5.0 Aerodynamic and Propulsive Decelerator Systems

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Part I - Introduction
- Capability Breakdown Structure
- Decelerator Functions
- Candidate Solutions

Part II - Performance and Technology
- Capability State-of-the-Art
- Performance Needs
- Candidate Configurations

Part III - Possible Technology Roadmaps
- Capability Roadmaps
Human Planetary Landing Systems
CRM # 7

5.1 Supersonic Aerodynamic Deceleraors
5.2 Subsonic Aerodynamic Deceleraors
5.3 Supersonic Propulsive Deceleraors
5.4 Systems Design, Development, Testing, and Qualification
Decelerator Functions

Decelerators typically provide one or more of the following functions in planetary landing systems:

- Deceleration from supersonic to subsonic speed
- Controlled acceleration
- Minimize descent rate
- Provide specified descent rate
- Provide stability (parachute drogue function)
- System deployment (parachute pilot function)
- Provide difference in ballistic coefficient for separation events
- Provide height
- Provide timeline
- Provide specific state (e.g., altitude, location, speed for precision landing)
Aerodynamic and Propulsive Decelerator Capabilities for Mars - Integrated Mission Architecture

Options for Hypersonic Decelerators

Parachutes  Inflatable Decelerators  Propulsion

Options for Supersonic & Subsonic Decelerators

Options for Terminal Descent Systems
<table>
<thead>
<tr>
<th>Candidate Mission Scenario</th>
<th>Candidate Solutions</th>
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<tbody>
<tr>
<td><strong>Mars Descent</strong></td>
<td><strong>Mars human and cargo landing</strong></td>
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<tr>
<td>Supersonic parachutes, subsonic</td>
<td>parachute clusters</td>
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<td>Inflatable decelerators</td>
<td>Supersonic and subsonic propulsion</td>
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<td>Combination</td>
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<td><strong>Earth Return (Mars)</strong></td>
<td><strong>Human direct entry or landing from orbit</strong></td>
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<td>Subsonic parachute cluster</td>
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<td><strong>Earth Return (Lunar)</strong></td>
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<td>Parafoils</td>
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</tr>
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Current Mars Aerodynamic Decelerator Technology
Capabilities and Limitations

Supersonic Parachutes

- Disk-Gap-Band (DGB) heritage parachutes
- Deployment at Mach number $M \cdot 2.1$ (Viking heritage)
- Deployment at dynamic pressure $q \cdot 800$ Pa (MER heritage)
- Nominal diameter, $D_0 \cdot 16.15$ m (Viking heritage)
- Maximum drag area, $C_D S \cdot 108$ m$^2$ (approximate for Viking parachute with $D_0 = 16.15$ m at $M = 2.1$)
- No reefing, clustering, or glide control
- Mortar deployment
Viking DGB Parachute Drag Model

\[ C_{D0} \]

0.9

0.8

Hi

M
Subsonic Parachutes

• DGB heritage parachutes (see supersonic parachutes)
  • Maximum drag area, $C_d S$ • 139 m$^2$

• Ringsail heritage parachutes
  • Beagle 2, MTP Subsonic Parachute, extensive Earth-flight experience (e.g., Mercury, Gemini, Apollo)
  • Deployment at Mach number $M$ • 0.8 (MTP Subsonic Parachute)
  • Nominal diameter, $D_0$ • 33.5 m (MTP Subsonic Parachute)
  • Maximum drag area, $C_d S$ • 679 m$^2$
  • Reefing
  • No clustering or glide control
Current Mars Aerodynamic Decelerator Technology Capabilities and Limitations

Drag vs Stability Comparison

- **Solid Textile Parachutes**
- **Slotted Textile Parachutes**
- **Disk-Gap-Band**
- **Guide Surface**
- **Conical Ribbon**
- **Ringsail**

**Average Angle of Oscillation (AAO), deg.**

**$C_{D0}$**
Inflatable Supersonic Decelerators

- No inflatable supersonic decelerators have been flown in planetary exploration missions
- Several concepts proposed, some tested
- Some concepts show promise

Materials

- Kevlar, Nylon, Polyester (Dacron) are “qualified” materials
- Vectran, Spectra, Technora, Nextel, Zylon now used in some “qualified” applications
- Coated materials (impermeable, ablative) have been used for munitions programs
Analysis Methods

- Current methods have a significant empirical component (need data to calibrate)
- First-principle methods (e.g., Fluid Structures Interaction analyses) are available but validation is lacking
- Scaling of results (physical size and test conditions) possible but poorly understood

Test Methods

- Need improvements in our ability to adjust results of all testing to other scales and different conditions
- Wind tunnel testing (sub-scale and full-scale)
  - Available facilities at risk of closing
- Low altitude flight testing (subsonic)
- High altitude flight testing (supersonic and subsonic)
  - Sounding rocket
  - Balloon
  - Balloon/Rocket
Current Earth and Mars Aerodynamic Decelerator Technology Capabilities and Limitations

- Sub-Scale Wind Tunnel Testing
- Balloon/Rocket
- Full-Scale Wind Tunnel Testing
- Full-Scale Flight Testing
- Sounding Rocket
Mars Propulsive Decelerators

- Supersonic deceleration at Mars may require a propulsive component
  - An aerodynamic-decelerator only solution may not be realistic (extremely large parachutes)
- Use of retrorockets to decelerate from supersonic to subsonic speeds has issues
  - Initiation of thrusting is likely to require blow-out covers in TPS
    - MER TIRS motor covers are a primitive example
  - Thermal protection must be provided while vehicle is enveloped in high enthalpy recirculating exhaust
  - Plume / freestream interaction will be fundamentally unsteady
    - Freestream Mach number and dynamic pressure change rapidly
    - Rapidly changing aerodynamic forces on aeroshell will require significant control authority, especially in the transonic regime
- Development of modeling capability for this “inverse base flow” problem will be likely require subscale wind tunnel tests and flight testing.
Supersonic-to-Subsonic Deceleration

- Larger aero decelerator drag area \( (C_{DS}) \) at supersonic speeds
- Aero decelerator drag area control at supersonic speeds (loads and trajectory)
- Aero decelerator deployment at Mach number > 4
- Propulsive supersonic deceleration

Subsonic Terminal Descent

- Larger aero decelerator drag area \( (C_{DS}) \) at subsonic speeds
- Large propulsive descent system

Pinpoint Landing Capability

- Ability to make parachute glide in a chosen direction
- Propulsive descent system guidance and hazard avoidance
Fluid-Structures Interaction Analyses

- Joining of Computational Fluid Mechanics (CFD) with structural Finite Element Methods (FEM)
- Allows for numerical design optimization
- Can yield insight on scaling of test results (physical size and test conditions)
- Can yield values of quantities usually obtained by test (e.g., $C_D$)
- Can yield values of quantities that are difficult to obtain by test (e.g., dynamic aero coefficients - $C_{mq}$)
- Has possibility of reducing testing and qualification costs by decreasing number of tests
- Works with trend of cheaper computing
- In need Verification (are we solving the equations right?) and Validation (are we solving the right equations?) to obtain level of trust suitable for exploration missions
- Must-have technology
Scaling

- Ability to scale test results to the system size and test conditions
- May allow for relevant sub-scale testing of systems in flight at supersonic conditions
- Must-have technology for large Mars systems

Testing

- Adequate wind tunnel and flight test (e.g., high-altitude balloons, sounding rockets) capabilities must be retained and in some cases expanded
- Capability to flight test supersonic systems will become a necessity for Mars systems

Materials

- Development of new space-qualified materials will have a significant impact on aerodynamic decelerator design (i.e., mass to drag area ratio)
- Materials with high temperature capabilities for parachutes (M > 2.5) and inflatable decelerators will be required
Earth and Mars: Aerodynamic Decelerators Technology Needs

Key Wind Tunnel Testing Facilities

NFAC at NASA ARC
Full- and Sub-Scale Testing
Subsonic

TDT at NASA LaRC
Sub-Scale Testing
Subsonic and Transonic

10’ x 10’ Supersonic at NASA GRC
Sub-Scale Testing Supersonic
Possible Mars Configurations

2 Metric Ton Entry Mass Level
- Disk-Gap-Band Supersonic Parachute
- Ringsail Subsonic Parachute (single canopy)

4 Metric Ton Entry Mass Level
- Disk-Gap-Band Supersonic Parachute (reefed)
- Ringsail Subsonic Parachute (cluster)

10 Metric Ton Entry Mass Level
- Inflatable Supersonic Decelerator
- Ringsail Subsonic Parachute (cluster)

50 Metric Ton Entry Mass Level (Human)
- Inflatable Supersonic Decelerator
- Ringsail Subsonic Parachute (cluster)
- Propulsion Assisted Deceleration
Team 7: Supersonic Decelerators Capability Roadmap

Key Assumptions:
- 2006 MRO Surface site Characterization
- Launch orbiter-based Mars Atmosphere Recon.
- Pin point landing at Mars (MSL)
- Capability to begin scaled Fly-off Tests (Earth) for System downselect
- 2017 Human Lunar Missions
- Project Start of Sub Scaled Mars Flight Model Validation Test. (phase A)

Capability Roadmap #7: HPLS
Begin AEDL System Design Modeling
Ensemble of Evaluation Architectures Selected
AEDLA System Architecture Down select
TRL 5 Sub Scale CRL 1
AEDL Subscale System at CRL 3

7.5 Aerodynamic and Propulsive Decelerator Capability
- 4MT 30m Supersonic Chute Capability
- Detailed testing & materials dev.
- TRL 5
- Sub scale Earth flight tests
- 4 MT 30m Supersonic Parachute
- Detailed testing & materials dev.
- 80x100 Wind Tunnel
- 10 MT >50 m dia. Sub scale Earth flight tests
- 10 MT Dia >50 m Chute or Propuls.
- Supersonic Decelerator Scaled Capability Data (TRL6)

Aerodynamic Decelarators
- 4 MT 30m Supersonic Parachute
- Detailed testing & materials dev.
- 80x100 Wind Tunnel
- 10 MT >50 m dia. Sub scale Earth flight tests
- Solution
- Mars Sub Scale Tests

AND/OR

Propulsive Decelarators
- CFD Analysis of Propulsion Methods
- Supersonic Wind Tunnel (9X7)
- If OK
- Sub scale Earth flight tests (10 MT)
- Mars Sub Scale Tests

Decision Point
Major Event / Accomplishment / Milestone
Ready to Use

2005  2010  2015
Team 7: Supersonic Decelerators Capability Roadmap

**Key Assumptions:**
- Subscale AEDL Model Validation Mission Launch
- AEDL Human Scale System at (CRL 1)
- AEDL Human Scale System at (CRL 3)
- AEDL Human Scale Sys Capability Qualified for Flt (CRL 5)
- AEDL Subscale = CRL 6

**Capability Roadmap 7: HLPS**
- Sub Scaled Mars Flight Model Validation Project
- PDR
- Launch
- Full Scale (Earth)
- Begin Full Scale (Earth)
- Sub Scale AEDL Capability Exists: System Model validated at Mars
- Project start of First Mars Human Mission
- PDR Full scale Flight Tests (Earth)
- Full scale Flight Tests (Earth)
- PDR
- CRL 5
- Full scaleintegration (Earth)
- AEDL Human Scale Sys at (CRL 7)
- Human Scale Operational (CRL 7)
- Launch First Human Mission to Mars

**7.5 Aerodynamic and Propulsive Decelerator Capability**
- 10 MT >50 m dia. Sub scale Mars flight tests
- Full scale Flight Tests (Earth)
- Full scale Flight Tests (Earth)
- Full scale Integ. Sys. Tests at Earth
- 50 MT >100 m Full Scale Mars Parachute Capability
- 50 MT >100 m Full Scale Parachute Development & Tests
- 50 MT >100 m Full Scale Parachute Integ. Sys. Tests at Earth
- 50 MT >100 m Full Scale Parachute Development & Tests
- 50 MT >100 m Full Scale Parachute Integ. Sys. Tests at Earth
- Full Scale (50 MT) Mars Propulsive Deceleration Capability
- Full Scale Propulsive Integ. Sys. Tests at Earth

**Aerodynamic Decelerators**
- 10 MT >50 m dia. Sub scale Mars sub scale flight tests
- 50 MT >100 m Full Scale Parachute Development & Tests
- 50 MT >100 m Full Scale Parachute Integ. Sys. Tests at Earth

**Propulsive Decelerators**
- Propulsive Mars sub scale flight tests (10 MT)
- Propulsive Decel. Full Scale Development & Tests (50 MT)

**Decision Point**
- Full scale Flight Tests (Earth)
- Full scale Integration (Earth)
- Full scale Mars Landing

**Major Event / Accomplishment / Milestone**
- Ready to Use

**Timeline**
- 2020
- 2025
- 2030
Backup Material
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$C_{D0}$</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>$C_{DS}$</td>
<td>drag area</td>
</tr>
<tr>
<td>$C_{mq}$</td>
<td>derivative of pitching moment with respect to pitch rate</td>
</tr>
<tr>
<td>$D_0$</td>
<td>nominal diameter</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$q$</td>
<td>dynamic pressure</td>
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### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AAO</td>
<td>Average Angle of Oscillation</td>
</tr>
<tr>
<td>ARC</td>
<td>Ames Research Center</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<tr>
<td>DGB</td>
<td>Disk-Gap-Band</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>FSI</td>
<td>Fluid Structures Interaction</td>
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<tr>
<td>GRC</td>
<td>Glenn Research Center</td>
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<tr>
<td>LaRC</td>
<td>Langley Research Center</td>
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<tr>
<td>MER</td>
<td>Mars Exploration Rover</td>
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<tr>
<td>MT</td>
<td>Metric Ton</td>
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<tr>
<td>MTP</td>
<td>Mars Technology Program</td>
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<tr>
<td>NFAC</td>
<td>National Full-Scale Aerodynamics Complex</td>
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<tr>
<td>TDT</td>
<td>Transonic Dynamics Tunnel</td>
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<tr>
<td>V&amp;V</td>
<td>Verification and Validation</td>
</tr>
<tr>
<td>WT</td>
<td>Wind Tunnel</td>
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