Case Study: ParaShield

• Origin of ParaShield Concept
• ParaShield Flight Test
• Wind Tunnel Testing
• Future Applications
Graduate Design Class: Fall, 1988

- Six students in graduate class in Aeronautics and Astronautics at MIT
- Project summary: Design an alternative manned spacecraft to supplement/replace the shuttle in the event of another Challenger-type accident
- Had to be capable of launch on Delta II, Atlas, Titan IIIC (existing ELVs)
Parametric Analysis of Heating

![Graph showing the relationship between maximum heating rate and ballistic coefficient. The graph includes three lines representing different values of L/D: L/D = 0.1, L/D = 0, L/D = 0.2.](image)
Parametric Analysis of Stagnation Temp

![Graph showing the relationship between peak ParaShield temperature (°F) and ballistic coefficient (Pa). The graph illustrates a linear increase in temperature with increasing ballistic coefficient.]
Parametric Analysis of Dynamic Pressure

![Graph showing the relationship between maximum dynamic pressure and ballistic coefficient for different L/D ratios.]

- max Q, L/D=.1
- max Q, L/D=0
- max Q, L/D=.2
Parametric Analysis of Peak Deceleration

![Graph showing the relationship between Maximum Deceleration (g's) and Ballistic Coefficient (Pa) for different L/D ratios. The graph indicates that as the Ballistic Coefficient increases, the Maximum Deceleration decreases for all L/D ratios tested.](image-url)
Comparison of Entry Trajectories

- ParaShield
- Gemini
Comparison of Heat Shield Temperatures
Comparison of Total Heat Loads
Required Heat Shield Diameter

![Graph showing the required heat shield diameter as a function of entry vehicle mass for different conditions.]
Payload Volume Protected from Wake

![Graph showing payload volume protected from wake vs. entry vehicle mass for different BC values (150 Pa, 300 Pa, Apollo config).]
Synopsis of Initial Feasibility Study

- Ultra-low ballistic coefficient vehicles provide significant advantages for atmospheric entry
  - Relief from restriction to conical configurations to avoid aft wake
  - Significantly lower peak shield temperatures, allowing the use of existing COTS materials
  - Little or no entry ionization creating blackouts for communications and navigation

- Terminal velocity in lower atmosphere is limited to 15-20 m/sec, requiring only impact attenuation
  - Aero decelerator deployed and verified before entry
ParaShield Flight Test Origins

- Discussion with officials of American Rocket Company (AMROC) in April, 1989
  - Single Engine Test (SET-1) vehicle being developed for suborbital test flight out of Vandenberg AFB
  - Existing payload compartment was empty and available
  - Targeted launch date: August, 1989 (four months!)

- Total available funding: $80K
- Total available personnel: 3 grad students, 2 undergrads (all volunteers), 1 faculty (part-time)
- Facilities: undergrad projects lab shop
Project Skidbladnir:
Flight Test of the
ParaShield Concept

Space Systems Laboratory
Massachusetts Institute of Technology

April 17, 1989
Introduction
Engineering Objectives

- Provide a flight demonstration of ParaShield concept
- Verify models of
  - flight dynamics
  - aerothermodynamics
  - structural loads
- Collect imaging data on launch vehicle separation, lee-side ionization, and landing phase
- Carry commemoratives for payload
Configuration
## Mass Budget

All masses in kilograms

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
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<tr>
<td>Payload</td>
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<tr>
<td>Avionics</td>
<td>5.1</td>
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<td>Sensors</td>
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<tr>
<td>Instruments</td>
<td>2.0</td>
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<tr>
<td>Electronics</td>
<td>2.0</td>
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<tr>
<td>Mechanisms</td>
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<tr>
<td>Deployment</td>
<td>18.0</td>
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<tr>
<td>Recovery</td>
<td>2.0</td>
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<td>Structure</td>
<td>79.5</td>
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<td>Thermal Protection</td>
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<td>Capsule</td>
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<tr>
<td>Power</td>
<td>14.0</td>
</tr>
<tr>
<td>Propulsion</td>
<td>21.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>147.1</strong></td>
</tr>
</tbody>
</table>
Trajectory
Trajectory Assumptions

Vehicle Assumptions

\[ m = 150 \text{ kg} \]
\[ \beta = 215.7 \text{ Pa} \]
\[ L/D = 0.177 \]

Flight Dynamics Assumptions

ParaShield deployment occurs 60 sec after passing 100 km mark

Time = 174 sec
Altitude = 148.8 km
Velocity = 832 m/sec
Flight path angle = 40.8°
Aerodynamic Similarity to Viking Lander

Skidbladnir in Entry Configuration (MIT SSL)

VIKING Lander in Aeroshell for Atmospheric Entry (Martin Marietta)
Comparison of Drag Coefficients: Parashield (Calculated) vs. Viking Lander (Wind Tunnel)
AMROC Trajectory
(Roll Angle = 0)

- Mach Number
- Altitude

Mach

Time (sec.)

km
AMROC Trajectory
(Roll Angle = 0)

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Dynamic Pressure        Heating Rate
AMROC Trajectory
(Roll Angle = 180°)

- Dynamic Pressure
- Heating Rate
## Key Trajectory Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Best Case</th>
<th>Worst Case</th>
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<tbody>
<tr>
<td>Roll angle:</td>
<td>0°</td>
<td>180°</td>
</tr>
<tr>
<td>Max. temperature:</td>
<td>910°F</td>
<td>913°F</td>
</tr>
<tr>
<td>Max. heating rate:</td>
<td>15.4 W/m²²</td>
<td>15.5 W/m²²</td>
</tr>
<tr>
<td>Touchdown time (after deployment):</td>
<td>805 sec</td>
<td>795 sec</td>
</tr>
<tr>
<td>Downrange distance (after deploy.):</td>
<td>149 km</td>
<td>130 km</td>
</tr>
<tr>
<td>Terminal velocity:</td>
<td>23.0 m/sec</td>
<td>23.0 m/sec</td>
</tr>
<tr>
<td>Max. dynamic pressure:</td>
<td>1690 Pa</td>
<td>1770 Pa</td>
</tr>
<tr>
<td>at Mach:</td>
<td>3.18</td>
<td>3.14</td>
</tr>
<tr>
<td>Max. Mach:</td>
<td>5.28</td>
<td>5.28</td>
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<tr>
<td>Max. g's:</td>
<td>7.64</td>
<td>8.00</td>
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<tr>
<td>Total flight duration:</td>
<td>16:19</td>
<td>16:15</td>
</tr>
<tr>
<td>Total downrange distance:</td>
<td>229 km (143 mi)</td>
<td>210 km (131 mi)</td>
</tr>
<tr>
<td>Apogee:</td>
<td>164 km (102 mi)</td>
<td>164 km (102 mi)</td>
</tr>
</tbody>
</table>
Entry with Total Deployment Failure

- Ballistic coefficient: 2150 Pa
- Maximum temperature: 2000° F
- Maximum deceleration: 9 g
- Maximum dynamic pressure: 20,000 Pa
- Terminal velocity: 75 m/sec

Prognosis: poor
Landing Loads

Acceptable Condition: Heat shield shredded
   Bent struts
   Intact capsule

Terminal Velocity $\sim$23 m/sec (51 mph)

For water penetration of 3 m,
   average deceleration is 9 g
Nominal Landing Footprint

Downrange Direction

18 mi

12 mi

Maximum likelihood landing is at periphery of footprint

Nominal search area of 170 sq. mi.
ParaShield Structure
Strut Structural Design

Radial Strut: 303 Stainless Steel

Brace: tubular Stainless Steel
1 in. O.D.
1/32 in. wall thickness

Maximum Stresses, roll angle 180°:
Brace Compression: 915 lbf./strut
Buckling limit: 1930 lbf./strut
Radial Strut Bending Stress: 21000 psi
Yield strength: 35000 psi

Project Skidbladnir
M.I.T. Space Systems Lab
Stress: Radial Strut #7

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- Lower Face of Strut
- Upper Face of Strut

**Graph Details:**
- **Axes:**
  - Y-axis: Stress (psi)
  - X-axis: Angle (°)

**Graph Description:**
- The graph shows the stress variation with angle for the lower and upper faces of a radial strut.
- The stress values range from -15,000 to 20,000 psi.
- The angles range from 0° to 45°.
- The graph highlights the stress distribution at different angles for both faces.
Attitude Control
Thrust vs. Time

(2 X 1/16" throat diameter thrusters, unregulated)
Attitude Control Propulsion

• Requirements
  – Damping 10 lbf-sec per axis
  – Position control 20 lbf-sec per axis
  – Total impulse requirement 90 lbf-sec

• Assumptions
  – Initial tank pressure 4500 psi, regulated to 125 psi
  – Tank volume 514 cu.in.
  – 2 thrusters, 0.156 in throat diameter

• Parametric Propellant Analysis

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Thrust (lbf)</th>
<th>Impulse (lbf-sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>8.15</td>
<td>89.6</td>
</tr>
<tr>
<td>Helium</td>
<td>7.65</td>
<td>93.6</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>8.15</td>
<td>334.8</td>
</tr>
<tr>
<td>CO2</td>
<td>8.44</td>
<td>485.9</td>
</tr>
</tbody>
</table>

Project Skidbladnir  M.I.T. Space Systems Lab
T + 245 sec., Mach 3.93, Q = 1.1 Pa
Initial Tumble Rate: 360°/sec.
Damping Control Only

---
Alpha (°) --- Total Impulse (lbf-s) --- Thrust (lbf)
---

Time (sec)
T + 361 sec., Mach 5.28, Q = 19.7 Pa

Alpha (°)  Total Impulse (lbf·s)  Thrust (lbf)
$T + 969$ sec., Mach .07, $Q = 391.4$ Pa

- Alpha ($^\circ$)
- Total Impulse (lbf-s)
- Thrust (lbf)
Avionics
<table>
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<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>T - 15 min</td>
<td>Power up internal systems; pressurize thruster manifold</td>
</tr>
<tr>
<td>T - 120 sec</td>
<td>Start video camera</td>
</tr>
<tr>
<td>T - 0 sec</td>
<td>Launch; start master event timer; start data recording</td>
</tr>
<tr>
<td>T + 80 sec</td>
<td>Thrust termination</td>
</tr>
<tr>
<td>T + 144 sec</td>
<td>Jettison payload shroud</td>
</tr>
<tr>
<td>T + 159 sec</td>
<td>Detach vehicle from booster; engage attitude rate damping;</td>
</tr>
<tr>
<td></td>
<td>start SLR camera; start mechanical deployment timer; arm ParaShield deployment</td>
</tr>
<tr>
<td>T + 174 sec</td>
<td>Begin nominal deployment of ParaShield</td>
</tr>
<tr>
<td>T + 184 sec</td>
<td>Nominal deployment of ParaShield completed</td>
</tr>
<tr>
<td>T + 220 sec</td>
<td>Begin contingency deployment of ParaShield</td>
</tr>
<tr>
<td>T + 230 sec</td>
<td>Contingency deployment of ParaShield completed</td>
</tr>
<tr>
<td>T + 345 sec</td>
<td>Encounter sensible atmosphere; engage attitude control</td>
</tr>
<tr>
<td>T + 370 sec</td>
<td>Disengage attitude control; engage attitude rate damping</td>
</tr>
<tr>
<td>T + 975 sec</td>
<td>Deploy recovery beacon</td>
</tr>
<tr>
<td>T + 980 sec</td>
<td>Touchdown</td>
</tr>
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Sensor Complement

- 16 RTD temperature transducers
  - 12 on ParaShield fabric
  - 3 on capsule exterior
  - 1 in capsule interior
- 4 strain gauge bridges
  - Strain on radial and brace struts
- 4 accelerometers
- 3 fluidic rate sensors
- 5 pressure transducers
  - Static pressure
  - Dynamic pressure
  - Capsule environment
  - Low pressure manifold
  - High pressure manifold
Control Electronics

- Primary Control and Data Computer
  - Ampro 80286 single-board (AT clone)
  - Coded in C and Assembler
  - Program stored in EPROM
  - Data recorded in EAROM
  - Total data capacity 128Kx8

- Distributed Redundant Data Computers
  - F86HC11 microcontroller boards
  - Coded in Forth
  - Program and data stored in nonvolatile SRAM
  - Total data capacity 16Kx8 each

- Master Event Timer
  - Master reference clock bused to all processors
  - Synchronized interrupt for data collection, main flight control

- Contingency Deployment Controller
  - 60 sec mechanical timer initiated at separation
Interfaces to Booster
Interface Plate Specifics

- Three to four pairs of ball-lock mechanism and guide pin assemblies--enough to support transverse loading and lateral vibrations during launch sequence.

- Guide pins prevent rotation and assist in mating of payload to interface plate on launch pad.

- Ball-lock and pin assemblies mate to outer flange of back plate of recovery module.

- Interface plate has space in middle for camera lenses and beacon assembly.

- Space is left around thrusters to ensure clean separation of payload from booster.
Summary
Payload Integration

Payload arrives July 1, 1989

Acceptance check: verify post-shipping integrity and repair if necessary

Functional check

- Fit check to payload interface plate—done previously at MIT if possible
- Verify operation of all systems

Booster mating

- Lift payload to top of booster—guidelines necessary to protect payload from support structure
- Engage ball-lock mechanisms and make electrical connections
- Remove lifting assembly—will need support scaffolding
- Attach front protective plate

System monitoring until launch

Project Skidbladnir
M.I.T. Space Systems Lab
Remaining Design Tasks

- Structural Dynamics
- Power Distribution System
- Data and Control System
- Optimal Control Algorithm
- Heat Transfer
- Low-Speed Aerodynamics
- Internal Layout
Planned/Potential Testing

- Systems Testing
  - Lab Bench
  - Integration (in lab)
  - Acceptance (at pad)

- Vacuum Chamber
  - Deployment Mechanism
  - Control System (single-axis)
  - Capsule Thermal Environment
  - End-to-end Mission Simulation

- Low-Speed Aerodynamics
  - Stability at Terminal Velocity
  - Water Impact Test
<table>
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<th>Date</th>
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<tr>
<td>2/25</td>
<td>Kickoff Meeting</td>
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<td>Locate Sources</td>
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<td>3/18</td>
<td>Design Review</td>
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<td>Vendor Quotes</td>
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<td>FMEA</td>
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<td>4/29</td>
<td>Analysis &amp; Simulation</td>
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<td>Internal Design</td>
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<td>5/20</td>
<td>Payload</td>
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<td>5/27</td>
<td>Parts on order</td>
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<td>6/3</td>
<td>Avionics Assembly</td>
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<tr>
<td>6/10</td>
<td>Develop Data Recorder</td>
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<td>6/17</td>
<td>Gyros Deliv.</td>
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<td>6/24</td>
<td>Integration</td>
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<td>7/1</td>
<td>Testing</td>
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<td>Vacuum Deploy Test</td>
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<td>Accept. Tests</td>
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Summary

- Designs and analyses complete enough to begin general procurement and fabrication
- Detailed analyses indicate ParaShield concept will meet or exceed original performance expectations
- Resolution of primary interface issues (mechanical and electrical) expected from this trip
- Major remaining concerns are operational details, such as visual acquisition of capsule following splashdown
- Program on track to support launch window beginning 20 July 1989
Early Assembly of Shield Structure
Shield Structure and Deployment
ParaShield Stowed and Deployed
Launch Vehicle Integration
October 5, 1989 - T+2 sec
October 5, 1989 - T+60 sec
October 6, 1989 - Aftermath
ParaShield in GLM Wind Tunnel
Schlieren Supersonic Flow Visualization
CFD Model
Configurations for Orbital Flight Test
ParaShield for ISS Crew Rotation Mission

Case Study: ParaShield
ENAE 791 - Launch and Entry Vehicle Design
ParaShield for Human Lunar Return

- **Altitude (km)** vs Downrange Distance (km)
  - Parashield
  - Apollo

- **Deceleration (g/s)** vs Time Since Entry (sec)
  - Parashield
  - Apollo

- **Stagnation Point Temperature (°C)** vs Time Since Entry (sec)
  - Parashield
  - Apollo
ParaShield for Human Mars Return

Graphs showing:
- Altitude vs. Downrange Distance (km)
- Altitude vs. Velocity (m/sec)
- Deceleration (g's) vs. Time Since Entry (sec)
- Stagnation Point Heating (°C) vs. Time Since Entry (sec)
Conclusions

- Ultralow ballistic coefficient entry vehicles can match performance of conventional capsule-type vehicles
- ParaShield approach provides both entry thermal protection and aerodynamic deceleration, except for impact attenuation
- Structural mass efficiencies and packing factors are improved by larger volume protected from aft wake
- Separation of entry/descent/landing systems from crew cabin provides additional margin for exploration missions to the moon and beyond
ParaShield Flight Test – 12/4/2011