



4.0 Hypersonic Systems

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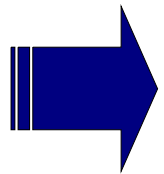
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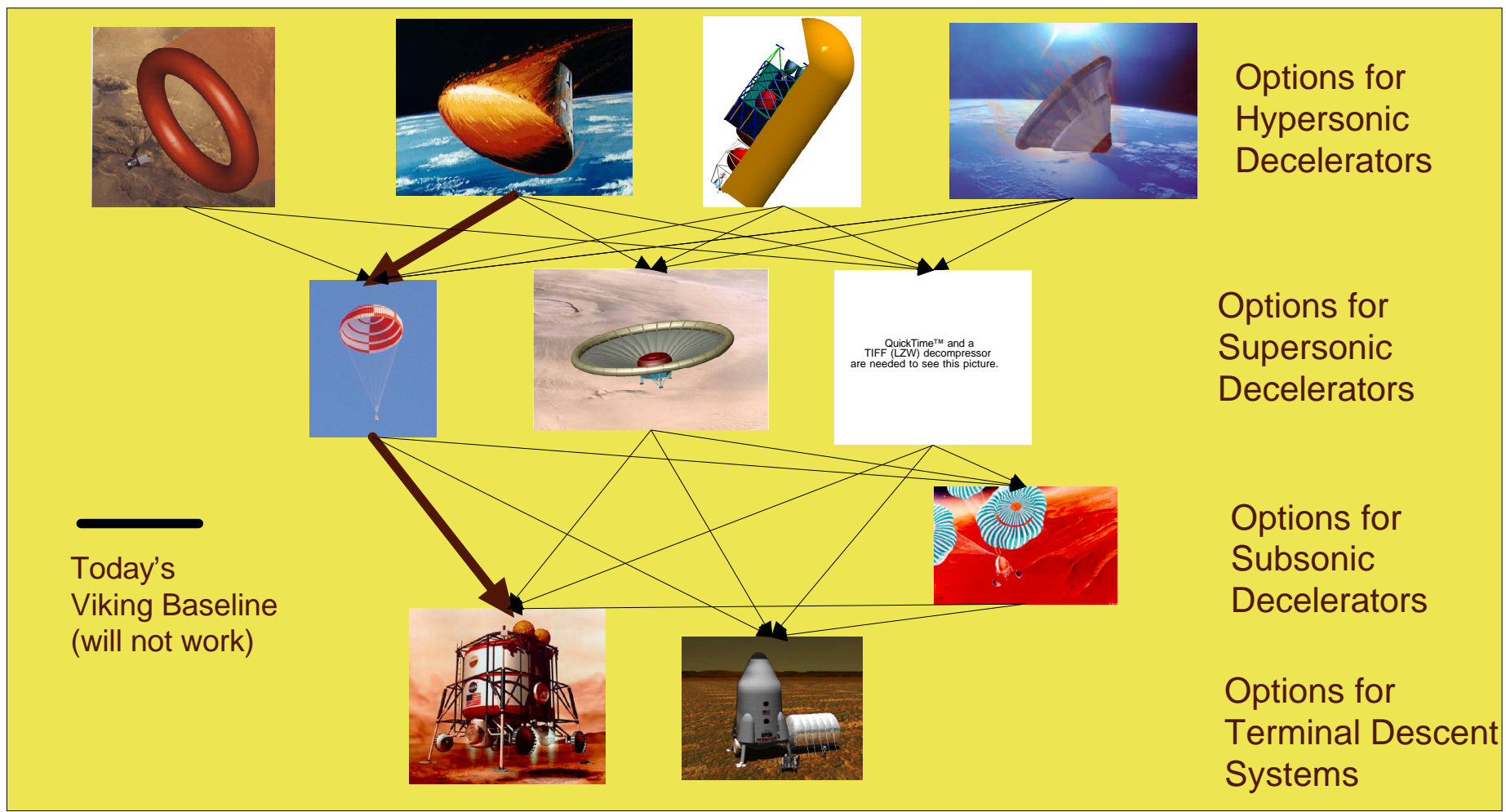
4.0 Hypersonic Systems - Outline

- Capability Description
- Some Initial Thoughts
- Capability State-of-the-Art, Gaps and Requirements
- Capability Roadmap
- Candidate Technologies
- Metrics



Flight Phases

- **Mars Entry:**
 - Aerocapture & Hypersonic Entry
- **Earth Return (Lunar and Mars)**
 - Aerocapture & Hypersonic Entry



- Hypersonic System has to be synergistic with descent and landing system and minimize the Mars EDL mass.



Hypersonic Systems Capabilities for Integrated Mission Architecture



	Candidate Mission Scenario	Candidate Capabilities
Mars Entry	Mars cargo aerocapture Mars cargo aerocapture followed by Entry Mars human and cargo aerocapture followed by Entry	Rigid Aeroshell Flexible /Deployables <u>Combination</u>
Earth Return (Mars)	Direct Entry Entry with skip-out Aerocapture followed by Entry	<u>Rigid Aeroshell</u> Flexible/ Deployables Combination
Earth Return (Lunar)	Direct Entry Entry with skip-out Aerocapture followed by Entry	<u>Rigid Aeroshell</u> Flexible / Deployables Combination



4.0 Some Initial Thoughts



- **Greater need to architect system around the “human system”**
 - **Need to ensure that hypersonic deceleration do not disable pilots.**
- **Lack of credible concept for human scale Mars EDL means**
 - **Candidate hypersonic systems capabilities have to be fully explored and exploited for optimal EDL performance**
 - **Need to establish both requirements as well as performance and operational limitations for flexible and rigid hypersonic systems, early enough, to impact architecture decision**
 - **Precision controlled Aerocapture has never been done into any planetary atmosphere but significant body of evidence exist to show this is achievable for capture into a low energy orbit**
 - **Aerocapture and Entry integration via early system engineering /system analysis studies to help set requirements for hypersonic systems DDT&E**
 - **Obtaining engineering data from Robotic Mars mission to establish confidence in hypersonic system design and analysis methods for human Mars mission**



4.0 Some Initial Thoughts (cont.)



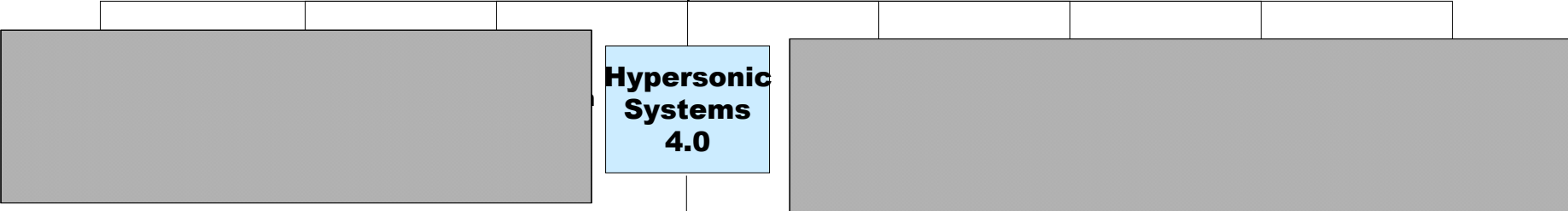
- **Large mass and volume system**
 - **Need improved or new ground test facilities**
 - **Entry heating conditions at Mars will be expected to be dominated by both convective and radiative heating and Entry and Aerocapture Systems have to be tested and validated for the flight environment**
 - **Need ground based testing and flight validation**
 - **Human rating and qualification will be more demanding than robotic missions**
 - **Reliability of systems such as TPS, Flexible/Deployables for Human missions will require higher level of confidence and demonstrating reliability in the system and sub-systems**
 - **Establishing the right combination of higher fidelity analysis, ground testing, scaled flight and integrated system testing and full scale component testing for V&V prior to full scale flight**
 - **Large mass and volume entry required for human Mars missions will be more demanding from manufacturing /scalability/ qualification**



Capability Breakdown Structure



**Human Planetary
Landing Systems
CRM # 7**



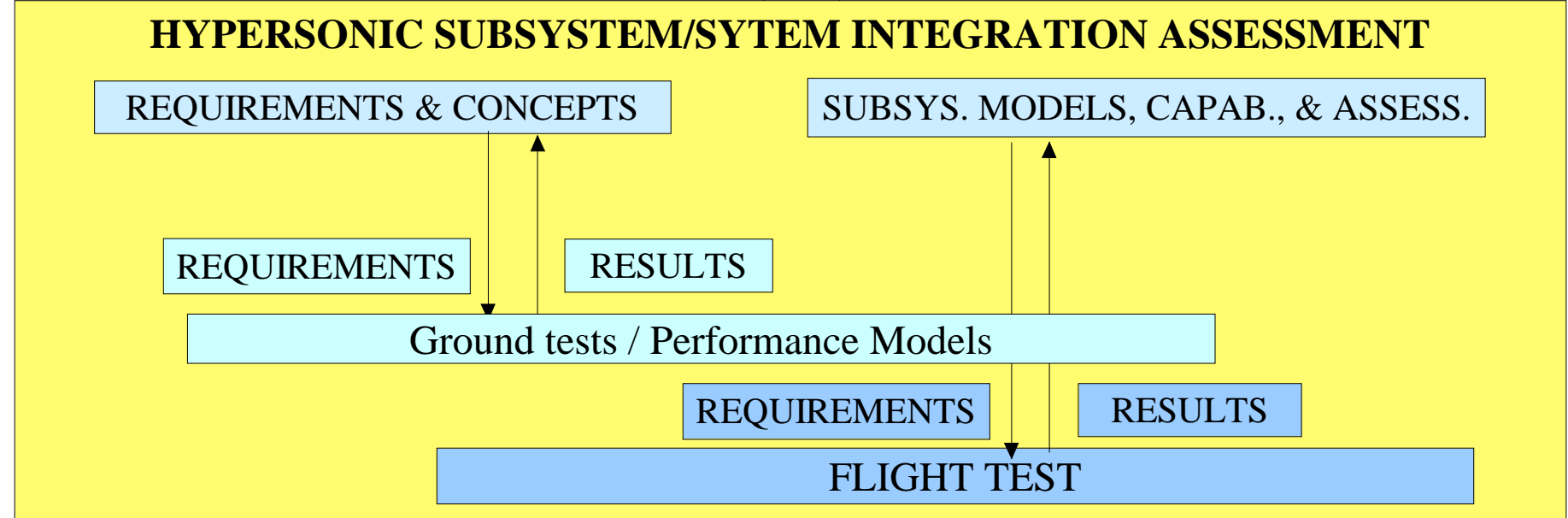
**Hypersonic
Systems
4.0**

- 4.1 Entry Vehicle configurations (Rigid)**
- 4.2 Deployable / Inflatables (Flexible)**
- 4.3 High-Performance, high reliability TPS for both rigid and flexible**
- 4.5 Aero-thermo-structural Dynamics Design**
- 4.4 Aerocapture / Entry GN&C**
- 4.6 Sensors and ISHM**

- 4.7 Ground and Flight Testing**
- 4.8 Aerocapture & Entry System**



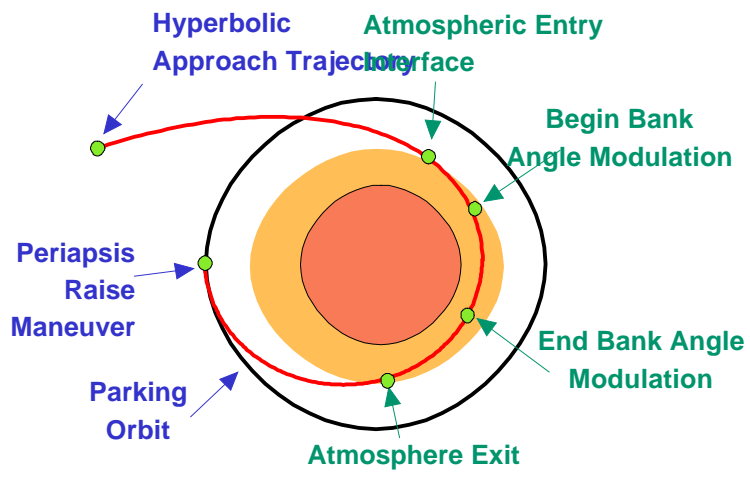
4.0 Hypersonic Capability Development





State-of-the-Art and Gaps

- **Precision controlled Aerocapture and Aerocapture/Entry Integration**
 - Never been done into any planetary atmosphere. Significant body of work shows that technology for aerocapture into low energy orbits is ready for program application
 - Aerocapture followed by Entry may require either multiple use ablative TPS and/or multiple aeroshell/TPS systems
- **Aerocapture capability, particularly for aerocapture from up to 13 km/s into high energy orbit may be required for Earth return from Mars.**
- **Aerocapture System architecture capability is required for:**
 - 70 - 100 MT at Mars with arrival speed (6 - 10) km/s





4.0 Current State-of-the-Art & Gaps (Cont.)



- **GN& C for Aerocapture:**

- **SOA:** Aerocapture GN&C using bank-angle control only is mature (TRL 6) for robotic missions with rigid aeroshells and atmospheric exit velocity <80% escape speed
 - Apollo capsule had human-rated aerocapture-like guidance mode (never flown)
 - Aeroassist Flight Experiment (1990's), Mars 01 Aerocapture Mission, CNES/NASA Mar Premier Orbiter all developed mature aerocapture guidance algorithms
 - Multiple detailed systems analysis for multiple destinations (Titan, Neptune, Venus, Mars) have all demonstrated that guidance algorithms can be developed that provide the required exit conditions
- **Gap:** Aerocapture guidance algorithms with atmospheric exit velocities > about 90% escape speed are immature and may required direct drag control (e.g. angle of attack modulation)



4.0 Current State-of-the-Art & Gaps (cont.)



- **GN& C for Aerocapture (cont.)**

- Very limited assessment of guidance algorithms and no flight experience for ballutes with very low ballistic coefficients that fly at very high altitudes and low aerodynamic heating rates
 - Determination of vehicle aerodynamics including control interactions required
 - Guidance algorithms developed for rigid aeroshells expected to be applicable for low ballistic coefficient systems but interaction of the guidance with the flexible structure and the control system is a concern that must be addressed
- Passive angle-of-attack control needs to be assessed for the HPLS systems
 - Addition of direct drag modulation should be considered to increase robustness
- Natural maturation of approach navigation to support robotic missions is adequate for aerocapture
- Inertial navigation system during atmospheric flight is sufficiently accurate



4.0 Current State-of-the-Art & Gaps (cont.)



- **GN& C for Entry to decelerator (e.g. parachute) deployment**
 - State of the art
 - Apollo demonstrated precision entry (position error < 10 km)
 - Apollo entry guidance adapted for Mars Science Laboratory (MSL) – proven through high fidelity flight simulations to provide precision entry capability (2-10 km range error at parachute deploy)
 - 3-axis control using reaction control system (thrusters)
 - Navigation is IMU-based until heatshield jettison (2.5 km AGL) – then radar data available
 - Implications for human missions
 - Direct measurement of altitude and altitude rate required
 - Mars relative navigation required
 - Pinpoint landing and deceleration control may required direct drag modulation
 - More detailed information on Mars climate (density and wind profiles) required for vehicle development and evaluation
 - Guidance algorithms developed for rigid aeroshells expected to be applicable to flexible aeroshells with low ballistic coefficient but interaction of the guidance with the flexible structure and the control system must be addressed
 - GN&C for very low ballistic coefficient inflatable aeroshells has not been assessed



4.0 Current State-of-the-Art & Gaps (Cont.)



Rigid Aeroshell:

- **Entry Vehicle Configuration - Mars Aerocapture / Entry**
 - SOA: Viking/Pathfinder/MER/MSL at Mars ; Shuttle at Earth
 - Gaps
 - scalable systems (combination of flexible and rigid) for 50 - 60 MT Mt and large volume (~ 10 m dia., ~40 m long) needed
 - need higher L/D for low G' loads and for precision landing (mid L/D, slender body shapes)
 - precision guided entry will require control authority and potentially movable control surfaces

- **Entry Vehicle Configuration - Mars Return**
 - SOA: Apollo
 - Gaps
 - Higher entry speed (up to 15 km/s) will require more capable Thermal Protection System

- **Entry Vehicle Configuration - Lunar Return**
 - SOA: Apollo
 - Gaps:
 - Larger aeroshell for 2 to 4 times the mass of Apollo



4.0 Current State-of-the-Art and Gaps (Cont.)



- **TPS for Mars**
 - Viking, Pathfinder, MER heritage - Heatshield material is SLA 561-V and backshell TPS is SLA and SIRCA
 - Other higher performance materials for Mars AE exists (TRL 6) but have not been flight qualified
 - A larger suite of TPS materials (more than 2) will be required
 - Human rating of TPS will require relatively more arcjet testing and flight verification of design methods
 - Manufacturability and integration for large volume system need development
- **TPS for Earth Entry (Lunar Return)**
 - Human rated ablative TPS - Apollo TPS does not exist - will require re-establishing manufacturing process and re-qualifying TPS
 - Other capable material will require human rating and establishing manufacturing capability for large scale system
- **TPS for Earth Entry (Mars Return)**
 - Will require more capable TPS compared to Mars Entry or Earth Entry from Moon due to higher entry velocity
- **TPS Development and Qualification for Mars and Earth Entry :**
 - Apollo era combined (convective + radiative) test facilities do not exist
 - Will require reestablishing/upgrading test facilities for TPS development, testing and qualification
 - Current facilities do not test in CO₂ - acceptable for Robotic missions
 - need to establish facility to flight relevance of testing for Mars in air either via analysis and flight data or modification of existing facilities for testing in CO₂

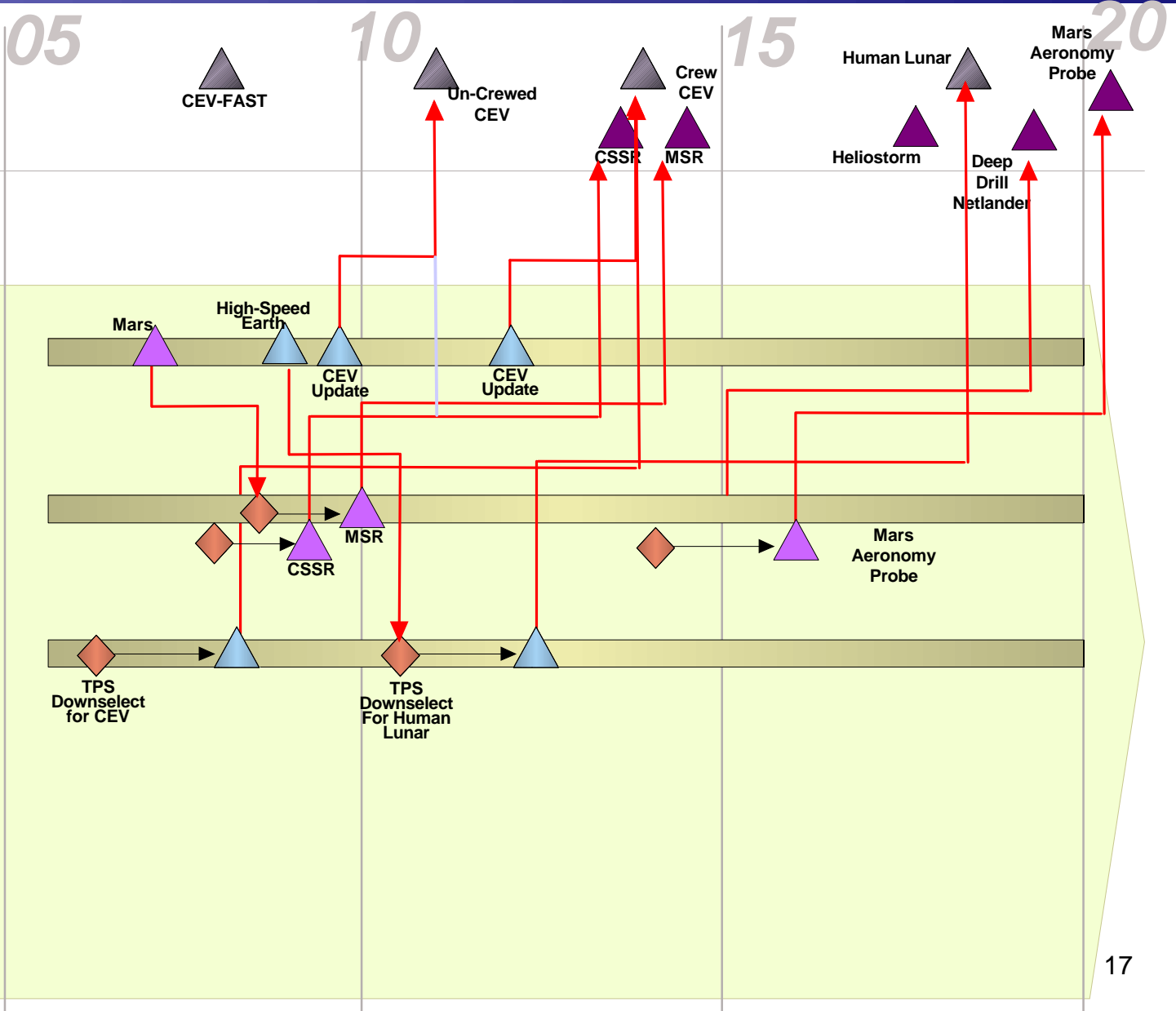


Thermal Protection System Roadmaps - 2005 to 2020



- ESMD Program Milestone
- SMD Program Milestone
- Downselect Decision
- Human Capability Infusion into FSD
- Robotic Capability Infusion into FSD
- Capability Infusion into Ops
- Capability Maturation

4.3 Thermal Protection System





Thermal Protection Systems Roadmaps - 2015 to 2030



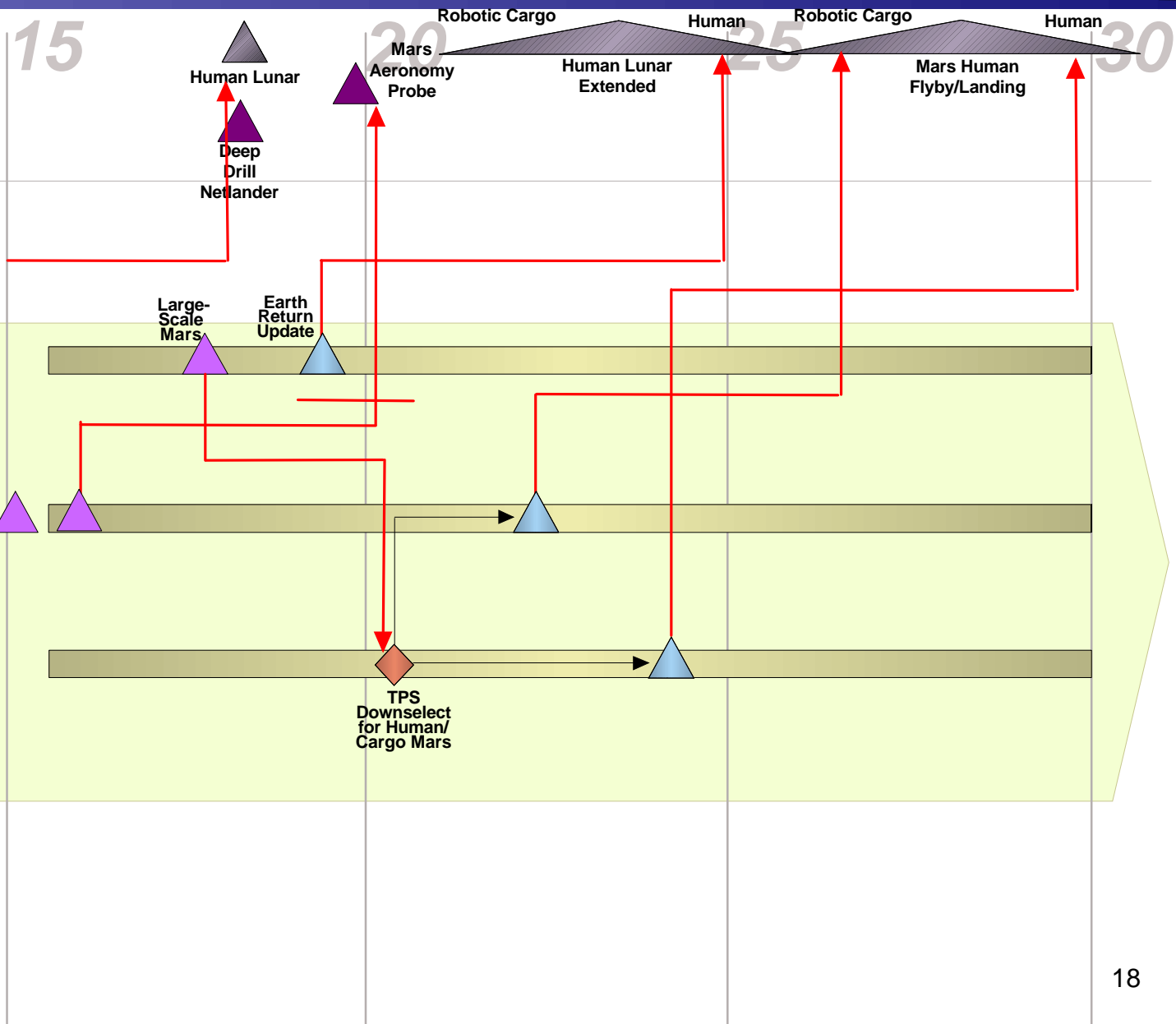
- ESMD Program Milestone
- SMD Program Milestone
- Downselect Decision
- Human Capability Infusion into FSD
- Robotic Capability Infusion into FSD
- Capability Infusion into Ops
- Capability Maturation

4.3 Thermal Protection System

Entry Vehicle Configuration Env.

Development and Validation of Optimized Robotic TPS

Human-Rated Lightweight Ablator Development, Validation, and Qualification





4.0 Current State-of-the-Art and Gaps (cont.)

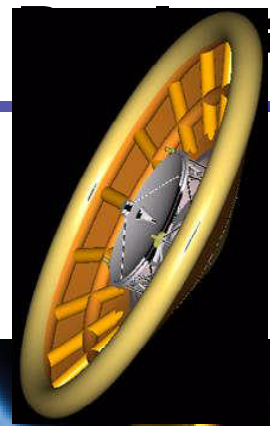


- **Inflatable aeroshell technologies are in very early stage of development**
 - Moderate to Low ballistic coefficient class
 - Russia designed, developed, and launched an inflatable aeroshell intended to enter the Mars atmosphere and decelerate aerodynamically with penetration of the Mars surface on landing – Launch system failure prevented the system from leaving earth orbit
 - Derivative of this system, Inflatable Reentry and Descent Technology (IRDT) is being flight tested with limited success
 - **Current technology development efforts including the following have proven feasibility of concept**
 - Testing of thin-film material properties in the expected environment
 - Development and testing of material seaming approaches
 - CFD modeling validated with hypersonic wind tunnel testing
 - Trajectory control for use in aerocapture
 - **Key issues still to be addressed**
 - Manufacturing on large scale (B ~ 10) required for human missions
 - Deployment of large system
 - Aeroelastic effects in hypersonic, rarefied flow
 - Trajectory control for precision landing
 - **Efforts to address aeroelasticity, manufacturing of complete system, applicability assessment for human system and low speed flight test are included in the Exploration Systems Research & Technology (ES&RT) Program.**



Inflatable Aeroshells

Inflatable Aeroshell



Attached Ballute



Trailing Ballute

Payoffs

- Reusability
 - Because the host structure does not have to withstand high heating rates, potential for reusability.
- Modularity & In-Space Assembly
 - May be packaged in a small volume and inflated to full size prior to use.
 - Technology has potential for scalability to a wide range of payload masses for deceleration at Earth and Mars.
- Affordability
 - Attaches to a wide range of payload configurations for logistics delivery.
 - Provides deceleration with a mass equivalent to a propulsion system having a specific impulse greater than 5000 sec.

Description

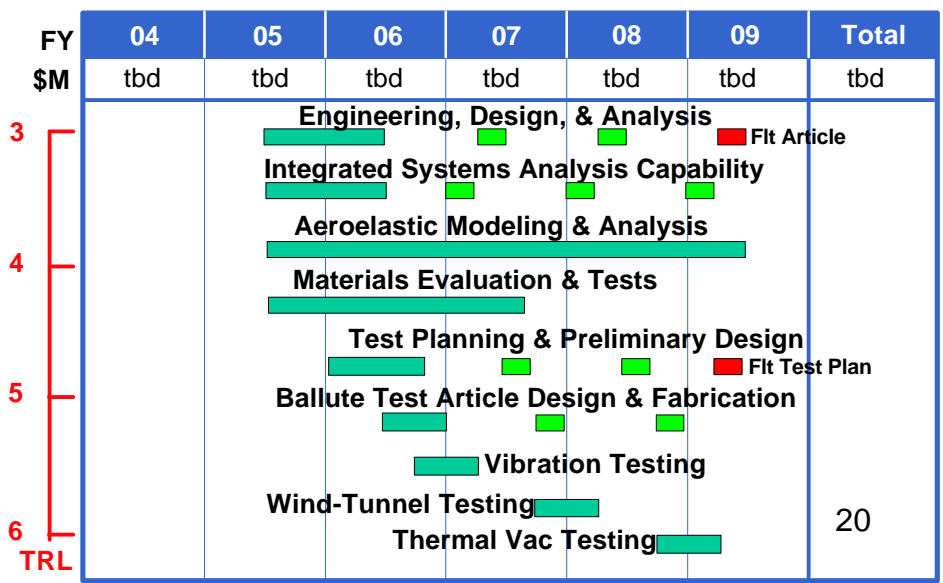
Objective

- Develop ultra lightweight inflatable ballute technology for use in return of humans or cargo from the Moon.

Approach

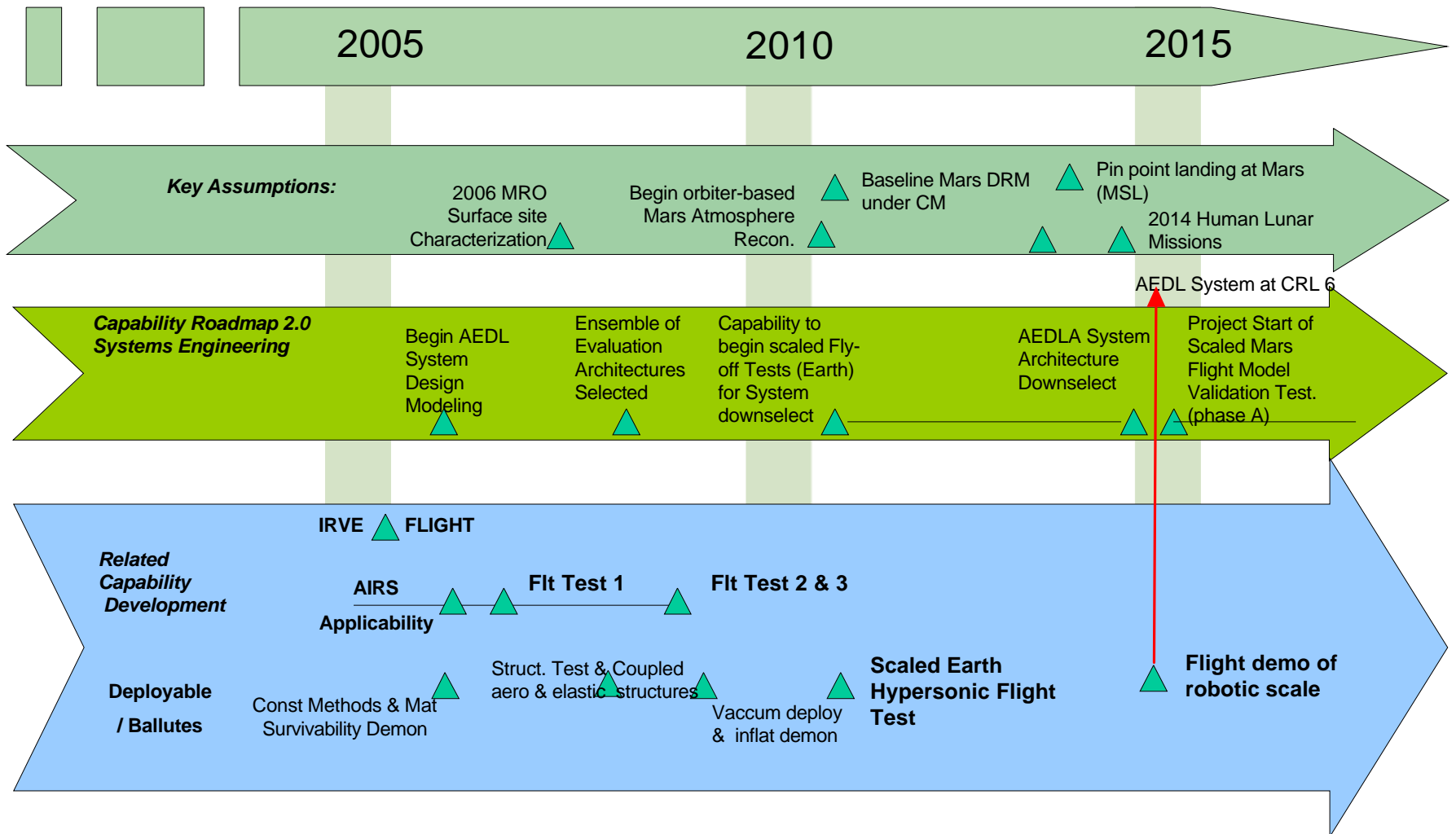
- Systems analysis to define the lunar return concepts, fully define operational environments, and develop testing requirements;
- Integration of computational tools to perform coupled hypersonic aerothermal, nonlinear structural, and thermal analyses;
- Materials, seam, and ballute component testing to characterize performance over the entire operational range;
- Design and fabrication of subscale (2 to 3-m diameter) thin film ballute system test articles to demonstrate manufacturing processes;
- Deployment, strength, and durability testing of the subscale articles at the dynamic pressures expected for a lunar return mission;
- Validation of analysis tools with data obtained from subscale tests;
- Definition of flight qualification approach for exploration missions.

Schedule



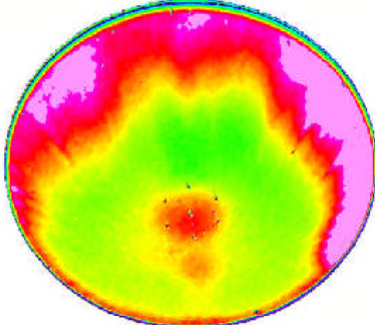


Deployable Aeroshell Roadmap



- Decision
- Milestone
- Ready to Use

Transition in Mach 6 Tunnel

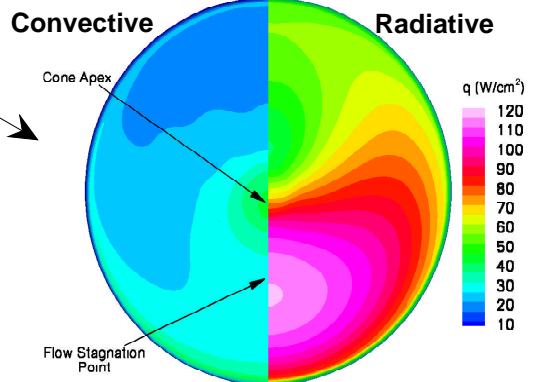


Shock Layer Radiation

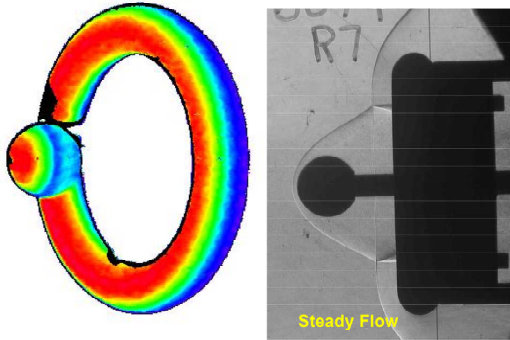
Transition to Turbulence

Coupling between radiation/TPS/fluids

Titan Aerocapture Peak Heating

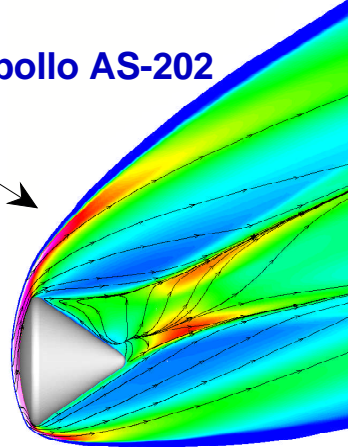


Trailing Ballute Test



Non-continuum flows and aeroelastic effects for low b entry systems

Apollo AS-202



- Gaps are addressed via:
- Mission-specific uncertainty analysis to rank importance
 - Ground testing *tailored* to reduce key uncertainties
 - Model development based on test results
 - Model validation with flight instrumentation



Capability (Metric)

- Rating Scale:**
- Critical Capability Gap
 - Important Capability Gap
 - Minor Capability Gap
 - No Gap or N/A



Backup



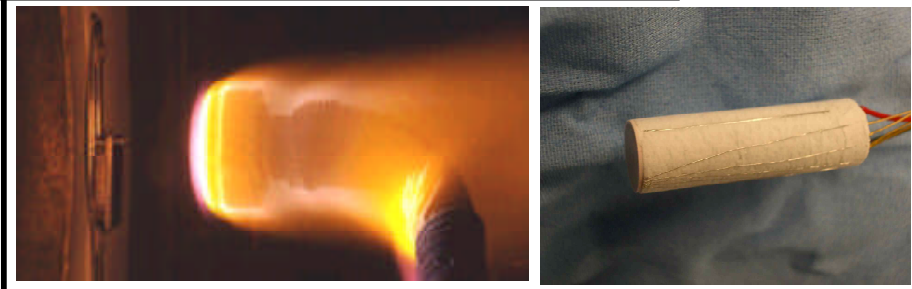
Development of High Performance/Reliable Human Rated TPS



Capability Objective and Current Capabilities

- **Objective:** To accurately predict the entry environments for future robotic and human exploration missions, to determine the applicability of existing ablative TPS materials to these missions, and to develop and validate new materials, if none exist.
- **Goal:** To produce multiple human-rated ablative TPS alternatives for application to missions in the various exploration spirals, enabling mass-efficient, robust entry systems. To ensure efficient alternatives are available for robotic exploration, as well.
- **SOA:** In-Space Propulsion Program investments in lightweight ablative TPS for robotic missions have brought some to TRL5+ since 2003;
 - Aerothermal Env. / High fidelity TPS response Design methods for large hypersonic systems needs of be validated with ground and flight data
 - flight qualification, validation for specific applications, and human rating are TPS gaps.

Capability Developed and Metrics



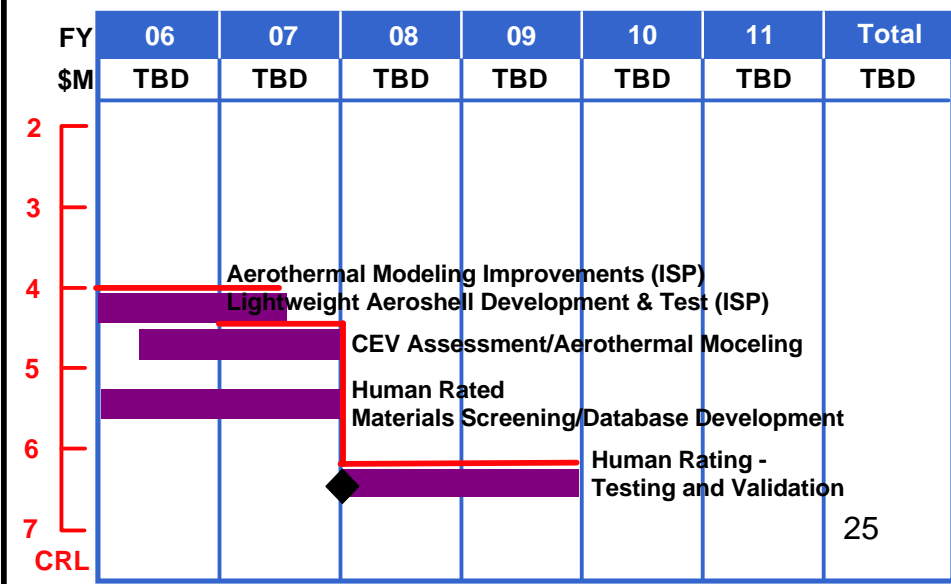
Lightweight Ablator Arcjet Testing **Heat Flux Gauge Ablator Plug**

- A suite of light weight TPS to result in aeroshell mass fraction of 10% - 25%
- Scalable to large size
- Capable of withstanding combined (convective+radiative) environment with non-catastrophic behavior

Development Approach

- Define the relevant environments in which the TPS materials must operate, using aerothermal modeling.
- Determine the applicability of existing ablative TPS materials, through laboratory characterization, screening test, and model development.
- Downselect alternatives and qualify the best candidates for robotic or human mission use.
 - Combined environments testing on coupons and sub-components
 - Instrumented flight testing to validate models and performance
 - Flight testing data from Earth and Mars (robotic) tests and verify design methods
 - *Aeroshell system* (structure, adhesive, TPS, and sensors) ground testing and qualification

Schedule





Aerocapture/EDL Thermal Protection System (TPS) Metrics



Capability (metric)	Figure of Merit	
	SOA	Long Term Need
Heat Flux (capability to withstand)	Space Shuttle: <math><40 \text{ W/cm}^2</math> acreeage Mars Robotic: ~100 W/cm ²	Approximately 400 W/cm ² for return from moon, 70 W/cm ² for Mars arrival, 800 W/cm ² for return from Mars
Ablator Density (g/cm³)	SLA-561V (Mars): 0.26 g/cm ³	Less than ~0.5 g/cm ³ for Mars missions, to keep aeroshell mass fraction <math><25-30\%</math>
Human Rating of Reusable TPS	Space Shuttle Tile and Leading edge	If true reusability necessary, need system to withstand return from Mars (up to 13 km/s).
Human Rating of Ablative TPS	None since Apollo	Necessary, if moon/Mars architectures only require 1-2 time reuse
Manufacturability at large scale (ablatives)	Mars landers: ~2.65 meter diameter (Viking blunt shape) Earth sample capsules: 1-1.5 meter diameter (blunt shape)	Payload-dependent. Estimate <u>slender</u> Mars aeroshell at 5 m dia x 15 m long. Estimate 4.4 m dia for Earth return capsule (blunt shape)
Aerothermal Environment Prediction Uncertainty	Varies with destination and geometry. Largest uncertainties are in radiative heating, afterbody flow structure, and transition to turbulence.	Must reduce uncertainties to ~20% to enable efficient feed-forward designs. Requires improvements in radiative heating, afterbody flows, turbulence, catalycity, dust interaction, and coupled ablation analyses.



Aerocapture/EDL Thermal Protection System (TPS) Gaps (1)



	Gap Identified			
Capability (metric)	Spiral I	Spiral II	Spiral III	Spiral IV/V
Heat Flux (capability to withstand)	None (if no feed-forward requirement for Spiral II)	Need validated ablators at ~400 W/cm ²	No additional; Earth return needs from Spiral 2 should be adequate; need to evaluate CO2 vs air effects. MSR EEV may require more capability.	Need validated ablators for Earth return from Mars (~600 - 1200 W/cm ² , depending on design).
Ablator Density (g/cm³)	TBD, depending on materials available and mass constraints	No additional, depending on materials available and mass constraints	No additional	Less than ~0.5 g/cm ³ for Mars missions, to keep aeroshell mass fraction <25-30%
Human Rating of Reusable TPS	None--use Space Shuttle, if architecture requires reusability	No additional	No additional	If true reusability necessary, need system to withstand return from Mars (up to 13 km/s).
Human Rating of Ablative TPS	Need 1-3 materials human-rated, for evaluation and selection	Need 1-3 materials human-rated, for evaluation and selection	No additional	Need 1-3 materials human-rated, for evaluation and selection



Aerocapture/EDL Thermal Protection System (TPS) Gaps (2)



	Gap Identified			
Capability (metric)	Spiral I	Spiral II	Spiral III	Spiral IV/V
Manufacturability at large scale (ablatives)	Demonstration and validation needed on ~4-meter diameter; not done since Apollo	No additional	Demonstration and validation may be needed, for up to 5- meter-diameter robotic Mars. If Earth return payloads increase substantially above Spiral I, need to address.	Payload-dependent. Possible order-of-magnitude increase in mass delivered to Mars, new shape of vehicle.
Aerothermal Environment Prediction Uncertainty	None	Earth radiative heating tools validated; expertise re-established; coupled ablation models developed and validated	Assume growing Mars missions: Mars analyses validated with ground and flight tests; coupling, ablation, catalycity, radiation, turbulence need to be well-understood, to within 30-60%.	All tools validated to human qualification levels using data from past instrumented flights. All flowfield parameters predicted within 20%.