal laboratories, industry, and academia. (4-3)
- The health and availability of facilities is closely linked to development of advanced technology. State-of-the-art facilities for aerospace research and development are often large, complex, and expensive. The need for such government-run facilities continues today. Adequate ground test facilities are required to validate analytical models, to benchmark complex computer simulations such as computational fluid dynamics models, and to examine new designs and concepts. Testing is a critical element

in material development, such as new TPS materials. Such testing is normally carried out in arcjet facilities that can produce convective heating rates and accommodate test articles in sizes of interest to simulate entry from LEO, NEO, and Mars missions. Large thermal vacuum chambers are needed to perform thermal response testing at or near vacuum or low pressure. As old facilities become obsolete, some may need to be replaced with modern facilities to support the development of new technology. (4-6)

- OCT should collaborate with the U.S. commercial space industry in the development of precompetitive technologies of interest to and sought by the commercial space industry. (4-9)
- EDL technologies that enable the broadest spectrum of future missions by accommodating the widest range of variations in destination and timing would be of particular value. (L-2)
- NASA's draft EDL roadmap may be too narrow because it is focused on the development of human class, large payload delivery to Mars as the primary emphasis, even though such a mission may be three decades away. (L-3)
- M&S tools are highly valued in every phase of design and analysis of EDL systems. In addition to development of physical models, numerical methodologies, and software tools to conduct M&S, this technology also includes development and application of experimental validation including flight tests. Only if high-fidelity models are also well validated can they be useful in reducing margins, thereby increasing mission capability without a loss in safety. (L-16)
- [NASA] currently possesses unique ground and flight test capabilities to conduct experimental validation required for EDL Modeling and Simulation. Continued investments in ground test facilities, such as large scale wind tunnels, arc-jet facilities, and supersonic and hypersonic wind tunnels, will ensure that the means to validate codes are available when required. NASA is uniquely motivated to pursue this technology and major investments from industry are not expected in the absence of NASA involvement. (L-17)
- The whole EDL technology portfolio would benefit from the expanded use of System Integration and Analysis technologies across a larger mission set since they can help to understand the benefits that other technologies can bring to a given mission or a whole set of missions once the systems integration and analysis techniques are validated. (L-19)
- Since EDL is not a high demand opportunity for industry, it is important that NASA maintain these capabilities. A successful technology program would preserve test capabilities and advance key technologies at a steady pace that does not depend solely on flight mission approvals. (L-20)

ACRONYMS

AAES	Aerobraking, Aerocapture, and Entry Systems
AEDC	Arnold Engineering Development Center
AFRSI	Advanced Flexible Reusable Surface Insulation
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
BLDT	Balloon Launch Decelerator Test
CFD	Computational Fluid Dynamics
C.G.	Center of gravity
COTS	Commercial Orbital Transportation Services
CUIP	Constellation University Institutes Program
CY	Calendar Year
DDT&E	Design, Development, Testing, and Evaluation
DGB	Disk Gap Band
DNS	Direct Numerical Simulation
DRA	Design Reference Architecture
EDL	Entry, Descent, and Landing
ESMD	Exploration Systems Mission Directorate
ETDD	Exploration Technology Development Demonstrations
FSI	Fluid-Structure Interaction
G	One Earth surface gravitational acceleration
GN&C	Guidance, Navigation & Control
HEO	High Earth Orbit
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
IAD	Inflatable Aerodynamic Decelerator
IR	Infrared
IRVE	Inflatable Reentry Vehicle Experiment
ISHM	Integrated System Health Monitoring
ISPT	In-Space Propulsion Technology
ISS	International Space Station
ITAR	International Traffic In Arms Regulations
kg	Kilogram
kN	Kilo Newton
L/D	Lift/Drag
LCC	Life Cycle Cost

LEO	Low Earth Orbit
m	Meter
MAV	Mars Ascent Vehicle
MAX-C	Mars Astrobiological Explorer - Cacher
MEMS	Micro Electro Mechanical Systems
MMOD	Micro Meteoroid Orbital Debris
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NEAR	Near-Earth Asteroid Rendezvous
NESC	NASA Engineering and Safety Center
NFAC	National Full-Scale Aerodynamic Complex
OCE	Office of the Chief Engineer
OCT	Office of the Chief Technologist
p	Pressure (stagnation)
PEPP	Planetary Entry Parachute Program
PICA	Phenolic Impregnated Carbon Ablator
q	Heat Rate
RCC	Reinforced Carbon-Carbon
RCS	Reaction Control System
RV	Reentry Vehicle
SHAPE	Supersonic High Altitude Parachute Experiment
SIAD	Supersonic Inflatable Aerodynamic Decelerator
SLA	Super Lightweight Ablator
SMD	Science Mission Directorate
SOA	State-of-the-Art
SPED	Supersonic Planetary Experiment Development
SRP	Supersonic Retro Propulsion
STEM	Science, Technology, Engineering, and Mathematics
t	Metric ton (1000 kg)
TABS	Technology Area Breakdown Structure
TDP	Technology Development Project
TPS	Thermal Protection System
TRL	Technology Readiness Level
U.S.	United States
V&V	Verification and Validation
VSTAA	Vehicle Systems Technology and Architecture Analyses
WLE	Wing Leading Edge

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