2.0 AEDL Systems Engineering

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2.0 AEDL Systems Engineering Topics

- Some Initial Thoughts
- Capability Description
- Capability State-of-the-Art
- Capability Requirements
- Systems Engineering
- Capability Roadmap
- Capability Maturity
- Candidate Technologies
- Metrics

Flight Phases

- **Mars AEDL**
- Earth Return Lunar and Mars
- Lunar Landing

2.0 Some Initial Thoughts

- **This part of the discussion is about AEDL from a system level perspective**
  - **Subsystems such as Structures, TPS, GN&C are discussed in subsequent sections**
- **AEDL capability roadmaps will evolve as the Exploration Initiative architecture and the resulting AEDL requirements mature**
  - **This AEDL capability roadmap is based on anticipated AEDL capabilities that accommodate a range of Exploration architectures but include core capabilities, such as Mars EDL, that are common to all of the architecture options**
- **A credible Mars EDL concept does not exist for the very large masses and volumes needed for human Mars exploration – perhaps 30 times present Mars EDL capabilities**
  - **Deceleration in the supersonic through terminal descent flight regime in the thin Mars atmosphere is the key to development of an EDL capability for human Mars missions**
    - **Robotic mission capability is not scalable to human mission size**
  - **"Minimize the Mars EDL mass" must be an objective of the Exploration architectures**
    - **The EDL system mass, and hence landed mass, will be limited by the size of the aeroshell that can be accommodated by the launch vehicle and by the TransMars injection system**
  - **Limited assessment of human scale EDL capability has identified candidate AEDL systems capabilities that may be combined to provide the EDL capability needed for human exploration**
  - **This EDL capability will be the driver for development of a combined AEDL capability for human Mars missions**

2.0 Some Initial Thoughts (Con't)

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- The technology for aerocapture into low energy orbits is ready for exploitation
  - Aerocapture is an essential element of some exploration architectures and must be included in the Human Planetary Landing Systems (HPLS) capability development until the Exploration architecture matures and the need for aerocapture is resolved
  - Aerocapture has not been flown at any destination, but Apollo experience and other significant work has established aerocapture as a viable technology
  - Aerocapture technology must be developed into an aerocapture system capability for specific applications
- Lunar landing will be much like Apollo but with 2 to 4 times the Apollo mass
  - The initial lunar landing capability will be based on the Apollo experience but incorporating modern technologies and capabilities – both analytical and hardware – but with much larger descent mass
  - Capability for autonomous hazard avoidance may be included as an enhancement to the Apollo capability
  - Experience with the larger landed mass, throttleable engines, and autonomous hazard avoidance and landing systems will be an asset in the development of these systems and capabilities for Mars missions

2.0 Some Initial Thoughts (Con't)

- **Return to Earth will build on the Apollo experience for lunar return and this capability will be expanded for the more demanding Mars return**
  - Initial return to Earth capability will be based on the Crew Exploration Vehicle (CEV) capability and may include Earth aerocapture into a low energy orbit
  - Return from Mars will have about 40% more energy than return from the moon for long duration Mars missions
- **Short duration Mars missions are difficult for several reasons including an increase in the Mars and Earth arrival speeds**
  - One year Mars missions increase the maximum Mars entry speeds to from 7^+ km/s to 10.0 km/s and Earth entry speed from 13.0 km/s to 15.0 km/s, respectively
  - For 580 day Mars missions the maximum Mars entry speed is the same as for long duration and the maximum Earth entry speed is 14^+ km/s
- **The human element provides challenges and opportunities**
  - Safety and risk challenges particular for the remote Mars operations with long transit times
  - Humans limit the aerodynamic and propulsive loads that can be accommodated, particularly after long periods of weightlessness – limit believed to be about 5 g's for sustained loads
  - Crew capabilities can be used to enhance mission success
- **Systems Engineering**
  - HPLS capability development depends on the integration of complex, high performance systems into AEDL capabilities that must perform in a wide range of environments – Earth, Moon, and Mars
  - An effective HPLS systems engineering effort is a key to successfully developing this capability

Capability Description

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2.0 AEDL Capability Description – at Mars

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- Mars EDL
  - Mass 50 to 60 Mt at entry interface
  - Land at up to 2.5 km above the mean surface throughout the Mars year – Mars has a wide variation of density profiles with season
  - Pin Point landing (accuracy of 100 m)
- Aerocapture into Mars orbit
  - Needed for some candidate exploration architectures
  - Mass 70 to 100 Mt
  - Mars arrival speeds
    - 6 to 7$^+$ km/s for long duration missions and for missions of about 580 days
    - 8$^+$ to 10$^+$ km/s for 1 year missions
  - Orbit altitude about 500 km or 17,000 km for a stationary orbit
- Mars AEDL Capabilities
  - Human and cargo missions and cargo only missions
  - Sustained loads limited to about 5 g's for AEDL with a flight crew
  - Autonomous operation capability
  - Use human capabilities to enhance success for crewed missions
- Candidate Mission Scenario at Mars
  - Mars cargo aerocapture
  - Mars cargo aerocapture followed by EDL
  - Mars human and cargo aerocapture followed by EDL

2.0 AEDL Capability Description - Return to Earth

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- **Lunar return – much like Apollo but may include aerocapture at the Earth**
  - Crew Exploration Vehicle (CEV) or enhanced CEV – mass 5^+ Mt
  - Return speeds of about 11.0 km/s
  - Options include short range direct entry, extended range with atmospheric exit and subsequent reentry and landing, or aerocapture followed by EDL
- **Mars return**
  - Mass 5 to 10 Mt without return of the crew transit vehicle
  - Return speeds
    - Up to about 13.0 km/s for long duration missions (40% increase in spacecraft energy compared to lunar return missions)
    - Up to 14^+ km/s and 15.0 km/s (86% increase in spacecraft energy compared to lunar return missions) for 580 day and 1 year missions, respectively
    - Increased aerodynamic heating results in more severe TPS environment
    - Effects entry corridor, aerodynamic loads, L/D requirement
  - Options include short range direct entry, extended range with atmospheric exit and subsequent reentry and landing, or aerocapture followed by EDL
    - Aerodynamic loads constraints for crewed vehicles may preclude direct entry
- **Earth return Scenarios**
  - Human missions with cargo
  - Sustained loads limited to about 5g's after long periods of weightlessness
  - Autonomous operations
  - Use human capabilities to enhance success

2.0 AEDL Capability Description - Lunar Landing

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- **Lunar Landing**
  - Concept Apollo like but with 2 to 4 times the mass at start of powered descent
  - Human and cargo missions
  - Pin Point landing capability
  - Autonomous operations
  - May include autonomous hazard avoidance capability

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State-of-the-Art

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2.0 Current State-of-the-Art – Mars EDL

- **Systems Capabilities of Current Mars Landers (Through 2009 MSL)**
  - **Limited entry mass capability – currently 2 Mt and may evolve to 4 to 6 Mt**
  - **Blunt body, rigid aeroshells**
    - **Blunt body, rigid aeroshells – 70 deg sphere cone**
    - **Maximum entry body diameter ~ 4.5 m**
    - **No movable aerodynamic surfaces**
    - **3-axis control or spinning ballistic entry**
    - **Direct entry or entry from orbit**
    - **Maximum design deceleration ~ 16 g's**
    - **L/D = 0.18 (constrained by angle of attack limits at parachute deployment)**
  - **Maximum landing site altitude ~ 2.0 km above MOLA (direct entry, no dust storm)**
  - **Parachute capability is based on Viking technology**
    - **Disk Gap Band design**
    - **Max diameter – 16.15m**
    - **Dynamic pressure deploy envelope 239 - 850 pa**
    - **Mach deploy envelope 1.13 - 2.2**
    - **Max deploy angle of attack – 15 deg**

2.0 Current State-of-the-Art – Mars EDL (Con't)

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- Systems Capabilities of Current Mars Landers (Through 2009 MSL)
  - Precision trajectory control to parachute deployment
    - Autonomous guided entry guidance to parachute deployment
      - Passive center-of-mass control to achieve low angle-of-attack
      - Bank angle modulation only for trajectory control
      - Position accuracy perpendicular to the radius vector at parachute deployment ~10 km and is driven by navigation accuracy – the effects of low altitude winds while on the parachute must be accommodated to attain precision landing
      - Control trajectory to density altitude at parachute deployment – results in large variation in geometric altitude
    - Autonomous flight control system
    - No hazard detection or avoidance capability

2.0 Current State-of-the-Art - Aerocapture

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- **The technology for aerocapture into low energy orbits is at a TRL of 6 – Based on Apollo experience and subsequent aerocapture assessments and experience**
  - **Never been done into any planetary atmosphere but a significant body of work shows that technology for aerocapture into low energy orbits is ready for program application**
    - **Apollo program human rated the capability for a controlled skip out of the Earth's atmosphere followed by a re-entry into the atmosphere and a precision landing in less that one orbit.**
      - **This capability was available on every Apollo lunar mission to fly over late developing bad weather in the landing area but was never needed or used.**
      - **This provided the atmospheric flight technology needed for aerocapture**
      - **The propulsive capability for orbit adjustment was not included**
    - **The Soviet Union returned two spacecraft from the moon – Zond 6 and Zond 7 in 1968 and1969, respectively with aerocapture like maneuvers in the Earth's atmosphere**
      - **The spacecraft entered the Earth's atmosphere, exited the atmosphere, and reentered the atmosphere to land in the Soviet Union in less than one orbit of the Earth**

2.0 Current State-of-the-Art - Aerocapture (Con't)

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– Never been done… (Con't)
  - Since Apollo many programs and detailed systems studies have shown the viability of aerocapture for Earth and other destinations
    - Aerocapture Flight Experiment (AFE) program analytically demonstrated aerocapture in the Earth's environment in the early 1990's – guidance algorithm ready for flight software coding and some hardware built.
    - Aeroassist Orbital Transfer Vehicles studies in 1980's (Industry and NASA) showed aerocapture feasibility at Earth – some hardware built.
    - Mars Atmospheric Knowledge Working Group in 1991 with NASA and industry participants concluded that aerocapture was a viable option for Mars orbit insertion.
    - Original Mars 2001 orbiter planned to use aerocapture – NASA, industry, and academia team completed a controlled rigorous assessment of aerocapture guidance algorithms before orbiter switched to aerobraking after failures of MPL and MCO.
    - CNES/NASA Mars Premier Orbiter was to use aerocapture in 2007.
      - CNES/NASA team evaluated aerocapture risk and concluded aerocapture was feasible with significant mass savings compared to all-propulsive capture, or all-propulsive capture followed by aerobraking.
    - Detailed NASA inter-center systems studies have demonstrated the viability and benefit of aerocapture at multiple destinations (Mars, Titan, Neptune, and Venus)

2.0 Current State-of-the-Art – Earth EDL

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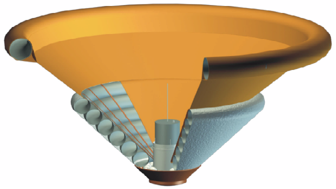
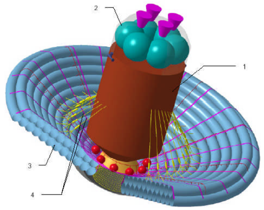
- Extensive experience with rigid aeroshells in the Earth's atmosphere for a wide variety size, shapes, and applications
  - Blunt Bodies
    - Human mission – Mercury, Gemini, Apollo, Vostok, Soyuz
    - Robotic missions – Zond 6 and 7, Discoverer, Genesis, Atmospheric Reentry Demonstrator
  - Slender bodies and winged vehicles
    - Human capability – Space Shuttle Orbiter, Buran, X-38
    - Fly at high angle-or-attack until aerodynamic heating has reduced to low levels. This creates a blunt body effect at high speeds to minimize aerodynamic heating.
  - Autonomous operation
  - Precision trajectory control and landing
  - Vertical and horizontal landings
  - Mass up to 105 Mt

2.0 Current State-of-the-Art – Earth EDL (Con't)

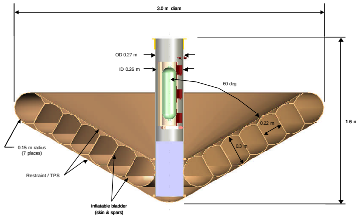
- Very limited experience with inflatable aeroshells, particularly in the United States
  - Russian experience
    - Mars '96 Mission
      - The Soviet Union designed, developed, and launched a small two stage, inflatable aeroshell in 1996 intending to use the aeroshell for Mars EDL as part of a surface penetrator mission.
      - Propulsion system failure prevented the system from leaving earth orbit
    - Have a flight test program, Inflatable Reentry And Descent Technology (IRDT) to further develop inflatable aeroshells based on Mars '96 technology and test in the Earth's atmosphere at near low energy orbital speeds
      - Two flight tests completed with very limited success
      - Ballistic entry, no data link, limited ground tracking, recovery beacon
      - Re-flight of IRDT-2 scheduled for 2005
    - Concept analytically assessed for Mars AEDL for 6 Mt and 60 to 70 Mt vehicles





2.0 Current State-of-the-Art – Earth EDL (Con't)

- **Very limited experience….. (Con't)**
  - **United States experience**
    - **Inflatable Re-entry Vehicle Experiment (IRVE)**



      - **Project led by LaRC**
      - **Low speed, ballistic flight test of 3 m diameter inflatable aeroshell**
      - **First flight of inflatable aeroshell in the United States scheduled for 2005**
    - **Aerossist Inflatable Reentry System (AIRS)**
      - **Project led by JSC with LaRC and ARC major contributors**
      - **Three low speed flight test of inflatable aeroshells – follow on to IRVE**
        - **Flight test 1 – 3 m aeroshell with non-zero angle-of-attack, aerodynamic lift, and attitude maneuvers or possible closed loop GN&C – Sept 06**
        - **Flight 2 – 8 m aeroshell scaled from flight 2 with closed loop GN&C – Aug 08**
        - **Flight 3 – 8 m aeroshell provided by open competition to provide design and construction innovation also with closed loop GN&C – Oct 08**
    - **Very low ballistic coefficient, high altitude inflatable decelerators**
      - **Technology development program led by Ball Aerospace Corp.**
        - **Demonstrate light weight decelerator construction methods and materials survivability**
        - **Structural testing**
        - **Validation of coupled hypersonic aerodynamics and nonlinear structural analysis**
        - **Demonstrate vacuum deployment**

2.0 Current State-of-the-Art – Lunar Landing

- Apollo Lunar Module is the system level experience base but subsystems for the Exploration Initiative will use available technologies
- Apollo Lunar Landing characteristics:
  - Two person crew for short stay
  - Mass at start of powered descent about 15 Mt
  - Limited landing site accessibility
  - Abort to orbit capability during powered descent
  - Landing radar provided altitude and 3 axis speed information – altitude and speed lock-up at about 8.5 km and 2.0 km altitude, respectively. Speed lock-up limited by geometry
  - Precision landing accuracy (accuracy of 10's of meters)
  - Hazard avoidance capability used crew-in-the-loop to detect hazards and to retarget to avoid hazards
  - No prediction of accessible landing area from a performance perspective - propellant remaining and T/W

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Mars AEDL Capability Requirements

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2.0 Mars AEDL Capability Requirements

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Aerocapture

- Mass 70 to 100 Mt
- Arrival speeds 6 to 7+ km/s
- Orbit altitude about 500 km or 17,000 km to achieve a stationary orbit

EDL

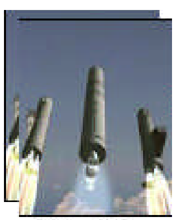
- Mass 50 to 60 Mt at entry interface
- Land at up to 2.5 km above the mean surface throughout the Mars year
- Pin Point landing (accuracy of 100 m)
- Hazard avoidance

Mars AEDL

- Human and cargo and cargo only flights
- Constrained loads to accommodate flight crew
- Autonomous operations
- Use human capabilities to enhance success for crewed missions

Launch

- Packaging
- Thermal control
- Communications
- Launch loads

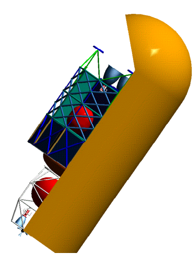


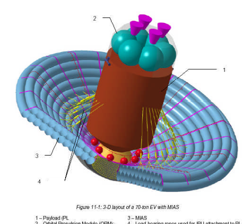
Trans Mars Injection & Transit

- Packaging
- Thermal control
- Communications
- AEDL preparation

Mars Aerocapture

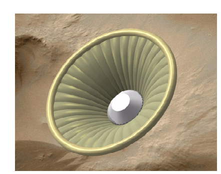
- Packaging
- Thermal control
- Communications
- Orbit adjustment after atmospheric exit

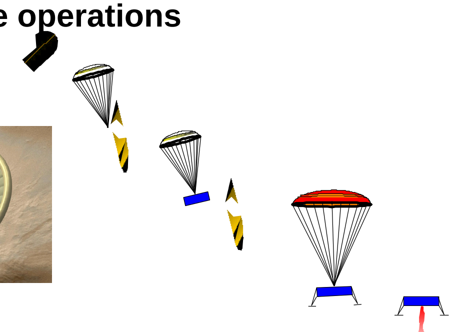




Mars EDL

- Packaging
- Communication
- Deorbit
- Decelerator deployment
- Safe disposal after use of unneeded and obstructing systems
- Pin Point landing near assets
- Emergency ascent and Earth return
- Surface operations





Systems Engineering

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2.0 HPLS Systems Engineering Description

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AEDL Systems Engineering function ….

provides analysis and direction for the development of the demanding, complex, and interrelated AEDL capabilities for the Exploration Initiative....

This is essential to avoid the pitfall of developing AEDL system and sub-system capabilities that may be significant achievements in themselves, but add little to achieving the Exploration Initiative objectives

2.0 HPLS Systems Engineering Description

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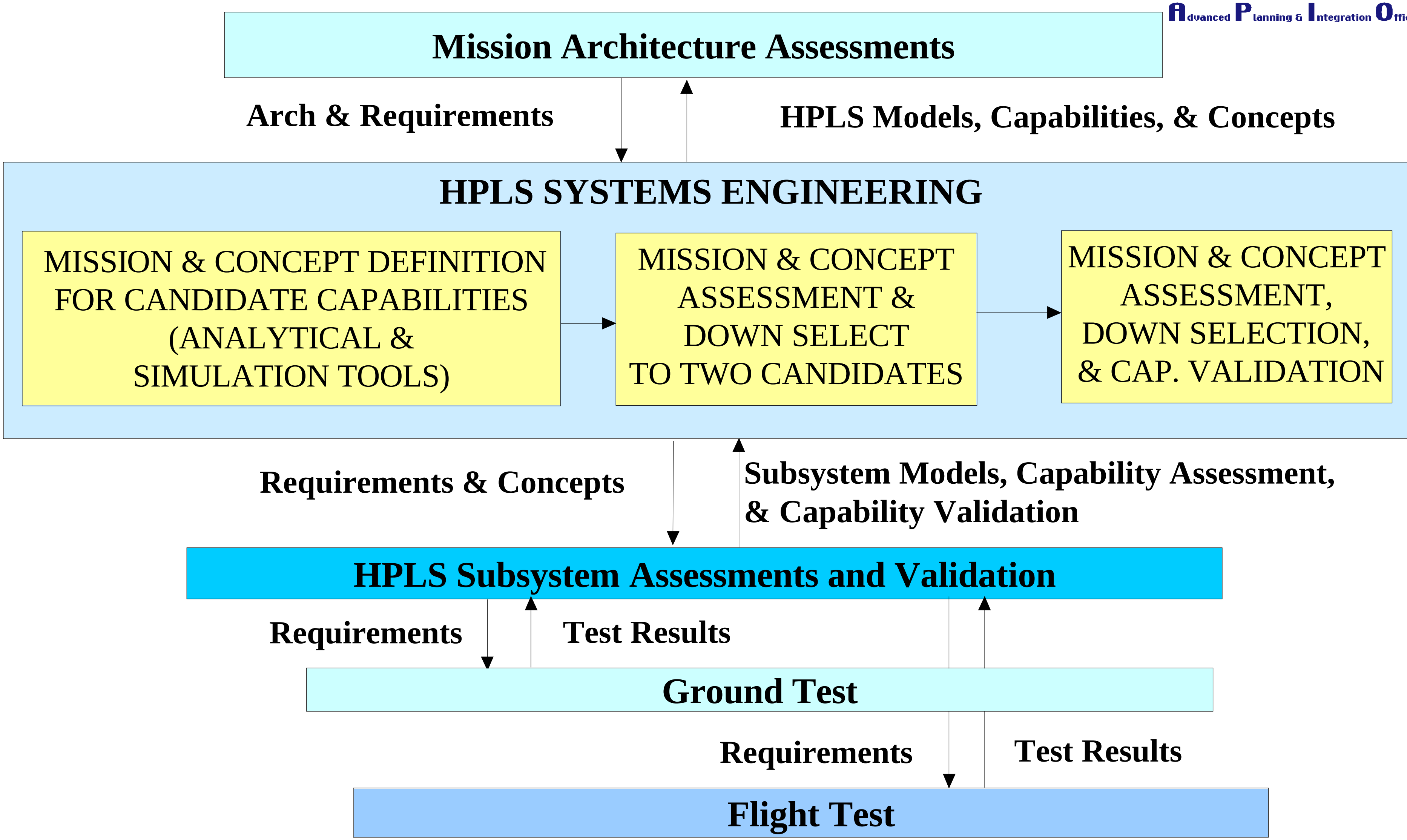
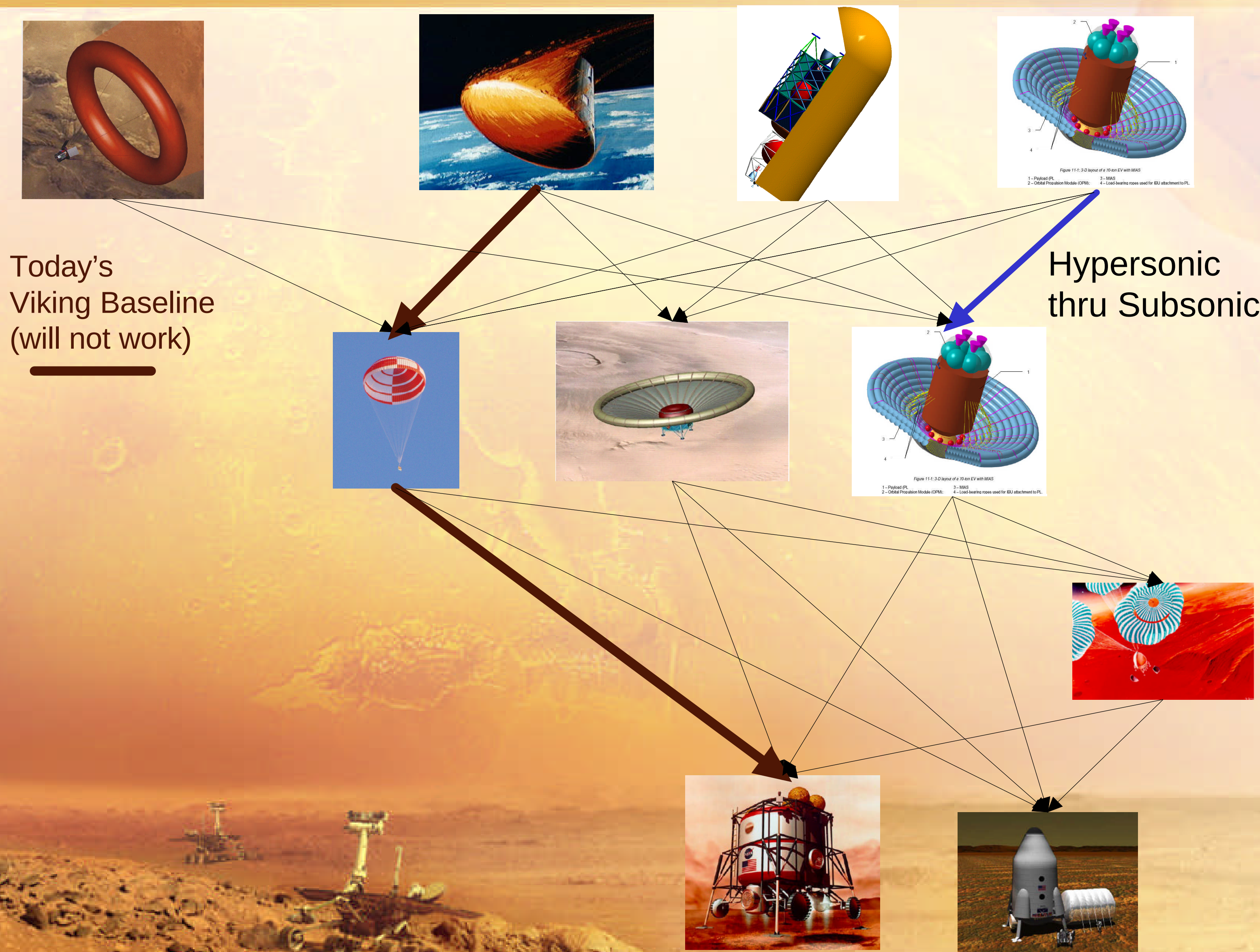
- Is an interactive process…
  - Inputs…
    - Requirements from Exploration Initiative (EI) architecture assessments
    - Subsystem and system models and capabilities
      - Sub-systems specialists
      - Lunar missions, Robotic exploration missions, and precursor missions
      - CEV program
    - Operations concepts
    - Human capabilities and limitations
    - Natural environment models
  - Define AEDL mission and system concepts….
    - Iterative process with the EI architects, other capability development elements, AEDL sub-systems, mission operations, and the flight crew
  - Define AEDL subsystem requirements
  - AEDL mission and system concept down selection
  - Validate the AEDL capabilities
    - Analytical assessments at both the system and sub-system level
    - Ground and flight test
      - Define test requirements
      - Assess test results
  - Update models and reassess concepts and capabilities

2.0 Systems Engineering Process



Which will it be?



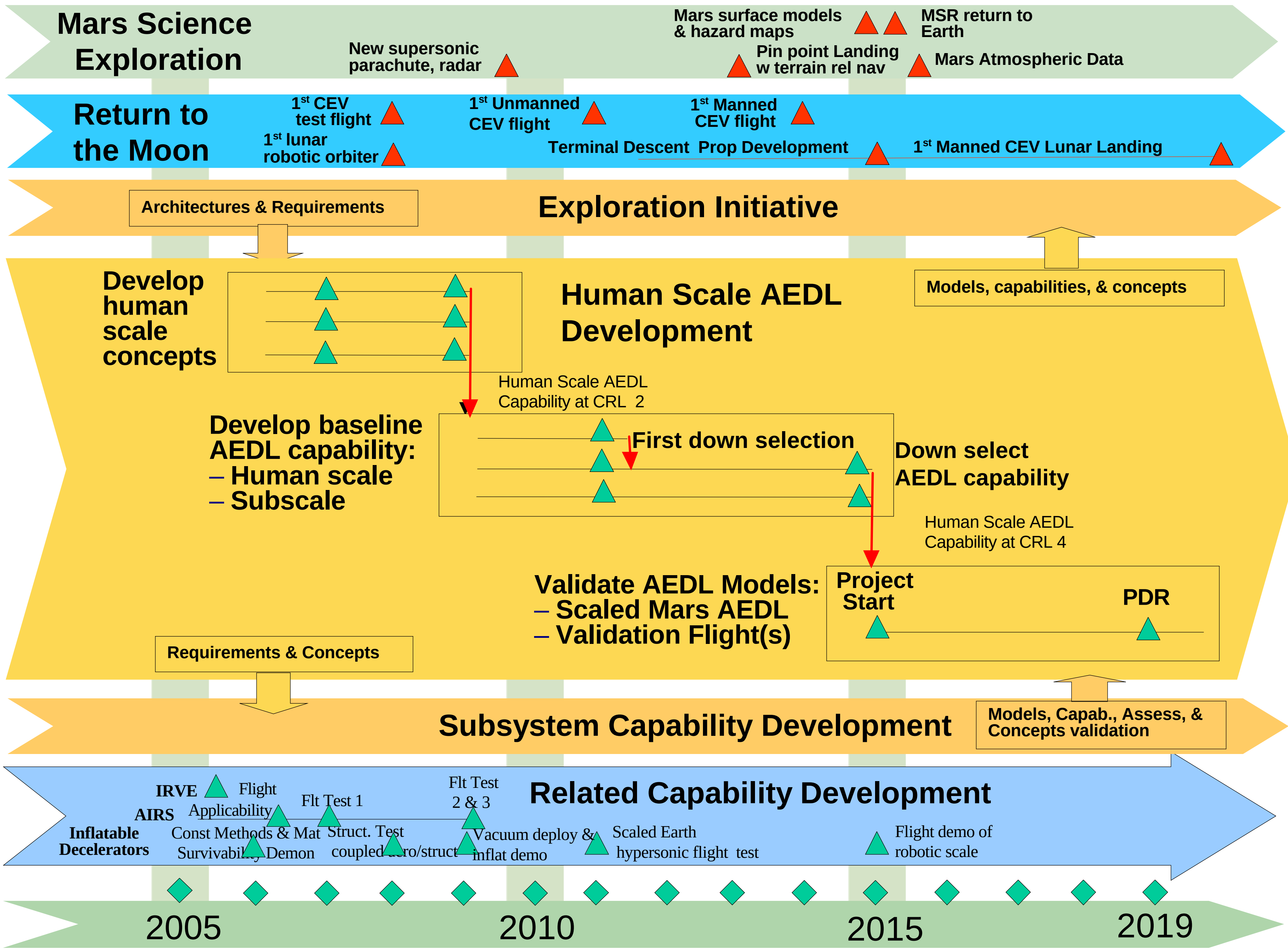
Options for Hypersonic Decelerators

Options for Supersonic Decelerators

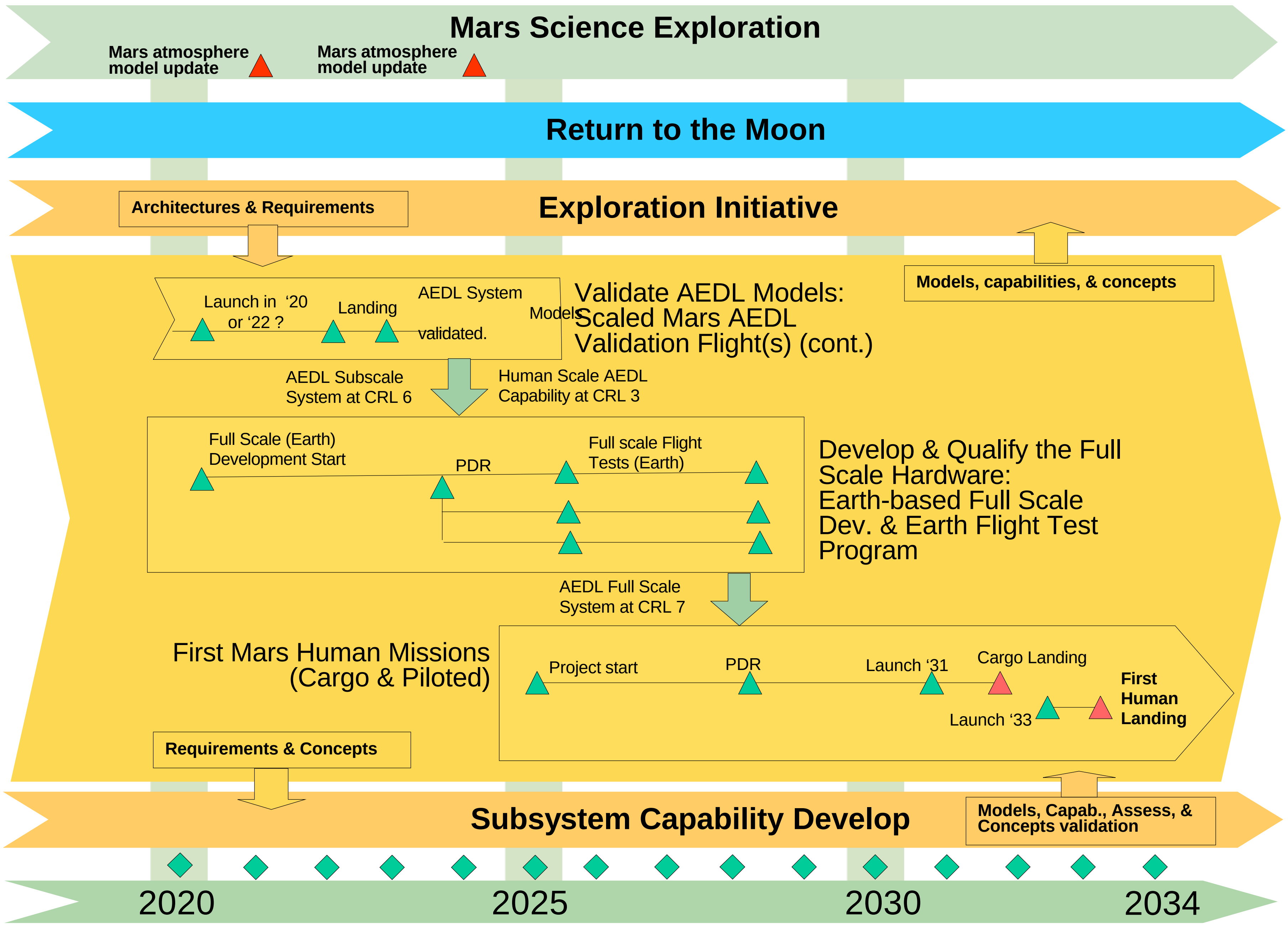
Options for Subsonic Decelerators

Options for Terminal Descent Systems

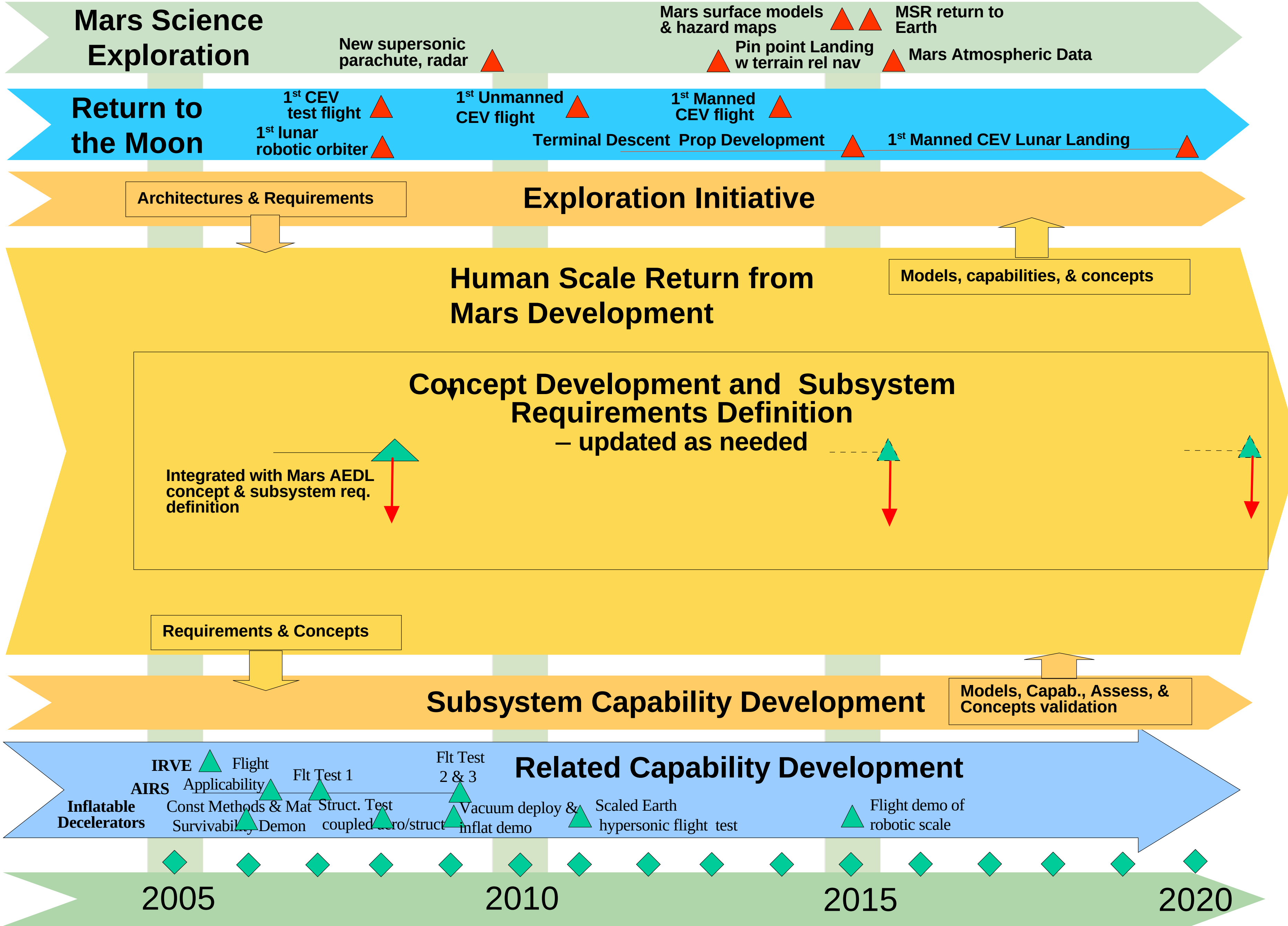
Detailed Mars AEDL Road Map: 2005 - 2020



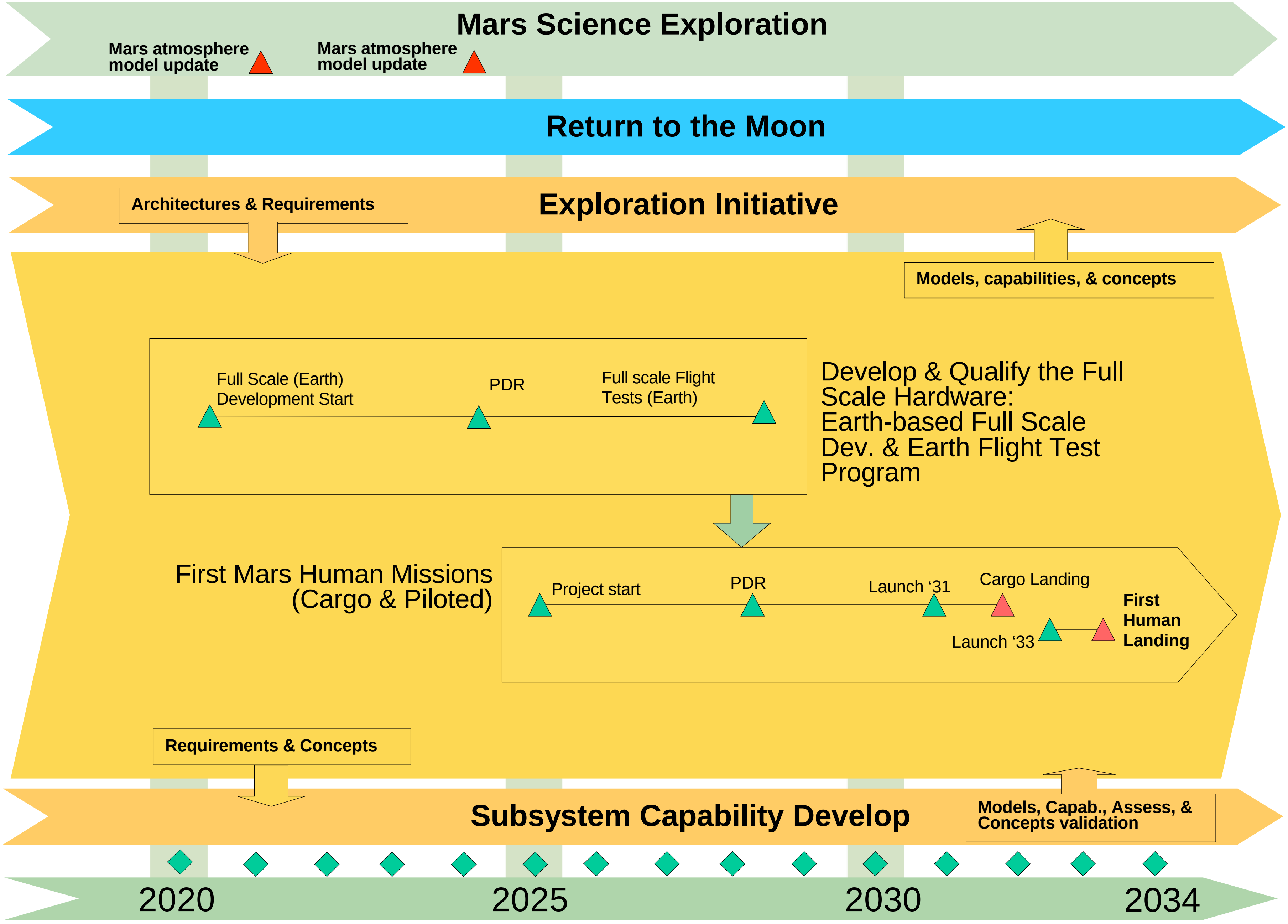
Detailed Mars AEDL Road Map: 2020 - 2034



Detailed Return from Mars Road Map: 2005 - 2020



Detailed Return from Mars Road Map: 2020 - 2034



Maturity Level

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Maturity Level – Capabilities for HPLS Systems

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- Mars AEDL
  - Current Mars EDL capability is not applicable for human scale Mars EDL
    - Current Mars EDL capabilities limit the EDL mass to about 2 Mt. This may be extendable to 4 to 6 Mt, the current EDL capability is simply not applicable for human scale Mars EDL
  - A credible concept for human scale EDL does not exist (TRL 2)
    - Limited assessment of EDL systems has identified candidate EDL aeroshell concepts that may provide the needed capability.
  - Mars Science Exploration missions will develop some capabilities needed for Mars AEDL
    - The entry GN&C algorithms developed for the MSL provide precision entry trajectory control (TRL 5 for rigid aeroshells; 3 for flexible aeroshells)
    - Pin Point Landing capability, supersonic parachutes, Mars environment modeling (TRL 2)
    - Mars Sample Return will provide experience for Earth return from Mars
  - Aerocapture into low energy orbits is feasible and ready for exploitation if needed (TRL 4-5 for rigid aeroshells; 3 for flexible aeroshells)
    - Development of this capability should be integrated with the EDL capability development to minimize overall AEDL risk and cost An existing AEDL modeling, simulation, and human resource capability can be expanded for human scale AEDL capability development (TRL 6 simulation, experience, and human resources; TRL 4 modeling)
    - Extensive system modeling, high fidelity simulation capability, operations experience, and human resources from previous programs, ongoing robotic

Maturity Level – Capabilities for HPLS Systems (Con't)

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- **Return from the Moon will be based on the CEV (TRL 6)**
  - The Apollo program demonstrated the use of rigid, blunt body aeroshells from the moon
  - Long duration missions will require reduced aerodynamic loads compared to Apollo which will result in reduced aerodynamic heating rate per unit mass but will increase the total heat input into the system
  - System options need to be assessed to incorporate new capabilities and to integrate with the remainder of the AEDL capabilities
- **Return from Mars will be an extension of the return from the moon (TRL 2 – 3)**
  - Mars return speeds will result in a 40% increase in spacecraft energy at the start of atmospheric flight compared to return from the moon
  - Aerocapture followed by EDL will reduce aerodynamic loads on the flight crew and may reduce the total heat compared to direct entry, but would require a TPS reuse
  - A rigid, blunt body aeroshell is a candidate for return from Mars
  - System options need to be assessed to incorporate new capabilities and to integrate with the reminder of the AEDL capabilities
- **Human rated TPS especially for large systems and inflatable systems is a capability gap that requires capability development. (TRL 5)**
  - Mars science missions will provided only limited assistance in addressing the scalability and manufacturability issues

Metrics for HPLS Systems

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- Metrics will include the traditional metrics – risk, cost, schedule, and performance – as this effects the AEDL but more importantly as it effects the Exploration Initiative – with more specific metrics to be added later
- Some important non-traditional metrics are:
  - Commonality of systems, subsystems, and components to maximize the benefits of ground test, flight test, and operational flight experience
  - Continuity of resources – skilled people, tools, practices, and facilities across all of the aeroassist efforts