Entry, Descent, and Landing Case Studies

- Entry, Descent, and Landing overview
- Case study: Mars EDL
- Case study: Mars Exploration Rovers
- Case study: Mars Science Laboratory
Shuttle in Gliding Landing
New Shepard Landing (Blue Origin)
Falcon 9 First Stage Landing
Dream Chaser – Sierra Nevada Corp.
Commercial Crew Size Comparison

Orion

CST-100

Apollo

Dragon

5.029m (198")

4.56m

3.912m (154")

3.7m

"SpaceX Dragon" © 2014
G. De Chiara
Spaceship Two - Virgin Galactic

Photo by MarsScientific.com and Clay Center Observatory
Lynx Suborbital Vehicle – XCOR
Mars Pathfinder/MER Landing Bags
Mission Overview Video

FOR MER PROJECT
USE ONLY

DO NOT DUPLICATE
OR DISTRIBUTE
MSL Skycrane Mars Landing System
Mars Colonial Transport – SpaceX
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, 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.
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
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 $-1$ 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 $\sim100-150$ 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

<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>
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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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<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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<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>
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<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
Rigid Aeroshells
Inflatable Aerodynamic Decelerators
Low-Density Supersonic Decelerator
LDSD Flight Test Profile

- **Launch**: 40-150 Nautical Miles
- **Test Period**: Powered Flight, Burnout, SIAD Deploy, Parachute Deployment Device Deploy, Supersonic Disksail Deploy
- **Descent**: Supersonic Disksail Deploy + 180 sec. Flight Information Recorder Cut, Return
- **Ocean Impact & Recovery**: 200 Nautical Miles

**Altitude (ft)**
- 180,000
- 119,000
- 117,000

**TEST VEHICLE DROP**
Supersonic Retropropulsion

First stage begins reentry burn at approximately 70km altitude

Powered flight through
Mars-relevant retropropulsion regime
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

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

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

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

![Diagram showing the comparison between different entry vehicle designs.](image-url)
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)

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

- **50 km**
- 1 km radius
- 10 km radius
- Perfect approach navigation
- Pathfinder landing dispersion ellipse

<table>
<thead>
<tr>
<th>Dispersion size, km</th>
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<tr>
<td>300</td>
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<td>150</td>
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<tr>
<td>100</td>
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<td>50</td>
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<tr>
<td>.1</td>
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<td>.01</td>
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</table>

N/A
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.
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 Rovers (Past, Present, Future)
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>
</tr>
<tr>
<td>Payload</td>
<td>10 instruments (75 kg)</td>
<td>5 instrument (~9 kg)</td>
</tr>
<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>
</tr>
<tr>
<td>Rover Range</td>
<td>&gt;20 km</td>
<td>&gt;5 km</td>
</tr>
<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 proceedings
MSL Rover Size Comparison

2009 MSL Rover

2005 MINI Cooper S
Rover Engineering Capabilities

- Radioisotope Power Source (Proposed)
- RTG fluid loop
- Heat Exchanger
- Mobility System (6 wheel drive, 4 wheel steer)
- Rear HAZCAMs
- Mobility System (6 wheel drive, 4 wheel steer)
- Rear HAZCAMs
- Front HAZCAMs (MER heritage)
- Rover Chassis/thermal enclosure
- Sample Processing and Handling (SPAH)
- Robotic arm for contact science and sample acquisition (SA)
- Comm to Mars Orbit (UHF Band)
- Comm to Earth (X-Band HGA)
- Remote Sensing Mast (RSM)
- X-Band LGA
- NAVCAMs (MER heritage)
MSL Payload

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
Comparison of Coordinate Systems
Cruise Stage Components Placement (1)
Cruise Stage Components Placement (2)

- Solar Array Surface
- Shunt Radiator
- MGA
- LGA
- Thrusters Cluster
Cruise Stage Dimensions

Diagram of cruise stage dimensions with measurements:
- 3080mm
- 1551mm
- 4081mm
- 4400mm
- 2510mm
- 1666mm
- 772mm
- 543mm
- 364mm
- 607mm
Cruise Stage Separation
Entry Vehicle
Aeroshell Overview

Aeroshell structure is shown transparent for clarity

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

## Backshell Penetration

<table>
<thead>
<tr>
<th>Feature</th>
<th>Locator</th>
<th>Size (mm)</th>
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<tbody>
<tr>
<td>Heatshield Sep Fitting/ Balance Mass Covers</td>
<td></td>
<td>Ø 127</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

- Cruise Stage Interface (x6)
- Parachute Support Structure (PSS) Close Out with TPS

Dimensions:
- Ø 2975 mm (117.1 in) Upper Cone “hip”
- Ø 4500 mm (177.1 in) OML-10b Configuration
- 369 mm (14.5 in)
- 1391 mm (54.7 in)
- 897.5 mm (35.3 in)
Descent Stage Components Placement

- 8x Mars Lander Engine (MLE)
- 4x Roll Control RCS Thrusters
- 4x Pitch/Yaw Control RCS Thrusters
- 4x Pyro Thermal Batteries
- 6x DS / BIP Sep Nuts
- 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

Components:
- 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
- 4x Roll Control RCS Thrusters
- 4x Pyro Thermal Batteries
- 4x Pitch/Yaw Control RCS Thrusters
- 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
Descent Stage Dimensions

BC 1481 mm (58.3’’)

763 mm

BC 1270 mm (50’’) (Rover)

BC 1352 mm (53.2’’)

1283 mm

2533 mm

2287 mm

865 mm

215 mm

1040 mm

719 mm

1481 mm

2988 mm

3088 mm

1246 mm
Rover Deployment - Touchdown Configuration
The Bigger Better Rover

Mars Science Laboratory - 2009

Mars Exploration Rover - 2003

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

Peak Heating  E + 86 s

Peak Deceleration  E + 99 s

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

Deploy Supersonic Parachute  h ≈ 10 km MSL  M = 2.0 (v=450 m/s)  E + 225 s

Exo-atmospheric

Entry
Event Timeline 2/2

**Supersonic Parachute Descent**
- Deploy Supersonic Parachute: E + 225 s
- Heatshield Separation:
  - h = ~8 km MSL
  - M = 0.7
  - E + 247 s
- Entry Balance Mass Jettison:
- Radar Activation and Mobility Deploy:
  - E + 252 s
- MLE Warm-Up:
  - E + 307 s

**Powered Descent**
- Backshell Separation:
  - h = ~800 m AGL
  - E + 309 s
- Cut to Four Engines:
  - E + 323 s
- Rover Separation
- Sky Crane
- Rover Touchdown:
  - E + 341 s

**Flyaway**
- 2000 m above MOLA areoid
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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<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>
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<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>
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<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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<td><strong>Control Method</strong></td>
<td>Guided/Lift-up</td>
<td>Ballistic</td>
<td>Ballistic</td>
<td>Guided/Lift-up</td>
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<tr>
<td><strong>L/D</strong></td>
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<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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<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>
</tr>
<tr>
<td><strong>Parachute Cd @</strong></td>
<td>0.677</td>
<td>~0.48</td>
<td>~0.48</td>
<td>0.677</td>
<td>0.677</td>
</tr>
<tr>
<td><strong>Parachute Diameter (m)</strong></td>
<td>16.15</td>
<td>12.4</td>
<td>14.1</td>
<td>11.5</td>
<td>19.7</td>
</tr>
<tr>
<td><strong>Parachute x/D</strong></td>
<td>8.5</td>
<td>9.4</td>
<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

![Graph showing peak bondline temperature vs. hot-wall heat flux](image)

**Post-test photo:** 180 W/cm²/6000 J/cm²

- 4 inch diameter samples
- 0.75 inches thick SRAM & SLA

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 Deployment

Mars Science Laboratory 05-22 Simulation

Mach Number vs. Dynamic Pressure (Pa)

- NASA-TM-X-1924
- NASA-TM-X-1623
- NASA-TM-D-6469
- NASA-TM-X-1575
- NASA-TM-X-1499
- NASA-TM-X-1451
- Viking BLDT AV-4
- Viking BLDT AV-1
- Viking BLDT AV-3
- MPF
- MER-B
- MER-A

01-Dec-2005

MSL 05-22 40°S, 2 km Synthetic Terrain, +/- 0.5 know quat error
MSL Parachute System Qualification

• 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
Powered Descent: Vehicle Configuration
Sky Crane Maneuver Description

One-Body Phase

*Duration* = ~2 sec

**Purpose:**
Damp throttle-down transients

**Entry State:** \( h = 19.5 \text{ m} \)
**Exit State:** \( h = 18 \text{ m} \)

**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:** \( h = 18 \text{ m} \)
**Exit State:** \( h = 13.5 \text{ m} \)

**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:** \( h = 13.5 \text{ m} \)
**Exit State:** \( h = 12 \text{ m} \)

**Event on entry:**

Ready for Touchdown Phase

*Duration* = 0-8 sec

**Purpose:**
Wait for touchdown

**Entry State:** \( h = 12 \text{ m} \)
**Exit State:** \( h = 9 \text{ m} \)

**Event on entry:**
Enable touchdown logic

**Exit Condition:**
Rover off-loaded for persistent time

Touchdown Phase

*Duration* < 2 sec

**Note:**
Touchdown K.E. \( \sim 450 \text{ J} \)
Traverse K.E. \( \sim 800 \text{ J} \)

Descent Stage commanded to follow Reference Trajectory: \( V_{\text{Vertical}} = 0.75 \text{ m/sec} \) & \( V_{\text{Horizontal}} = 0.0 \text{ m/sec} \)
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</th>
<th>$\beta$ on Chute (kg/m²)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Work-to-date</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>Baseline</td>
<td>755/2675</td>
<td>0.23</td>
<td>13</td>
<td>19.7 m Vik</td>
</tr>
<tr>
<td><strong>MSL w/MER chute</strong></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>
**Uniform Slack Maintenance**

- **Fully Deployed**
- **Snatch**
- **Umbilical Bridles**
- **Umbilical Retraction Leash**
- **20 turns produces 4 m of recoil at the small radius**
- **Bridles**
- **Recoil Spool**
- **Umbilical and Bridles are retracted to prevent slacking**
Pre-Touchdown
Initial Touchdown
Complete Touchdown
Bridle & Umbilical Initial Retraction
Bridle & Umbilical Complete Retraction
Fly Away
Fly Away
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
Gemini Rogallo Wing Recovery
X-38 Parasail Landing System
SpaceX Propulsive Landing Tests
Evolvable Mars Campaign Overview to FISO Telecon

June 10, 2015

Douglas Craig
Strategic Analysis Manager
Advanced Exploration Systems
Human Exploration and Operations Mission Directorate
NASA HQ
Largest Indivisible Payload Element and Options for Size of the Lander

2015 Assessment in work

- ISRU Plant: 1.0t
- Power: 8.0t
- Mobility: 1.0t
- Total: 10.0t

ISRU?

- LOX and CH4
- LOX only

Support First Crew?

- Yes
- No

Min. # of Landers?

- Yes
- No

Did Not Assess: 30t minimum payload

Surface Prop Xfer?

- Yes
- No

Xfer LOX and CH4?

- Yes
- No

Xfer LOX only?

- Yes
- No

Payload Elements

- Inerts: 10.5t
- CH4: 5.8t
- LOX: 19.2t
- Total: 35.5t

Crew

Payload Options

- 27 t Payload (57 t Lander)
  - First short stay mission requires 2 landers
- 18 t Payload (43 t Lander)
  - First short stay mission requires 3 landers
- 15 t Payload (33 t Lander)
  - First short stay mission requires 4 landers
- 40 t Payload (90 t Lander)
  - First short stay mission requires 1 lander

Minimum lander size driven by Crew Ascent Stage. Various techniques (and risks) for loading or producing propellant on Mars can reduce lander payload requirement from 40 t to 15 t (but increase number of landers required).
A Scenario for a Human Mission to Mars Orbit in the 2030s

Thoughts Toward an Executable Program

Fitting Together Puzzle Pieces & Building Blocks

Future In-Space Operations (FISO) Telecon
May 20, 2015

Hoppy Price*
John Baker*
Firouz Naderi*

*Jet Propulsion Laboratory
California Institute of Technology
Short-stay Mars Lander Concept

Attributes of the Mission

- 23 t useful-landed-mass lander
  - Crew of 2 to the surface, 24-day stay
  - (Could support crew of 4 for 6 days)
- Architecture re-uses the Phobos approach for getting crew to HMO and back to Earth (already tested in 2033)
- The lander requires 2 additional SLS launches relative to Phobos mission, bringing total SLS launches to 6
- Lander sent to Mars with 2-SLS launch scenario and aerocaptures into HMO to await crew arrival
- Lift off from Mars surface is achieved through a two-step ascent to High Mars Orbit (HMO)
  - MAV: Surface to Low Mars Orbit (LMO), then boosted to HMO
  - Minimizes the MAV propellant load to enable 23 t lander
Short-stay Surface Mission Concept

24-Day Surface Stay; Crew of 2; 6 SLSLaunches

Architecture was analyzed for a crew of 4, of which 2 land on Mars
Descent/Ascent Vehicle (DAV)

Can support crew of 2 for 28 days, or crew of 4 for 6 days
EDL Concept for Blunt Body Mars Lander

Entry
Peak Heating
Peak Deceleration: 6.4 g
Hypersonic Aeromaneuvering
Supersonic Retropropulsion
Powered Descent: Const. V Phase

Ground Acquisition

Note: There are no deployable decelerators or parachutes. We will be examining options to utilize an LDSD-type SIAD to increase performance.

Touchdown Vrel < 5 m/s
Supersonic Retro-Propulsion (SRP)

- Mars landers to date have used subsonic retro-propulsion
- Analyses have indicated the need for SRP for landing large payloads on Mars
- CFD analysis and wind tunnel tests have been performed, and now SRP data utilizing actual flight data has become available from Space X Falcon 9 stage recovery flights
  - 7 flights have been conducted with a portion of the flight regime being analogous to Mars atmospheric conditions
Landed Configuration
MAV Separation and Ascent

Mars Ascent Vehicle (MAV)

Contoured aerodynamic fairing

Descent Stage

H2M Minimal Architecture
<table>
<thead>
<tr>
<th>Vehicles</th>
<th># Vehicles per Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion</td>
<td>1</td>
</tr>
<tr>
<td>SLS</td>
<td>6</td>
</tr>
<tr>
<td>SEP Tug</td>
<td>2</td>
</tr>
<tr>
<td>Deep Space Habitat</td>
<td>2</td>
</tr>
<tr>
<td>In-Space Chemical Propulsion Stages</td>
<td>3</td>
</tr>
<tr>
<td>Mars Lander</td>
<td>1</td>
</tr>
</tbody>
</table>
Toward a Permanent Presence

- Follow-on missions would have 1 year surface stays supported by a habitat and other supplies
  - Same descent stage design as crewed lander
  - Would support a landed crew of 4
  - Infrastructure would be built up on Mars to provide power, ISRU, food production, and increasing habitable volume

- The Mars program would evolve a reusable transportation architecture between Earth and Mars with an increased flight rate

- With an in-situ water source on Mars, a permanent presence with an Antarctica-type population could be achieved