Entry and Fluid Dynamics

- Rarified gas Newtonian flow
- Continuum Newtonian flow (hypersonics)
- SphereConeAero software
- Case study: ParaShield concept and flight test
Newtonian Flow

- Mean free path of particles much larger than spacecraft --> no appreciable interaction of air molecules
- Model vehicle/atmosphere interactions as independent perfectly elastic collisions
Newtonian Analysis

\[ \text{mass flux} = (\text{density})(\text{swept area})(\text{velocity}) \]

\[
\frac{dm}{dt} = (\rho)(A \sin(\alpha))(V)
\]
Momentum Transfer

- Momentum perpendicular to wall is reversed at impact
- “Bounce” momentum is transferred to vehicle
- Momentum parallel to wall is unchanged

\[
F = \frac{dm}{dt} \Delta V = \rho V A \sin \alpha (2V \sin \alpha) = 2\rho V^2 A \sin^2 \alpha
\]
Lift and Drag

\[ L = F \cos \alpha = 2\rho V^2 A \sin^2 \alpha \cos \alpha \]

\[ D = F \sin \alpha = 2\rho V^2 A \sin^3 \alpha \]

\[ c_L = \frac{L}{\frac{1}{2} \rho V^2 A} = 4 \sin^2 \alpha \cos \alpha \]

\[ c_D = \frac{D}{\frac{1}{2} \rho V^2 A} = 4 \sin^3 \alpha \]

\[ \frac{L}{D} = \frac{\cos \alpha}{\sin \alpha} = \cot \alpha \]
Flat Plate Newtonian Aerodynamics

![Graph showing Flat Plate Newtonian Aerodynamics](image)
Example of Newtonian Flow Calculations

Consider a cylinder of length l, entering atmosphere transverse to flow

\[ dA = r \, d\theta \, dl \]
\[ dm = \rho dA \cos \theta V = \rho V \cos \theta r \, d\theta \, dl \]

\[ dF = dm \Delta V = 2 \rho V^2 \cos^2 \theta r \, d\theta \, dl \]
\[ dD = dF \cos \theta = 2 \rho V^2 \cos^3 \theta r \, d\theta \, dl \]
\[ dL = dF \sin \theta = 2 \rho V^2 \cos \theta \sin \theta r \, d\theta \, dl \]
Integration to Find Drag Coefficient

Integrate from $\theta = -\frac{\pi}{2} \rightarrow \frac{\pi}{2}$

$$D = \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_{0}^{\ell} dD = 2\rho V^2 r \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_{0}^{\ell} \cos^3 \theta d\theta d\ell$$

$$= 2\rho V^2 r \ell \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \cos^3 \theta d\theta = \frac{4}{3} \rho V^2 r \ell$$

By definition, $D = \frac{1}{2} \rho V^2 A c_D$ and, for a cylinder $A = 2r\ell$

$$\rho V^2 r \ell c_D = \frac{4}{3} \rho V^2 r \ell \implies c_D = \frac{4}{3}$$
Continuum Newtonian Flow (Hypersonics)

- Air molecules predominately interact with shock waves.
- Effect of shock wave passage is to decelerate flow and turn it parallel to vehicle surface.
Continuum Newtonian Flow (Hypersonics)

- Treat hypersonic aerodynamics in manner similar to previous Newtonian flow analysis
- All momentum perpendicular to wall is absorbed by the wall
Mass Flux (unchanged)

\[ \frac{dm}{dt} = (\rho)(A \sin \alpha)(V) \]
Momentum Transfer

- Momentum perpendicular to wall is absorbed at impact and transferred to vehicle
- Momentum parallel to wall is unchanged

\[ F = \frac{dm}{dt} \Delta V = \rho V A \sin \alpha (V \sin \alpha) = \rho V^2 A \sin^2 \alpha \]
Lift and Drag

\[ L = F \cos \alpha = \rho V^2 A \sin^2 \alpha \cos \alpha \]

\[ D = F \sin \alpha = \rho V^2 A \sin^3 \alpha \]

\[ c_L = \frac{L}{\frac{1}{2} \rho V^2 A} = 2 \sin^2 \alpha \cos \alpha \]

\[ c_D = \frac{D}{\frac{1}{2} \rho V^2 A} = 2 \sin^3 \alpha \]

\[ \frac{L}{D} = \frac{\cos \alpha}{\sin \alpha} = \cot \alpha \]
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 for different L/D ratios.](image)
Parametric Analysis of Stagnation Temp

Graph showing the relationship between Peak ParaShield Temperature (°F) and Ballistic Coefficient (Pa). The temperature increases linearly with the Ballistic Coefficient.
Parametric Analysis of Dynamic Pressure

![Graph showing the relationship between Maximum Dynamic Pressure (Pa) and Ballistic Coefficient (Pa). The graph includes three lines, each representing different L/D ratios: max Q, L/D=.1, max Q, L/D=0, and max Q, L/D=.2. The y-axis represents the maximum dynamic pressure in Pascals (Pa), ranging from 0 to 120,000. The x-axis represents the ballistic coefficient in Pascals (Pa), ranging from 0 to 12,000. The lines show an increase in maximum dynamic pressure as the ballistic coefficient increases.]
Parametric Analysis of Peak Deceleration

![Graph showing parametric analysis of peak deceleration with respect to ballistic coefficient.](graph.png)

- **Maximum Deceleration (g's)**
- **Ballistic Coefficient (Pa)**

- max G, L/D = 0.1
- max G, L/D = 0
- max G, L/D = 0.2
Comparison of Entry Trajectories
Comparison of Heat Shield Temperatures
Comparison of Total Heat Loads

![Graph showing comparison of total heat loads over time](image)
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

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<tr>
<th>Category</th>
<th>Mass (kg)</th>
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<td>Payload</td>
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<td><strong>Total</strong></td>
<td><strong>147.1</strong></td>
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</table>
Trajectory
Trajectory Assumptions

Vehicle Assumptions

\[
m = 150 \text{ kg} \\
\beta = 215.7 \text{ Pa} \\
L/D = .177
\]

Flight Dynamics Assumptions

ParaShield deployment occurs 60 sec after passing 100 km mark

\[
\text{Time} = 174 \text{ sec} \\
\text{Altitude} = 148.8 \text{ km} \\
\text{Velocity} = 832 \text{ m/sec} \\
\text{Flight path angle} = 40.8^\circ
\]
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

Time (sec.)

Mach

km
AMROC Trajectory
(Roll Angle = 0)

- Dynamic Pressure
- Heating Rate

Altitude (m)

kW/m$^2$

Pa
AMROC Trajectory
(Roll Angle = 180°)

Dynamic Pressure  Heating Rate

Altitude (m)
## Key Trajectory Parameters

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<tr>
<th>Parameters</th>
<th>Best Case</th>
<th>Worst Case</th>
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<tr>
<td>Roll angle:</td>
<td>0°</td>
<td>180°</td>
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<td>Max. temperature:</td>
<td>910° F</td>
<td>913° F</td>
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<td>Max. heating rate:</td>
<td>15.4 W/m^2</td>
<td>15.5 W/m^2</td>
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<td>Touchdown time (after deployment):</td>
<td>805 sec</td>
<td>795 sec</td>
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<td>Downrange distance (after deploy.):</td>
<td>149 km</td>
<td>130 km</td>
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<td>Terminal velocity:</td>
<td>23.0 m/sec</td>
<td>23.0 m/sec</td>
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<td>Max. dynamic pressure:</td>
<td>1690 Pa</td>
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<td>at Mach:</td>
<td>3.18</td>
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<td>7.64</td>
<td>8.00</td>
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<td>Total flight duration:</td>
<td>16:19</td>
<td>16:15</td>
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<tr>
<td>Total downrange distance:</td>
<td>229 km (143 mi)</td>
<td>210 km (131 mi)</td>
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<tr>
<td>Apogee:</td>
<td>164 km (102 mi)</td>
<td>164 km (102 mi)</td>
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</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 $\sim 23 \text{ m/sec (51 mph)}$

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

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

- Lower Face of Strut
- Upper Face of Strut

Stress (psi)

0 5 10 15 20 25 30 35 40 45

Angle (°)
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 Propellent Analysis

<table>
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<tr>
<th>Propellant</th>
<th>Thrust (lbf)</th>
<th>Impulse (lbf-sec)</th>
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<tbody>
<tr>
<td>Hydrogen</td>
<td>8.15</td>
<td>89.6</td>
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<td>Helium</td>
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<tr>
<td>Nitrogen</td>
<td>8.15</td>
<td>334.8</td>
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<tr>
<td>CO2</td>
<td>8.44</td>
<td>485.9</td>
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</tbody>
</table>
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)
$T + 361$ sec, Mach 5.28, $Q = 19.7$ Pa

- $\alpha$ (°)
- Total Impulse (lbf-s)
- Thrust (lbf)
$T + 969$ sec., Mach .07, $Q = 391.4$ Pa
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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>
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<tr>
<td>T - 120 sec</td>
<td>Start video camera</td>
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<tr>
<td>T - 0 sec</td>
<td>Launch; start master event timer; start data recording</td>
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<td>T + 80 sec</td>
<td>Thrust termination</td>
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<td>T + 144 sec</td>
<td>Jettison payload shroud</td>
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<td>T + 159 sec</td>
<td>Detach vehicle from booster; engage attitude rate damping; start SLR camera; start mechanical deployment timer; arm ParaShield deployment</td>
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<td>T + 174 sec</td>
<td>Begin nominal deployment of ParaShield</td>
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<td>T + 184 sec</td>
<td>Nominal deployment of ParaShield completed</td>
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<td>T + 220 sec</td>
<td>Begin contingency deployment of ParaShield</td>
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<td>T + 230 sec</td>
<td>Contingency deployment of ParaShield completed</td>
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<td>T + 345 sec</td>
<td>Encounter sensible atmosphere; engage attitude control</td>
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<td>T + 370 sec</td>
<td>Disengage attitude control; engage attitude rate damping</td>
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<tr>
<td>T + 975 sec</td>
<td>Deploy recovery beacon</td>
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<td>T + 980 sec</td>
<td>Touchdown</td>
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**Project Skidbladnir**

M.I.T. Space Systems Lab
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
Payload Interface Plate

Project Skidbladnir

M.I.T. Space Systems Lab
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
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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
The Skidbladnir Development Team
Shield Structure and Deployment
ParaShield Stowed and Deployed
Launch Vehicle Integration
October 6, 1989 - Aftermath