The Challenge of Mars EDL (Entry, Descent, and Landing)

Ron Sostaric
NASA Johnson Space Center
AIAA Senior Member
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The information contained in this presentation reflects the collective wisdom and experience of a large number of individuals across the EDL community. It would be very difficult to attempt to list them all individually without missing a major contributor.

However, I would like to acknowledge Carlos Westhelle of NASA who directly provided much of the data shown here.
Mars Design Reference Architecture 5.0 Mission

1. 4 Ares-V Cargo Launches
2. Cargo: ~350 days to Mars
3. Aerocapture Habitat Lander into Mars Orbit
4. In-Situ propellant production for Ascent Vehicle
5. Aerocapture / Entry, Descent & Land Ascent Vehicle
6. 3 Ares-V Cargo Launches
7. Ares-I Crew Launch
8. Crew: Jettison drop tank after trans-Mars injection ~180 days out to Mars
9. Crew: Use Orion to transfer to Habitat Lander; then EDL on Mars
10. ~500 days on Mars
11. Crew: EDL to Habitats and Habitat Lander
12. Crew: Prepare for Trans-Earth Injection
13. Crew: ~180 days back to Earth
14. Orion direct Earth return

-26 to -30 months

-30 months

~26 months
Why is Mars EDL so difficult?

ATMOSPHERE:

- Thin Martian atmosphere (surface density equivalent to Earth’s at 30 km)
- Too little atmosphere to decelerate and land like we do at Earth
- Atmosphere is thick enough to create significant heating during entry

- Lack of understanding of the atmosphere:
  - Aerodynamics, aeroheating, winds, and density variations
GEAR RATIOS:

- All Propulsive: 1 metric ton (MT) on surface of Mars requires 20 MT in Low Earth Orbit (LEO). This would lead to unreasonably large masses in LEO.
- Using the Atmosphere allows a significant reduction in the gear ratio
  - 1 MT on surface of Mars requires 5-6 MT in LEO

WILL IT WORK?

So far all potentially feasible human-scale Mars EDL architectures require the successful development of SEVERAL low TRL elements.

There are many promising ideas that need assessment and testing. These include:
- Large rigid heat shields (10m diameter by 30m length)
- Inflatable heat shields (20 to 25 m diameter)
- Inflatable aerodynamic decelerators
- Supersonic retro-propulsion
- Precision landing
6 U.S. Mars Entry, Descent, and Landing Successes
All six of the successful U.S. Mars EDL systems had:

- **Low Landing Site**: elevation sites below −1 km MOLA ← that’s Mars Sea Level
- **Low Mass**: Had landed masses of less than 0.6 MT
- **UNGUIDED**: Had large uncertainty in targeted landing location (300 km for Mars Pathfinder, 80 km for MER)

Mars Science Laboratory (MSL) ‘11 EDL Architecture:

- **Low Landing Site**: Landed elevation requirement for sites below 0 km MOLA
- **Low Mass**: Has landed mass of 0.9 MT
- **GUIDED**: Has uncertainty in targeted landing location of 10km

HUMANS need more capability:

- All of the current Mars missions have relied on large technology investments made in the late 1960s and early 1970’s as part of the Viking Program (heatshield shape, thermal protection material, and parachute)
- **Large Mass** (Entry Mass of ~100 – 150 MT)
- **Higher elevations** – interesting science
- **Precision Landing**
Previous Viking derived EDL systems and the thin Martian atmosphere and small scale height have limited accessible landing sites to those below -1.0km MOLA.

To date the southern hemisphere has been largely out of reach (approximately 50% of the planet surface remains inaccessible with current EDL technologies).

(Courtesy of Rob Manning, JPL)
Landing Site Elevation / Accessibility

MOLA 1/4° Topographic Data

< 2.5 km (90% of Surface)

< 1.0 km (65% of Surface)

< -1.0 km (45% of Surface)
Core Viking Technologies: 70° sphere-cone aeroshell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Viking</th>
<th>MPF</th>
<th>MER</th>
<th>Phoenix</th>
<th>MSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Mass (kg) / Ballistic Coeff. (kg/m²)</td>
<td>980 / 66</td>
<td>585 / 63</td>
<td>836 / 90</td>
<td>603 / 65</td>
<td>3257 / 140</td>
</tr>
<tr>
<td>Lander/Rover Mass (kg)</td>
<td>612</td>
<td>11</td>
<td>173</td>
<td>64</td>
<td>850</td>
</tr>
<tr>
<td>Aeroshell Diameter (m)</td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td>Angle-of-Attack (deg) / L/D</td>
<td>11.1° / 0.18</td>
<td>0° / 0.0</td>
<td>0° / 0.0</td>
<td>0° / 0.0</td>
<td>-15.5° / 0.24</td>
</tr>
<tr>
<td>Peak Heatrate (W/cm²)</td>
<td>21</td>
<td>106</td>
<td>44</td>
<td>59</td>
<td>&lt;210</td>
</tr>
<tr>
<td>Parachute Diameter (m)</td>
<td>16.15</td>
<td>12.4</td>
<td>14.1</td>
<td>11.5</td>
<td>19.7</td>
</tr>
<tr>
<td>Landing Site Elevation (km)</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-1.3</td>
<td>-3.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>
### Comparison with Previous Missions

**Core Viking Technology**
- 70° sphere-cone aeroshell
- SLA-561V TPS
- Supersonic DBG parachute

#### Table: Engineering vs. Human Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Entry Mass (kg) / Ballistic Coeff. (kg/m²)</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lander/Rover Mass (kg)</td>
<td>612</td>
<td>100-150 MT/150-600 kg/m²</td>
</tr>
<tr>
<td>Aeroshell Diameter (m)</td>
<td>3.5</td>
<td>10-30</td>
</tr>
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<td>Angle-of-Attack (deg) / L/D</td>
<td>11.1° / 0.18</td>
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</table>
EDL Phase Plot – A Handy Way to Visualize EDL

When entering from low Mars orbit, start here.

Subsonic parachute inflation
“Mach - dynamic pressure box”

Supersonic parachute inflation
“Mach - dynamic pressure box”

Subsonic propulsion
“Mach - thrust/weight box”

Goal is to land here.

Ref: Braun & Manning IEEE-AC 0076
Robotic program: No gap so far ....

Entry at 6000 m/s

Supersonic Parachute Inflation

Start subsonic propulsive descent here (< 1 km AGL)
How would Humans Land?

Entry at 3400 m/s

- Supersonic parachute inflation “Mach - dynamic pressure box”
- Supersonic Decelerator “gap”

**Technology Gap:**
This gap can be closed using a supersonic aerodynamic or propulsive decelerator.

Without new technologies we have surface impact at Mach 2.5
EDL Technology Development

- Technologies that can help close the “gap”
  - Rigid Aeroshell
  - Inflatable Aerodynamic Decelerator (IAD)
  - Supersonic Retro-Propulsion

- Other technologies of interest
  - Aerocapture
  - Precision Landing
  - Hazard Detection and Avoidance
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Inflatable Aerodynamic Decelerators
What about Large Inflatable Entry Vehicles? (ballistic coefficient = 50 kg/m² & L/D = 0.3)

With large enough inflatables, it may be possible to achieve subsonic speeds in some cases.

30-40 m diameter inflatable or other hypersonic drag system
Supersonic Retro-Propulsion

- **Advantages:**
  - More precise landing – aerodynamics / winds now secondary effect
  - Control authority and altitude from Mach > 3 to the ground
  - Fewer complex systems (e.g. parachutes, deployable systems)

- **Disadvantages:**
  - Large propellant mass fractions
  - Aerodynamic stability of the vehicle plume and flow impingements
  - RCS / flow interactions
    - Aerodynamic / propulsion flow interactions
    - Plume / flow aeroheating
  - Surface contamination issues
Potential Exploration Architectures

Some possible combinations...
EDL Technology Development

- Technologies that can help close the “gap”
  - Rigid Aeroshell
  - Hypersonic Inflatable Aerodynamic Deceleration (HIAD)
  - Supersonic Retro-Propulsion

- Enabling technology
  - Aerocapture

- Risk reduction and performance enhancement
  - Precision Landing
  - Hazard Detection and Avoidance
Aerocapture saves mass by using the atmosphere rather than a propulsive maneuver to capture into orbit.

1. Hyperbolic approach trajectory
2. Enter Atmosphere
3. Begin Bank Angle Modulation, Equilibrium Glide Phase (g-load trigger)
4. Peak heat rate, g-load
5. Periapsis
6. Begin Exit Phase (velocity trigger)
7. End Bank Angle Modulation (g-load trigger)
8. Exit Atmosphere
9. Periapsis Raise Maneuver
10. Orbit Adjust Maneuver

Target Orbit

Note: target orbit shown here is notional, and is not necessary circular.
The Case for Precision Landing, Hazard Avoidance, and Pinpoint Landing

- Pathfinder, Mars 98
- Improved approach navigation
- Autonomous aeromaneuvering $L/D < 0.3$
- Autonomous aeromaneuvering $L/D > 0.8$
- Autonomous terrain matching
- Obstacle avoidance

- 1 km radius
- 10 km radius
- Perfect approach navigation
- Pathfinder landing dispersion ellipse
- Dispersion size, km
- 50 km
Precision Landing

- Precision landing is the capability to land very accurately.
- Requires very good knowledge of the vehicle state (navigation) at the right time, in addition to the ability to correct for state errors (guidance and control).
- A combination of sensors including star tracker, inertial measurement unit (IMU), altimeter, and velocimeter are used for state estimation.
- Terrain Relative Navigation is a technology being developed for the Moon and Mars which may enable a precision landing level of performance.
Hazard Detection and Avoidance (HDA)

- HDA is the capability to detect and avoid hazards during the landing
- An onboard hazard map is developed real time during the descent using flash LIDAR
- The flash LIDAR returns a 3-D image of the landing area which contains higher resolution information of the landing area than currently possible using orbit reconnaissance
- An updated landing point is then selected (either automatically or via crew intervention) and the vehicle re-targets to the new landing point
Example Flash Lidar Image

- 3D Points
- Elevation Map

- 128x128 pixels
- 430m Range
- 7° Off Nadir

- Top View
- Oblique View
- Side View

- 1x1x1m box
- 2x2x1m box
- 0.9m radius hemispheres
- 0.6m radius hemispheres

- 20m
Conclusion

- Current state of the art has a gap for large robotic (> 1 MT) and human Mars EDL
- NASA is developing a number of promising technologies that may eliminate the gap and enable future missions to Mars
- In addition, a general planetary capability for Safe and Precise Landing is being developed under the ALHAT (Autonomous Landing and Hazard Avoidance Technology) project
BACKUP
Low Ballistic Coefficient Hypersonic Decelerator Development Challenges

- For 50-100 MT entry masses we need a 20-40 m diameter aeroshell.
- Large uncertainties (unknown-unknowns):
  - Lift control (how to modulate drag) with large density uncertainties
  - Dynamic stability issues at supersonic and transonic conditions
  - Subsonic position correction
  - Subsonic separation mechanism

Specifically for an Inflatable Hypersonic Decelerator:
- Lift control
- RCS
- Fluid structures interactions
- Light weight flexible TPS with large radiative heating

Specifically for a Rigid On-orbit-deployed Hypersonic Decelerator:
- Mass fraction of Aeroshell & deployment device

- Again, there are NO Earth analog for these systems.
  - NASA, Russia and ESA have tested very small scale inflatable Earth entry systems (IRVE, IRDT)