Aeromaneuvering/Entry, Descent, Landing

- Aeromaneuvering
- Entry, Descent, and Landing
- Case study: Mars EDL
- Case study: Mars Exploration Rovers
- Case study: Mars Science Laboratory
The Challenge of Mars EDL (Entry, Descent, and Landing)

Ron Sostaric
NASA Johnson Space Center
AIAA Senior Member
April 2010
Aeromaneuvering

- Using atmospheric flight forces to affect orbit changes while minimizing propellents
- Aerocapture - decelerating into planetary orbit from a single pass
- Aerobraking - lowering apoapsis by atmospheric passes (single or multiple)
- Aeromaneuvering - using aerodynamic forces (e.g., lift) to perform advanced maneuvers such as plane change
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, gload
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

Note: target orbit shown here is notional, and is not necessary circular.
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

![Local Atmospheric Density at 500 m Altitude](image)

- Lack of understanding of the atmosphere:
  - Aerodynamics, aeroheating, winds, and density variations
Atmospheric Thermal Profiles

from Justus and Braun, “Atmospheric Environments for Entry, Descent, and Landing”, 5th International Planetary Probes Workshop, August 2006
Atmospheric Density Profiles

from Justus and Braun, “Atmospheric Environments for Entry, Descent, and Landing”,
5th International Planetary Probes Workshop, August 2006
Mars EDL History

All six of the successful U.S. Mars EDL systems had:

- **Low Landing Site**: elevation sites below $-1\text{ km MOLA}$ ← 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 10 km

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 $\sim 100 – 150\text{ MT}$)
  - **Higher elevations** – interesting science
  - **Precision Landing**
6 U.S. Mars Entry, Descent, and Landing Successes
Current Mars Accessibility

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)
## Mars Heritage Aeroshell - Mission Comparisons

### Core Viking Technologies:
- 70° sphere-cone aeroshell

![Characteristics of different aeroshells](image)

<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 Coef. (kg/m²)</td>
<td>980 / 66</td>
<td>585 / 63</td>
<td>836 / 90</td>
<td>603 / 65</td>
<td>3257 / 140</td>
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<tr>
<td>Lander/Rover Mass (kg)</td>
<td>612</td>
<td>11</td>
<td>173</td>
<td>64</td>
<td>850</td>
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<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>
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<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>
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<tr>
<td>Peak Heatrate (W/cm²)</td>
<td>21</td>
<td>106</td>
<td>44</td>
<td>59</td>
<td>&lt;210</td>
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<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>
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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
Inflatable Aerodynamic Decelerators
Viking Parachute Configuration

- “Disk-Gap-Band” (DGB) or “bandgap” parachute
- Deployed at Mach 2
- Had to have sufficient deceleration to allow jettison of heat shield and dropping of lander from aeroshell

Viking Chute Drag Coefficient Model

Terminal Velocity

Full form of ODE -

\[
\frac{d (v^2)}{d \rho} - \frac{h_s}{\beta \sin \gamma} v^2 = \frac{2gh_s}{\rho}
\]

At terminal velocity, \( v = \text{constant} \equiv v_T \)

\[
- \frac{h_s}{\beta \sin \gamma} v_T^2 = \frac{2gh_s}{\rho}
\]

\[
v_T = \sqrt{- \frac{2g\beta \sin \gamma}{\rho}}
\]
Viking Terminal Velocity Under Chute

\[ \beta = \frac{m}{c_D A} = \frac{930 \text{ kg}}{0.62 \left( \frac{\pi}{4} \right) (16.15 \text{ m})^2} = 7.322 \frac{\text{kg}}{\text{m}^2} \]

\[ v_T = \sqrt{-\frac{2 g \beta \sin \gamma}{\rho}} = \sqrt{-\frac{2 (3.711 \text{ m/s}^2) (7.322 \text{ kg/m}^2) \sin (-30^\circ)}{0.02 \text{ kg/m}^3}} = 36.9 \frac{\text{m}}{\text{sec}} \]

\[ \beta_{crit} = -\frac{\rho_o h_s}{\sin \gamma} = -\frac{0.02 \text{ kg/m}^3 (10,800 \text{ m})}{\sin (-30^\circ)} = 432 \frac{\text{kg}}{\text{m}^2} \]
Rigid and Inflatable Aeroshell vs. Chute

![Graph showing the comparison between different descent systems](image)
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)
What about Large Inflatable Entry Vehicles? (ballistic coefficient = 50 kg/m² & L/D = 0.3)

Low Beta, Mid L/D Trajectory

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...
The Case for Precision Landing, Hazard Avoidance, and Pinpoint 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.
Viking Panoramas (1976)
Mars Pathfinder Rover ("Sojourner")
Mars Exploration Rover
Opportunity Landing Targeting

Mars approach DSN tracking

Surface Odyssey & DSN Doppler

Descent DSN Doppler (cut off at chute deploy)
Sometimes the Bounces Go Your Way...
...Opportunity Scores a Hole in One
Spirit Lands in Gusev Crater
Odyssey Finds its Heat Shield...
Mars Phoenix Lander Touchdown
Mars Rovers (Past, Present, Future)

Present
Mars Science Laboratory
Project Introduction

Richard Cook
Project Manager

December 7, 2005
Salient Features

Mobile Science Laboratory
One Mars Year surface operational lifetime (669 sols/687 days)
Discovery Responsive over wide range of latitudes and altitudes
Controlled Propulsive Landing
Precision Landing via Guided Entry

Science
Mission science will focus on Mars habitability
Next generation analytical laboratory science investigations
Remote sensing/contact investigations
Suite of Environmental Monitoring Instruments
# MSL-MER Comparison

<table>
<thead>
<tr>
<th></th>
<th>MSL</th>
<th>MER</th>
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<tbody>
<tr>
<td>LV/Launch Mass</td>
<td>Delta 4/Atlas V/3600 kg</td>
<td>Delta II/1050 kg</td>
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<tr>
<td>Design Mission Life</td>
<td>1 yr cruise/2 yrs surface</td>
<td>7m cruise/3 mo surface</td>
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<tr>
<td>Redundancy</td>
<td>Redundant Surface, Single String Cruise/EDL</td>
<td>Limited/Dual Mission</td>
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<tr>
<td>Payload</td>
<td>10 instruments (75 kg)</td>
<td>5 instrument (~9 kg)</td>
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<tr>
<td>Sample Acquisition</td>
<td>Arm + RAT + Corer + Scoop</td>
<td>Arm + RAT</td>
</tr>
<tr>
<td>Sample Processing</td>
<td>Rock Crusher</td>
<td>None</td>
</tr>
<tr>
<td>EDL System</td>
<td>Guided Entry/Skycrane</td>
<td>MPF Heritage/Airbags</td>
</tr>
<tr>
<td>Heatshield Diam</td>
<td>4.5 m</td>
<td>2.65 m</td>
</tr>
<tr>
<td>EDL Comm</td>
<td>UHF + Partial DTE or DTE</td>
<td>DTE + Partial UHF</td>
</tr>
<tr>
<td>Rover Mass</td>
<td>775 kg (allocation)</td>
<td>170 kg (actual)</td>
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<tr>
<td>Rover Range</td>
<td>&gt;20 km</td>
<td>&gt;5 km</td>
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<tr>
<td>Surface Power</td>
<td>RTG*/2500 Whr/sol</td>
<td>Solar/&lt;900 Whr/sol</td>
</tr>
<tr>
<td>Surface Comm</td>
<td>X-band DTE + UHF</td>
<td>X-band DTE + UHF</td>
</tr>
</tbody>
</table>

* - PreDecisional, RTG selection is contingent on NEPA/PD proces
MSL Rover Size Comparison

2009 MSL Rover

2005 MINI Cooper S
Rover Engineering Capabilities

- Mars Science Laboratory

- Rover Engineering Capabilities

- Rover Chassis/thermal enclosure

- Mobility System (6 wheel drive, 4 wheel steer)

- Rear HAZCAMs

- X-Band LGA

- RTG fluid loop
  - Heat Exchanger

- Radioisotope Power Source (Proposed)

- Comm to Mars Orbit (UHF Band)

- Comm to Earth (X-Band HGA)

- NAVCAMs (MER heritage)

- Sample Processing and Handling (SPAH)

- Robotic arm for contact science and sample acquisition (SA)

- Front HAZCAMs (MER heritage)
Remote Sensing (Mast)
ChemCam – Laser Induced Breakdown Spectrometer
MastCam - Color Stereo Imager

Contact Instruments (Arm)
MAHLI - Microscopic Imager
APXS - Proton/X-ray Backscatter Spectrometer

Analytical Laboratory (Front Chassis)
SAM - Gas Chromatograph/Mass Spectrometer/ Tunable Laser Spectrometer (Sample Composition / Organics Detection)
CheMin - X-ray Diffraction / Florescence (Sample Mineralogy)

Environmental Characterization (Body-mount)
MARDI - Descent Imager
REMS - Meteorological monitoring
RAD - Surface Radiation Flux Monitor (future human health & safety)
DAN - Neutron Backscatter subsurface hydrogen (water/ice) detection
Flight System Design Overview

Presented at
Mars Science Laboratory PMSR
December 7-9, 2005

Christopher G. Salvo
Flight System Engineering Manager
Launch Configuration

- 5m Fairing with 4.56 m internal envelope.
- 66” Payload interface to MSL Spacecraft.
- RTG integration access
- Heat Rejection System (HRS) loading access
- Emergency de-fueling access
Cruise Configuration
Cruise Configuration: Bottom View
Comparison of Coordinate Systems

- $+X_C$
- $+X_{S/C}$
- $+X_{DS}$
- $+X_R$
- $+Y_C$
- $+Y_{S/C}$
- $+Y_{DS}$
- $+Y_R$
- $+Z_C$, $+Z_{S/C}$, $+Z_{DS}$, $+Z_R$
- $+Z_C$, $+Z_{S/C}$, $+Z_{DS}$, $+Z_R$
Cruise Stage Components Placement (1)
Cruise Stage Dimensions
Aeroshell Overview

Aeroshell structure is shown transparent for clarity

- Backshell Interface Plate
- Parachute Support Structure
- Parachute Support Structure Close Out
- Backshell
- Heatshield Separation Mechanisms (x9)
- Heatshield
- Ejectable Balance Mass* (x2)
- Ejectable Balance Mass Separation Mechanisms (x4)
Aeroshell Features

<table>
<thead>
<tr>
<th>Backshell Penetration</th>
<th>Locator</th>
<th>Size (mm)</th>
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</thead>
<tbody>
<tr>
<td>Heatshield Sep Fitting/</td>
<td></td>
<td>Ø 127</td>
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<tr>
<td>Balance Mass Covers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Ring Balance Mass Covers</td>
<td></td>
<td>Ø 101.6</td>
</tr>
<tr>
<td>UHF Antennae Windows</td>
<td></td>
<td>Ø 190</td>
</tr>
<tr>
<td>RCS Windows, Roll Thrusters</td>
<td></td>
<td>80 x 205</td>
</tr>
<tr>
<td>RCS Windows, Pitch/Yaw (Z)</td>
<td></td>
<td>Ø 120</td>
</tr>
<tr>
<td>Vent &amp; Propulsion Access Door</td>
<td></td>
<td>450 x 450</td>
</tr>
<tr>
<td>RTG Access Door</td>
<td></td>
<td>750 x 750</td>
</tr>
</tbody>
</table>
Entry Vehicle Dimensions

Parachute Support Structure (PSS) Close Out with TPS

Ø 2975 mm (117.1 in)
Upper Cone “hip”

Ø 4500 mm (177.1 in)
OML-10b Configuration

Cruise Stage Interface (x6)
Descent Stage Components Placement

- 8x Mars Lander Engine (MLE)
- 4x Roll Control RCS Thrusters
- 4x Pitch/Yaw Control RCS Thrusters
- 4x Pyro Thermal Batteries
- 2x Power Thermal Batteries
- BUD
- DMCA & DPRA
- 6x DS / BIP Sep Nuts
- Descent Low Gain Antenna (DLGA)
- DPAM & DPJB
- 6x DS / CS Sep Nuts
- UHF Antenna
- 3x 23” x 24” Fuel Tanks
- 2x 16” x 26” Helium Pressurant Tanks

- TWTA, Diplexer, Isolator, LPF, etc
- Pad Access Deck with Pressurant Control Assy
- Terminal Descent Sensor
- 4x Mega Cutter
- 6x BIP/DS Rollers
- Descent Inertial Measurement Unit
- 3x 23” x 24” Fuel Tanks
- 2x 16” x 26” Helium Pressurant Tanks
Descent Stage Dimensions

BC 1481 mm (58.3”)

BC 1270 mm (50”) (Rover)

BC 1352 mm (53.2”)

1283 mm

763 mm

719 mm

1481 mm

2533 mm

2287 mm

865 mm

215 mm

1040 mm

1246 mm

2988 mm

3088 mm
Rover Deployment - Touchdown Configuration
The Bigger Better Rover

Mars Exploration Rover - 2003

Mars Science Laboratory - 2009

Mars Pathfinder Sojourner Rover - 1996

NASA Standard Astronaut
Mars Science Laboratory Project
Project Mission System Review

Entry, Descent and Landing

Adam Steltzner
Flight System Engineering Manager
Entry, Descent and Landing
EDL Driving Requirements

Key Driving EDL Requirements:

• Deliver 775 kg rover
  – Eliminates the use of airbag landing system due to interfaces, egress and mass scaling of airbags
• 2.0 km MOLA or greater altitude
  – Results in lifting element of entry design, ballistic entry will not meet performance
• Landing with a maximum error of 10 km from the targeted point
  – Results in guided entry to fly-out atmospheric and vehicle uncertainties

Detailed Requirements:

  – See below
Event Timeline 1/2

Cruise Stage Separation  E-10 min

Despin (2 rpm → 0 rpm)

Cruise Balance Mass Jettison

Turn to Entry Attitude

Entry Interface  E+0, r = 3522.2 km

Exo-atmospheric

Peak Heating  E + 86 s

Peak Deceleration  E + 99 s

Heading Alignment  v = 900 m/s  E + 170 s

Deploy Supersonic Parachute

Entry

h = ~10 km MSL  
M = 2.0 (v=450 m/s)  
E + 225 s
Event Timeline 2/2

Heatshield Separation
- \( h = \sim 8 \text{ km MSL} \)
- \( M = 0.7 \)
- Entry Balance Mass Jettison
- \( E + 247 \text{ s} \)

Deploy Supersonic Parachute
- \( E + 225 \text{ s} \)

MLE Warm-Up
- \( E + 252 \text{ s} \)

Rover Touchdown
- \( E + 341 \text{ s} \)

Flyaway
- \( 2000 \text{ m above MOLA areoid} \)

Sky Crane

Backshell Separation
- \( h = \sim 800 \text{ m AGL} \)
- \( E + 309 \text{ s} \)

Cut to Four Engines
- \( E + 323 \text{ s} \)

Rover Separation
- \( E + 307 \text{ s} \)

Powered Descent

Radar Activation and Mobility Deploy

Entry Balance Mass Jettison
- \( h = \sim 8 \text{ km MSL} \)
- \( M = 0.7 \)
- \( E + 247 \text{ s} \)
EDL Design Comparison and Trades
### MSL EDL Design Table

<table>
<thead>
<tr>
<th></th>
<th>Viking</th>
<th>MPF</th>
<th>MER</th>
<th>Phoenix</th>
<th>MSL</th>
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<tbody>
<tr>
<td><strong>EFPA (deg)</strong></td>
<td>-16.99</td>
<td>-13.8</td>
<td>-11.5</td>
<td>-12.5</td>
<td>-15.2</td>
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<tr>
<td><strong>Entry Velocity, Inertial (km/s)</strong></td>
<td>4.61</td>
<td>7.26</td>
<td>5.5</td>
<td>5.5</td>
<td>5.3-6.0</td>
</tr>
<tr>
<td><strong>Landing Sol, (Ls)</strong></td>
<td>97</td>
<td>143</td>
<td>330</td>
<td>90</td>
<td>120-150</td>
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<tr>
<td><strong>Heatshield Geometry</strong></td>
<td>70 sphere-cone</td>
<td>70 sphere-cone</td>
<td>70 sphere-cone</td>
<td>70 sphere-cone</td>
<td>70 sphere-cone</td>
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<tr>
<td><strong>Heatshield Diameter (m)</strong></td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
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<tr>
<td><strong>Ballistic Coefficient (kg/m^2)</strong></td>
<td>63</td>
<td>62.3</td>
<td>88</td>
<td>71</td>
<td>121</td>
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<tr>
<td><strong>Entry Mass (kg)</strong></td>
<td>930</td>
<td>585</td>
<td>836</td>
<td>608</td>
<td>2804</td>
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<tr>
<td><strong>Control Method</strong></td>
<td>Guided/Lift-up</td>
<td>Ballistic</td>
<td>Ballistic</td>
<td>Guided/Lift-up</td>
<td>Guided</td>
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<tr>
<td><strong>L/D</strong></td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>0.06</td>
<td>0.24</td>
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<tr>
<td><strong>Trim angle @ M=24 (deg)</strong></td>
<td>-11</td>
<td>0</td>
<td>0</td>
<td>-4</td>
<td>-15.5</td>
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<tr>
<td><strong>Landing Ellipse Semi-Major Axis (km)</strong></td>
<td>100</td>
<td>75</td>
<td>60</td>
<td>90-125</td>
<td>10</td>
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<tr>
<td><strong>Peak Heating Rate (W/cm^2)</strong></td>
<td>21.02</td>
<td>106</td>
<td>44</td>
<td>58.7</td>
<td>140 - 155 (margined)</td>
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<tr>
<td><strong>Integrated Heat Load (J/cm^2)</strong></td>
<td>1100</td>
<td>3865</td>
<td>3687</td>
<td>3245</td>
<td>~ 6000 (margined)</td>
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<tr>
<td><strong>Heatshield TPS Material</strong></td>
<td>SLA561-V</td>
<td>SLA561-V</td>
<td>SLA561-V</td>
<td>SLA561-V</td>
<td>SLA561-V (TBC)</td>
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<tr>
<td><strong>Heatshield TPS Thickness (in)</strong></td>
<td>0.54</td>
<td>0.75</td>
<td>0.62</td>
<td>0.55</td>
<td>0.9</td>
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<td><strong>Parachute Type</strong></td>
<td>D-G-B</td>
<td>D-G-B</td>
<td>D-G-B</td>
<td>D-G-B</td>
<td>D-G-B</td>
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<tr>
<td><strong>Parachute Cd @ 0.677</strong></td>
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<td>~0.48</td>
<td>~0.48</td>
<td>0.677</td>
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<tr>
<td><strong>Parachute Diameter (m)</strong></td>
<td>16.15</td>
<td>12.4</td>
<td>14.1</td>
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<td>19.7</td>
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<tr>
<td><strong>Parachute x/D</strong></td>
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<td>9.8</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Touchdown Velocity (m/s)</strong></td>
<td>2.4</td>
<td>25</td>
<td>25</td>
<td>2.4</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Descent Propulsion</strong></td>
<td>Throttled N2H4</td>
<td>Solid</td>
<td>Solid</td>
<td>Pulsed N2H4</td>
<td>Throttled N2H4</td>
</tr>
<tr>
<td><strong>Landing Site Elevation (km)</strong></td>
<td>-3.5</td>
<td>-1.5</td>
<td>-1.3</td>
<td>-3.5</td>
<td>+2.0</td>
</tr>
<tr>
<td><strong>Landed Mass, Dry (kg)</strong></td>
<td>590</td>
<td>360</td>
<td>539</td>
<td>364</td>
<td>1541</td>
</tr>
<tr>
<td><strong>Mobile Mass (kg)</strong></td>
<td>0</td>
<td>11</td>
<td>173</td>
<td>0</td>
<td>775</td>
</tr>
<tr>
<td><strong>Usable Equipment (kg)</strong></td>
<td>244</td>
<td>92</td>
<td>173</td>
<td>167</td>
<td>775</td>
</tr>
<tr>
<td><strong>Payload Inst. and Accmd. (kg)</strong></td>
<td>92</td>
<td>6</td>
<td>9.3</td>
<td>55</td>
<td>140</td>
</tr>
<tr>
<td><strong>Usable/Entry Ratio (non-structure and propulsion for landers)</strong></td>
<td>26%</td>
<td>16%</td>
<td>21%</td>
<td>27%</td>
<td>28%</td>
</tr>
</tbody>
</table>
EDL Design Topic Areas

Guided Entry and TPS
Parachute Descent
Powered Descent/Sky Crane
**Entry: Aerodynamic Deceleration and Control**

- Primary decelerator is entry body drag
  - Approximately 99% of approach kinetic energy is dissipated to the atmosphere

- Lifting entry configuration
  - Viking, Phoenix(?)
  - Shuttle, Apollo, Gemini, etc.

- CM offset calculated to provide
  - ~15 degree AOA @ max Q
  - ~19 deg AOA @ parachute deploy
  - Produces a nominal L/D of .24 @ M 24

- Apollo Guidance Algorithm
  - Guidance achieved by “rolling” around velocity vector
    - Apollo, Viking
Entry: Thermal Protection

- Heritage SLA 561-V material has demonstrated performance in MSL flight regime
  - Test conducted at NASA Ames have shown SLA and other materials can meet the heat rate and heat load requirements of MSL

Post-test photo: 180 W/cm\(^2\)/6000 J/cm\(^2\)

4 inch diameter samples
0.75 inches thick SRAM & SLA

SLA-561V

With SIRCA collar
Total diameter 4 inches
Parachute Descent

- Secondary decelerator is Parachute drag
  - Approximately 95% of remaining Kinetic energy is dissipated to the atmosphere

- Viking configuration parachute
  - Larger diameter (19.7 m vs 16.1 m)
  - Modern materials (kevlar vs. polyester)

- Deployment conditions
  - Mach number < 2.15 (Viking)
  - Dynamic Pressure < 850 Pa (MER)
  - Deployment AoA @ deploy < 15 deg. (Viking)

- Parachute scaled to closely match Viking test post deployment flight conditions
  - Area ratios
  - On chute ballistic coefficient
  - Area oscillations matched
Parachute Qualification requires validation of:
- Deployment
- Initial Inflation (Will it open?)
- Inflation Strength (Will its structure survive inflation loads?)
- Inflated Performance (Drag and Stability)

MSL will make use of an augmented MER approach to qualification
- Deployment: **Test**: Ground-based Mortar Firing tests of MSL system
- Initial Inflation: **Heritage argument** by similarity to existing Mars flight and Earth high altitude test data (See *MSL Parachute Qualification Review Package*).
- Inflation Strength: **Test**: Subsonic, full-scale windtunnel strength test of MSL system, augmented to include cyclic loading to cover the possibility of area oscillation in supersonic conditions
- Inflated Performance: **Existing Data**: Viking and MER windtunnel data in conjunction with Viking, MPF, and MER flight data

Parachute qualification program review results will be discussed later
Sky Crane Maneuver Description

One-Body Phase

*Duration* = ~2 sec
Purpose: Damp throttle-down transients
Entry State: \( h = 19.5 \) m
Exit State: \( h = 18 \) m
Event on entry: “Shut-down” 4 (of 8) MLE’s (to < 1% of total)

Deployment Phase

*Duration* = ~6 sec
Purpose: Rover/DS separation
Entry State: \( h = 18 \) m
Exit State: \( h = 13.5 \) m
Events on entry:
- Stop TDS altimetry
- Change controller gains
- Fire rover deployment pyros

Post-Deploy Settling Phase

*Duration* = ~2 sec
Purpose: Damp separation transients
Entry State: \( h = 13.5 \) m
Exit State: \( h = 12 \) m
Event on entry:

Ready for Touchdown Phase

*Duration* = 0-8 sec
Purpose: Wait for touchdown
Entry State: \( h = 12 \) m
Exit State: \( h = 9 \) m
Event on entry:
- Enable touchdown logic
Exit Condition:
- Rover off-loaded for persistent time

Touchdown Phase

*Duration* < 2 sec
Note:
- Touchdown K.E. ~ 450 J
- Traverse K.E. ~ 800 J

Descent Stage commanded to follow Reference Trajectory: \( V_{\text{Vertical}} = 0.75 \) m/sec & \( V_{\text{Horizontal}} = 0.0 \) m/sec
Sky Crane System Architecture

Two-Body Architecture
Decouples descent stage control from touchdown event and allows persistent touchdown signature

Prop and GNC Away from Surface
Closed loop during the touchdown event

High Bandwidth Vertical Velocity Control
results in low and near constant D/S velocity

Higher Stability
Persistence of tethering during touchdown improves landing stability on rough terrain

Lower Loads
Low velocities allows rover landing loads to be similar to the rovers driving loads

System Design
High stability and low landing loads mean:
• Separate TD system not required
• Egress system not required

Rover Becomes the Touchdown System
Rover provides ground clearance, static stability, and terrain adaptation
# Mass Growth and Configuration

Comparison of mass growth and on-chute ballistic coefficient

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Rover/Entry Mass (kg)</th>
<th>Capsule/Chute Diameter Ratio (kg)</th>
<th>$\beta$ on Chute (kg/m²)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSL MCR 10/03</td>
<td>900/2400</td>
<td>0.28</td>
<td>17.3</td>
<td>16.15 m Vik</td>
</tr>
<tr>
<td>MSL M2 7/04</td>
<td>550/1883</td>
<td>0.23</td>
<td>13.6</td>
<td>16.15 m Vik</td>
</tr>
<tr>
<td>MSL Costing 6/05</td>
<td>725/2705</td>
<td>0.28</td>
<td>19.5</td>
<td>16.15 m Vik</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>755/2675</td>
<td>0.23</td>
<td>13.0</td>
<td>19.7 m Vik</td>
</tr>
<tr>
<td>MSL w/MER chute</td>
<td>755/2675</td>
<td>0.36</td>
<td>28.7</td>
<td>14.1 m MER</td>
</tr>
<tr>
<td>Viking</td>
<td>NA/1168</td>
<td>0.22</td>
<td>8.42</td>
<td>16.15 m Vik</td>
</tr>
<tr>
<td>MER</td>
<td>174/845</td>
<td>0.22</td>
<td>12.4</td>
<td>14.1 m MER</td>
</tr>
</tbody>
</table>

Viking: 16.15 m, Vik
MER: 14.1 m, MER
Baseline: 19.7 m, Vik
Uniform Slack Maintenance

- Fully Deployed
- Snatch
- Umbilical and Bridles are retracted to prevent slacking
- Umbilical Retraction Leash
- 20 turns produces 4 m of recoil at the small radius
- Spool
- Recoil
Initial Touchdown
Complete Touchdown
Bridle & Umbilical Initial Retraction
Bridle & Umbilical Complete Retraction
Sky Crane: Touchdown

- Touchdown is triggered from the **post-touchdown state** NOT the touchdown event
  - Design allows 1-2 seconds of persistence
- Slack is managed within bridle system
  - Descent stage can continue downward for 2-3 meters