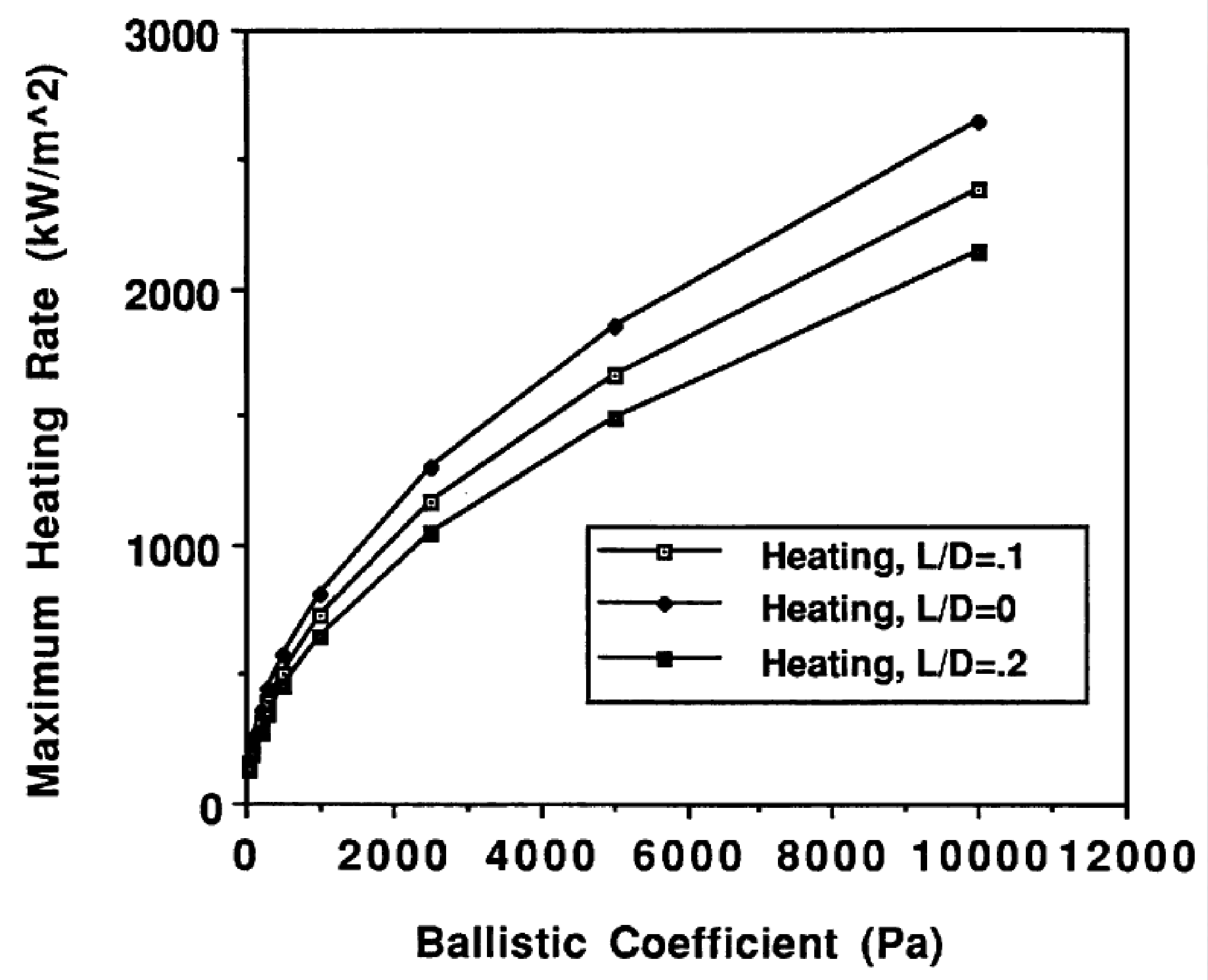
Case Study: ParaShield

- Origin of ParaShield Concept
- ParaShield Flight Test
- Wind Tunnel Testing
- Future Applications

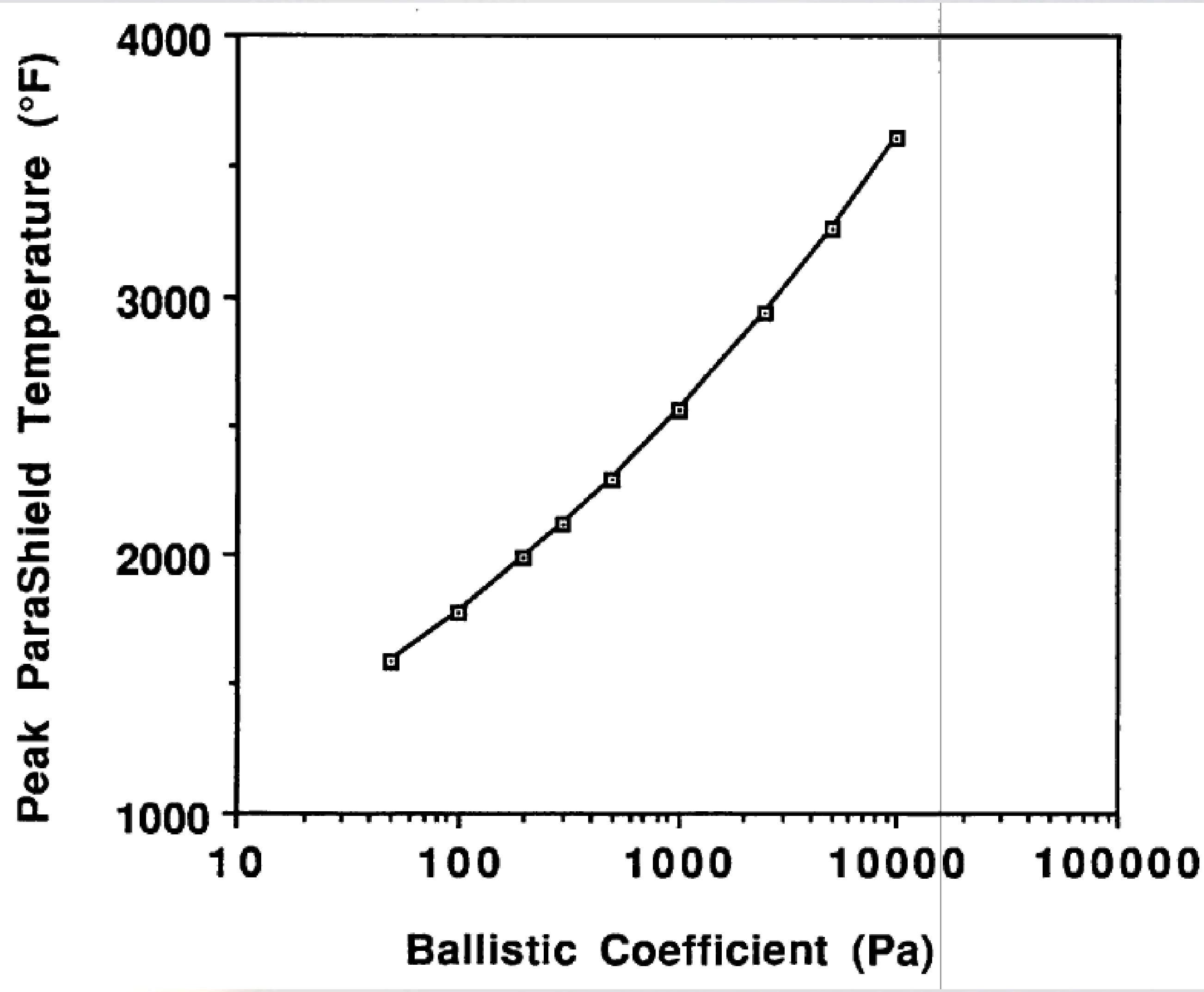
Graduate Design Class: Fall, 1988

- 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)

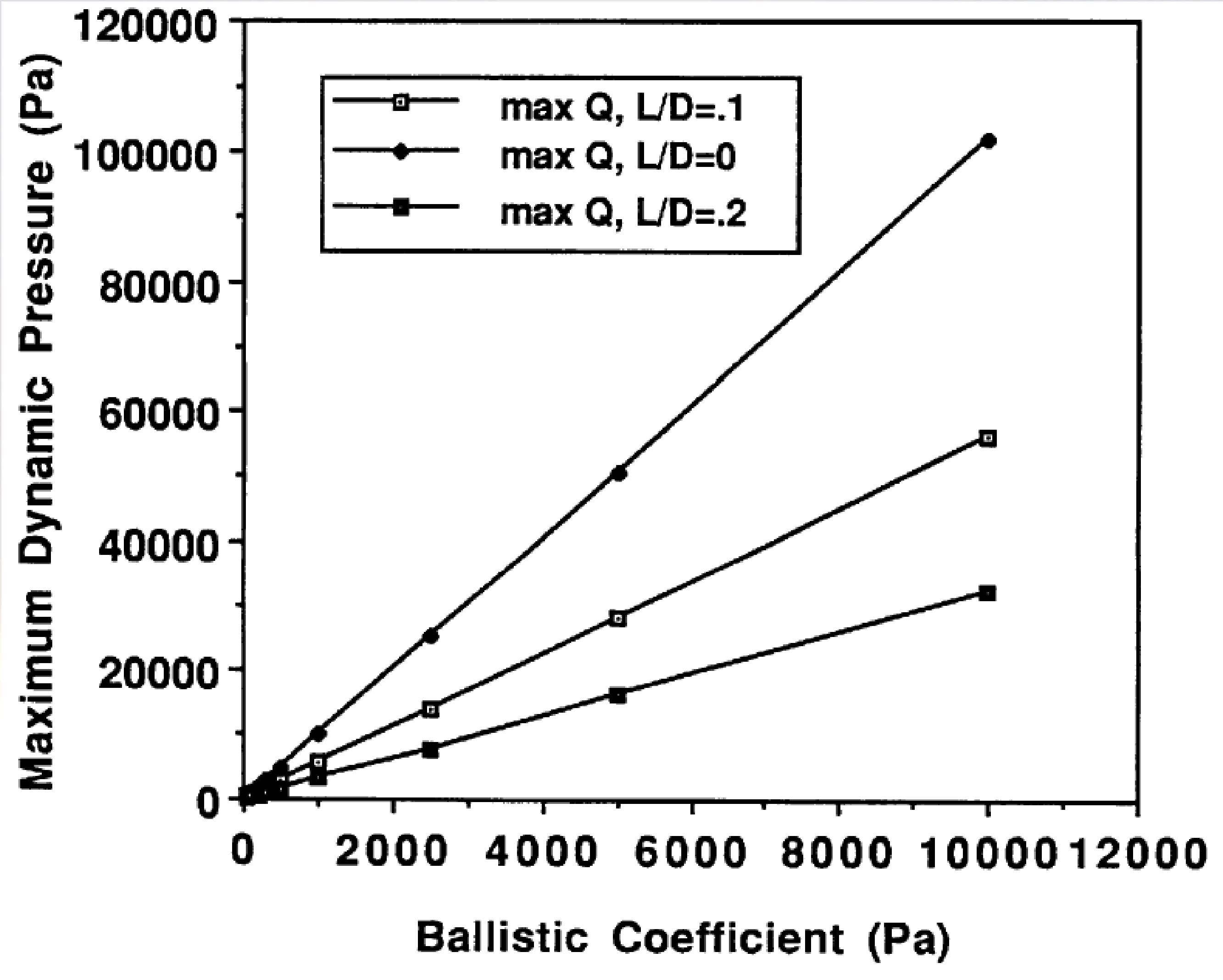
Parametric Analysis of Heating



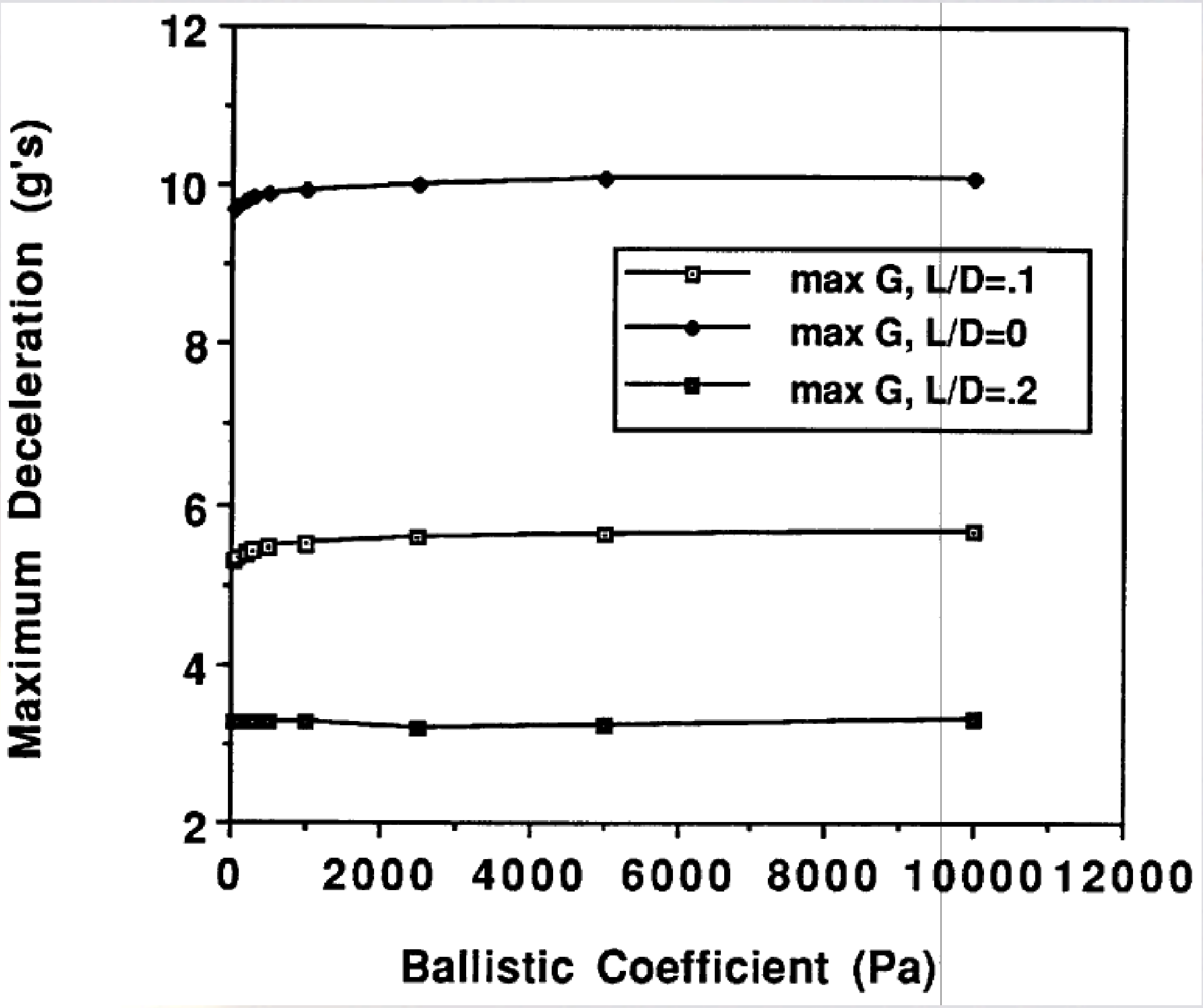
Parametric Analysis of Stagnation Temp



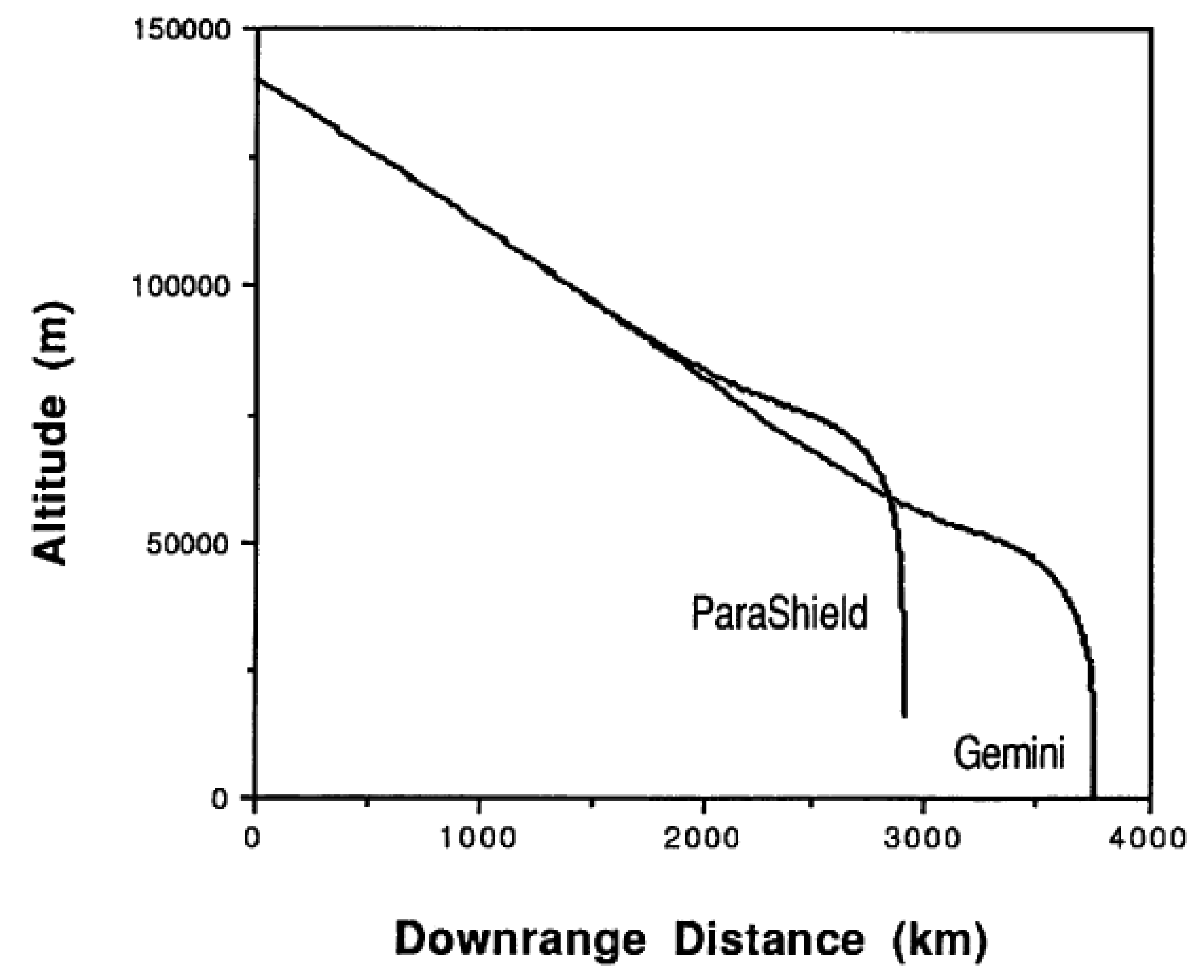
Parametric Analysis of Dynamic Pressure



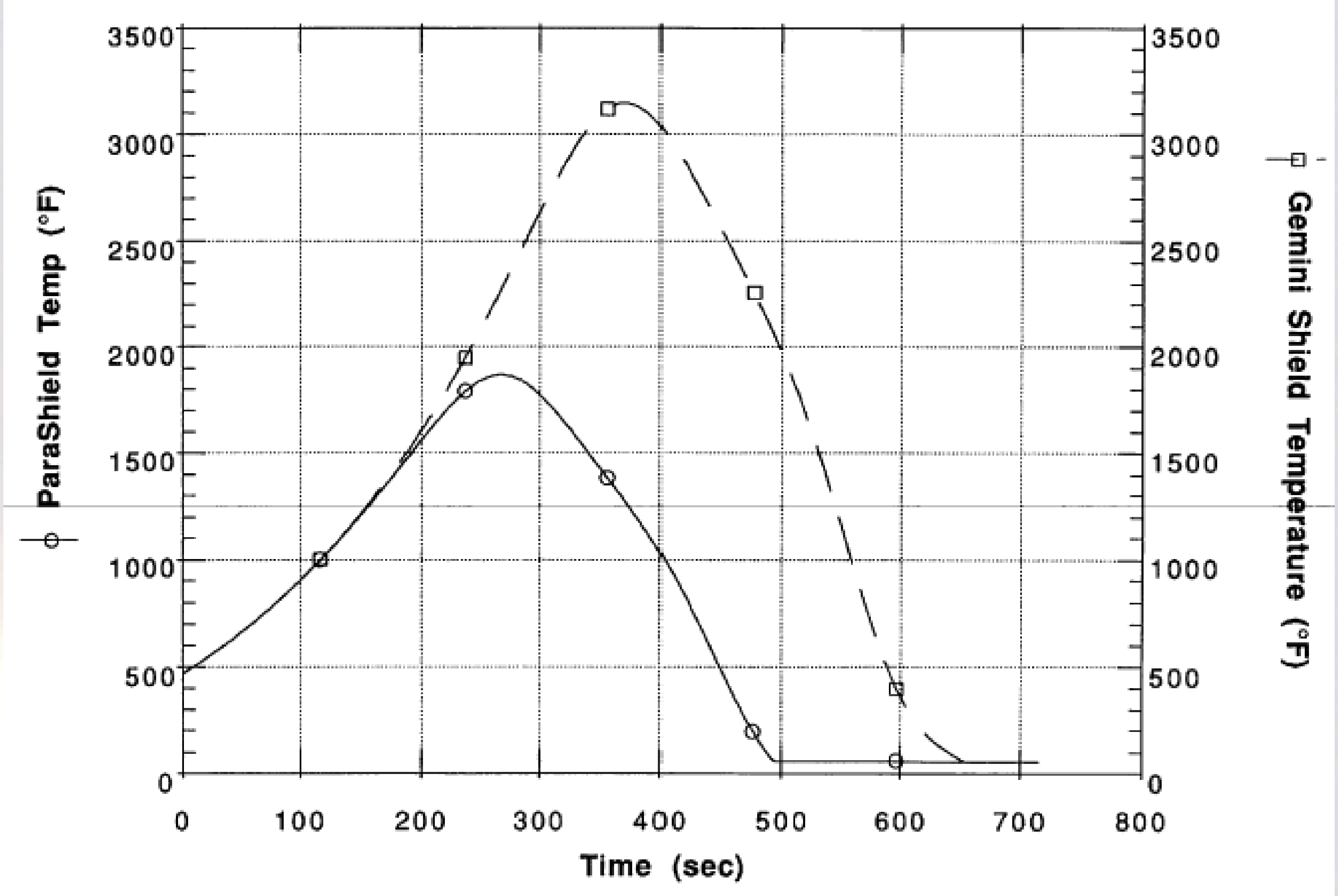
Parametric Analysis of Peak Deceleration



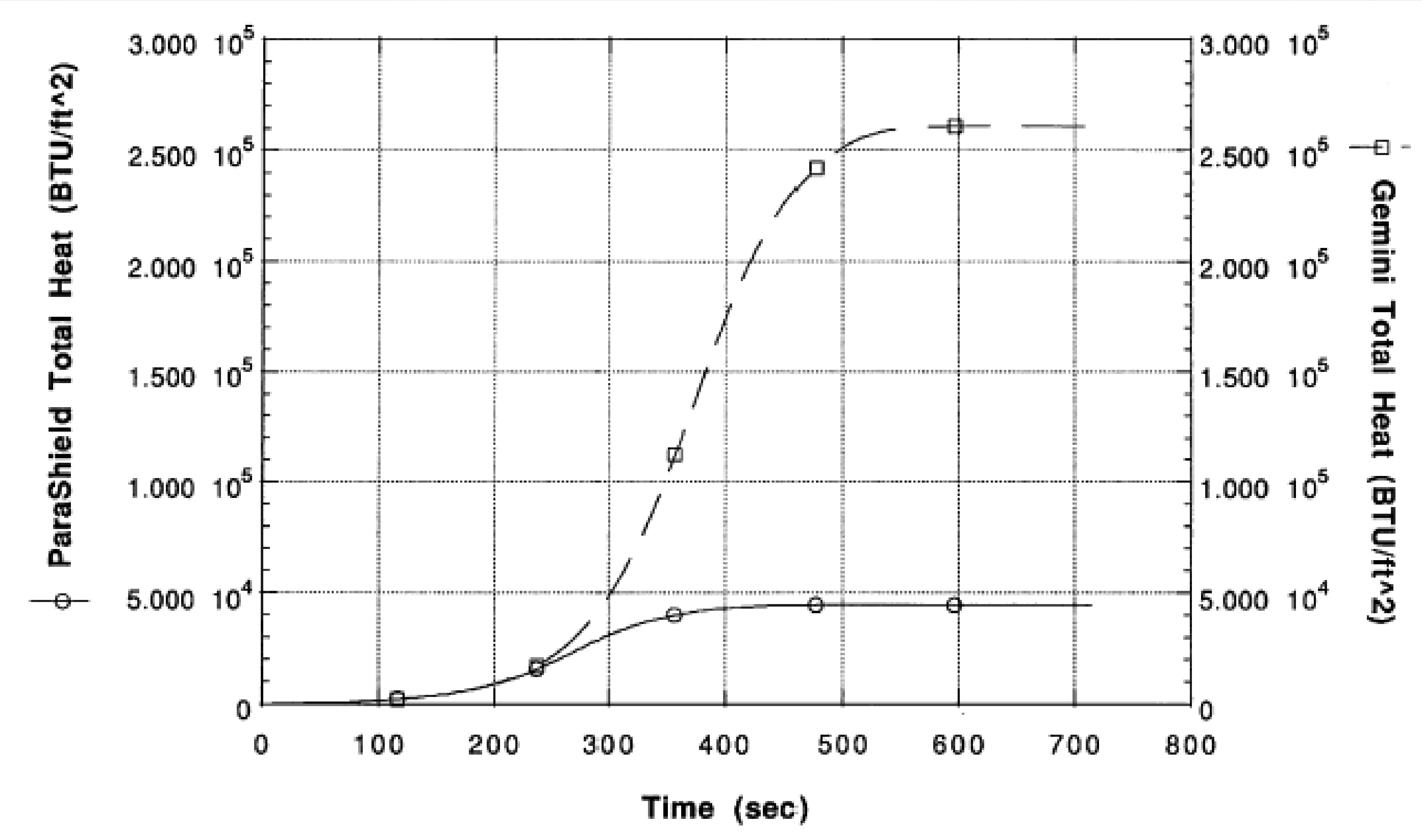
Comparison of Entry Trajectories



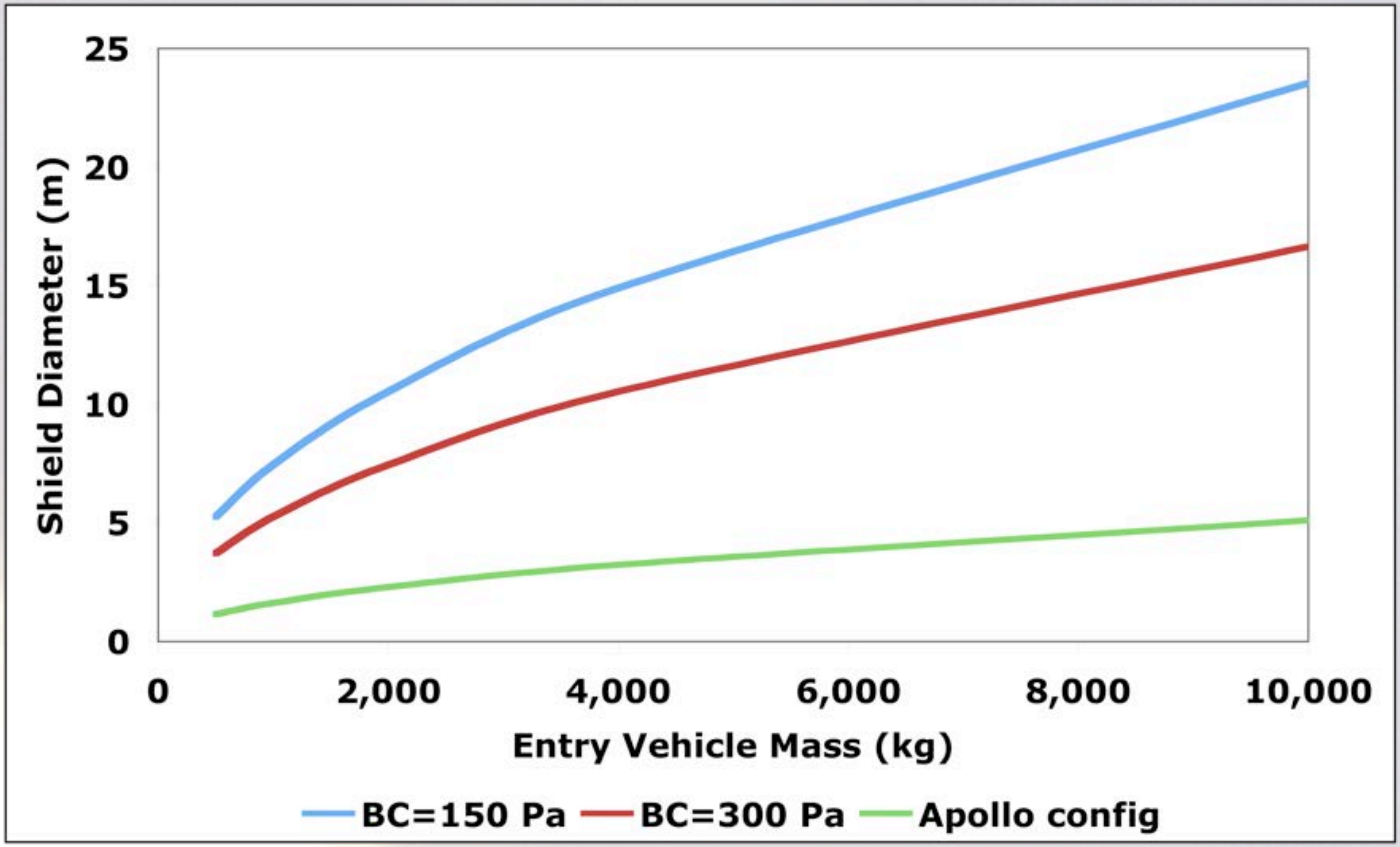
Comparison of Heat Shield Temperatures



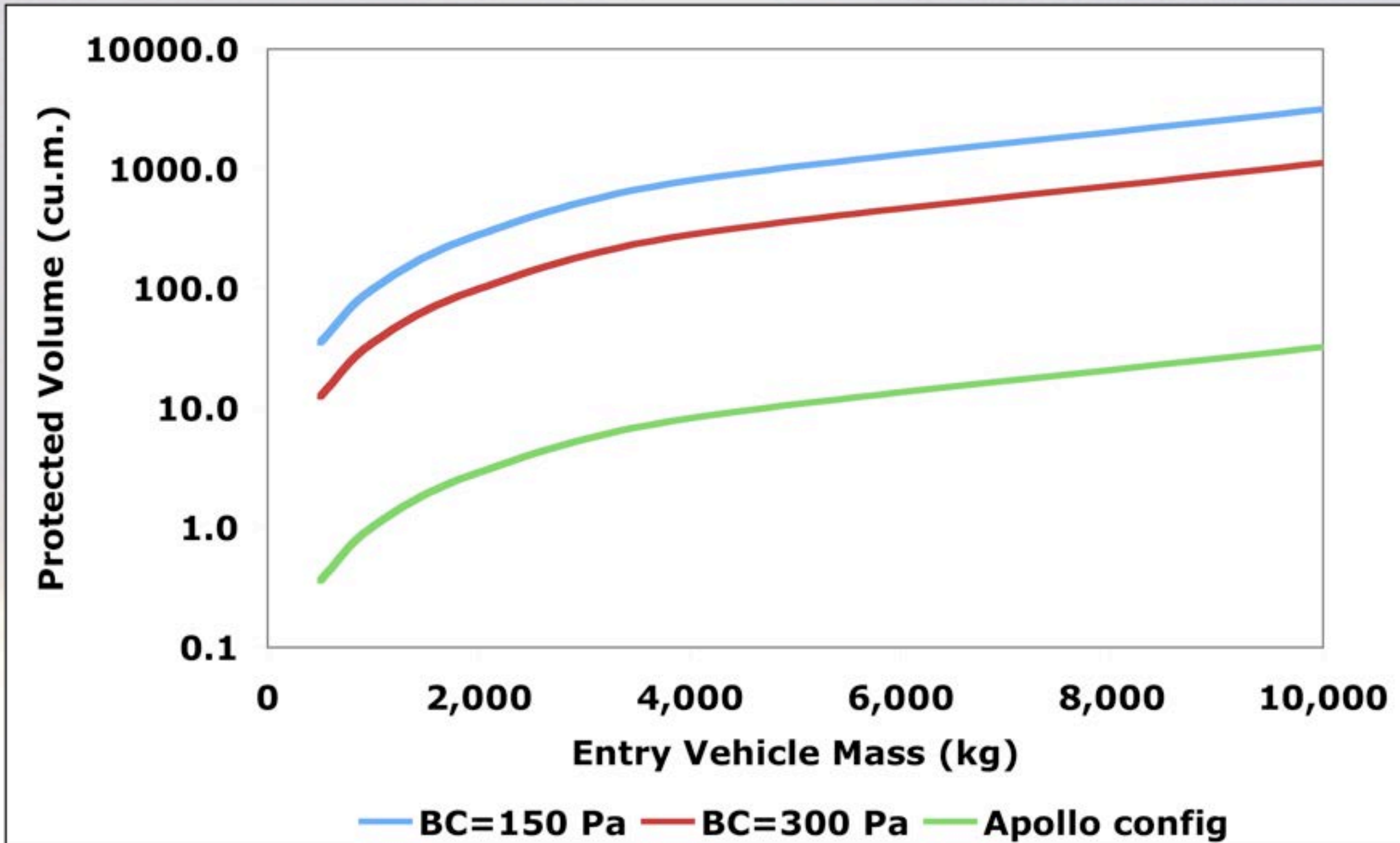
Comparison of Total Heat Loads



Required Heat Shield Diameter



Payload Volume Protected from Wake



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

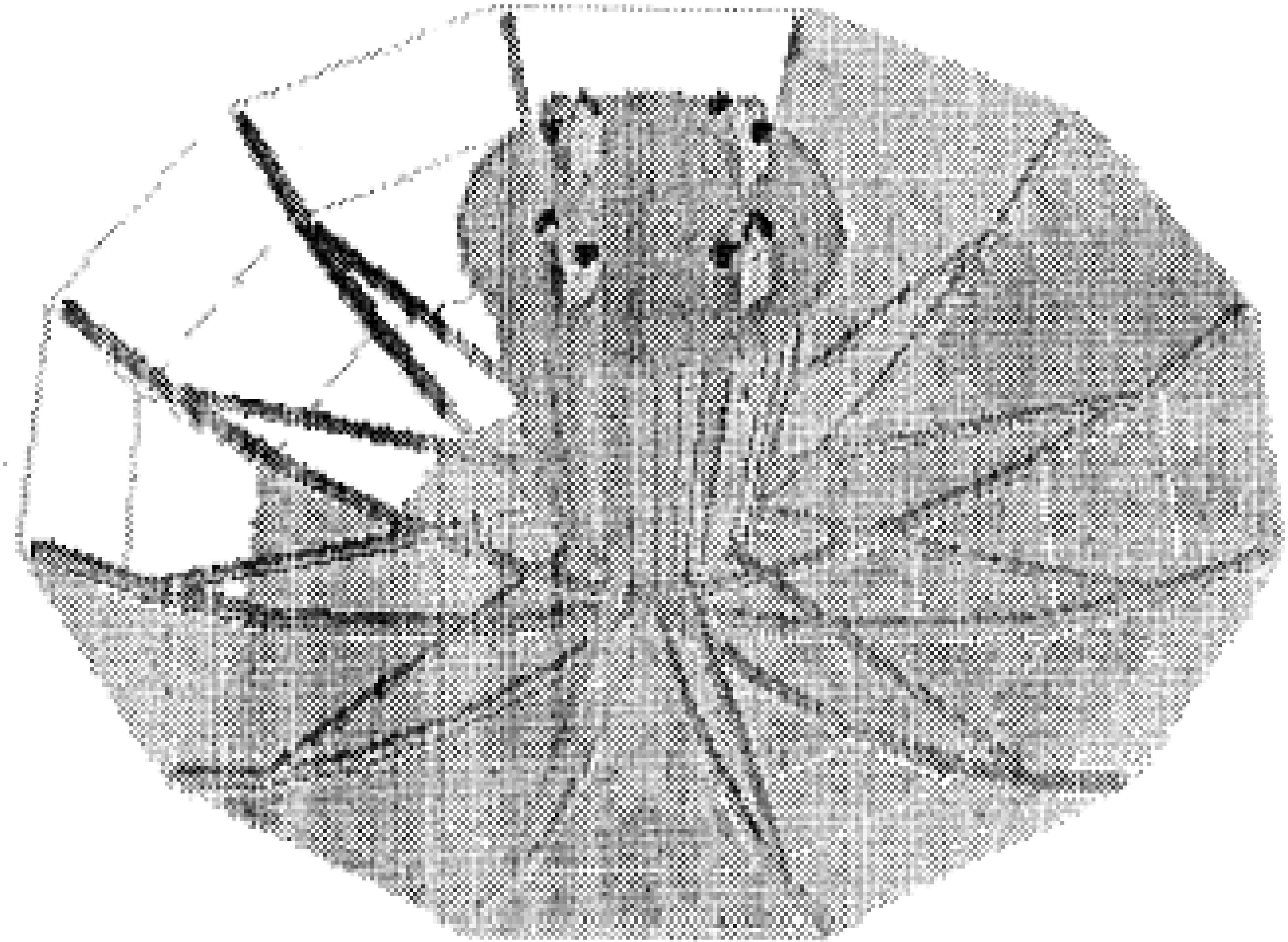
April 17, 1989

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

Payload		7
Avionics		5.1
Sensors	(1.1)	
Instruments	(2.0)	
Electronics	(2.0)	
Mechanisms		20.0
Deployment	(18.0)	
Recovery	(2.0)	
Structure		79.5
Thermal Protection	(38.9)	
Capsule	(40.6)	
Power		14.0
Propulsion		21.5
Total		**147.1**

Trajectory

Trajectory Assumptions

Vehicle Assumptions

$m = 150$ kg

$\beta = 215.7$ Pa

L/D = .177

Flight Dynamics Assumptions

ParaShield deployment occurs 60 sec after passing 100 km mark

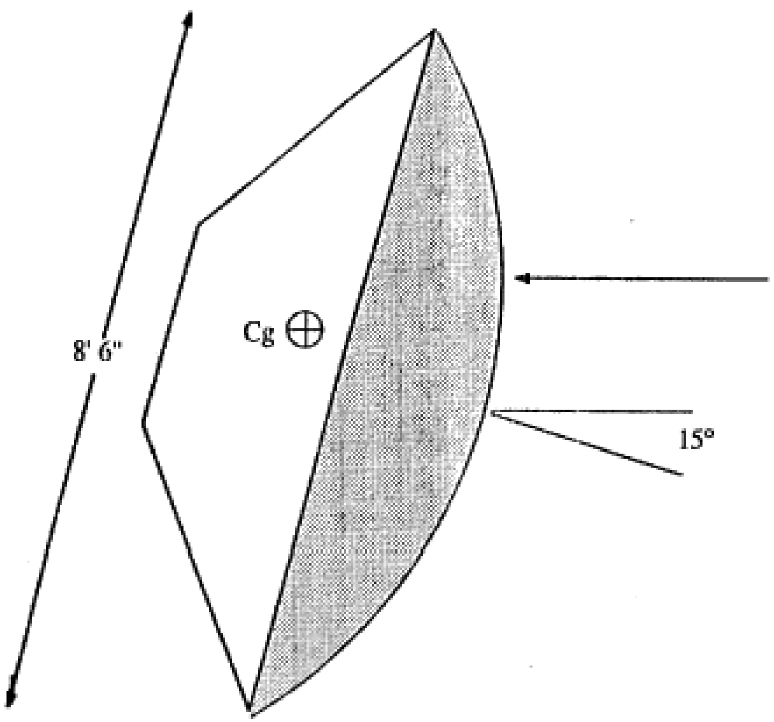
Time = 174 sec

Altitude = 148.8 km

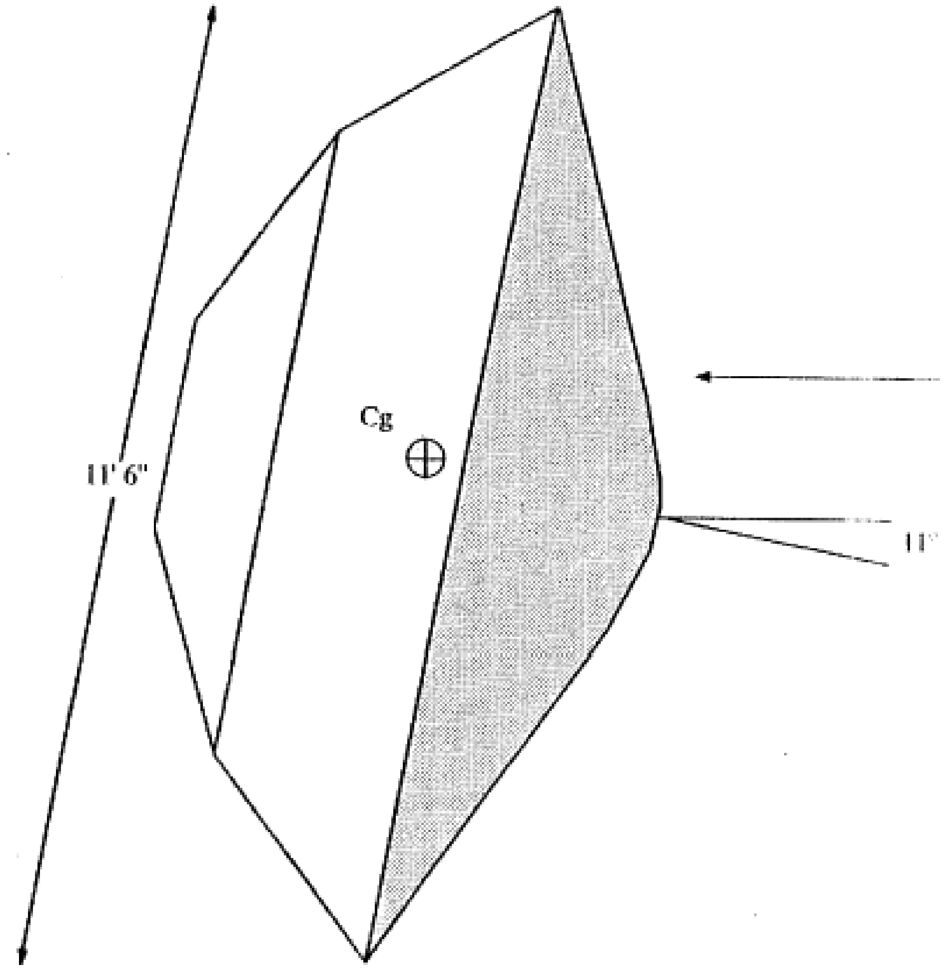
Velocity = 832 m/sec

Flight path angle = 40.8°

Aerodynamic Similarity to Viking Lander

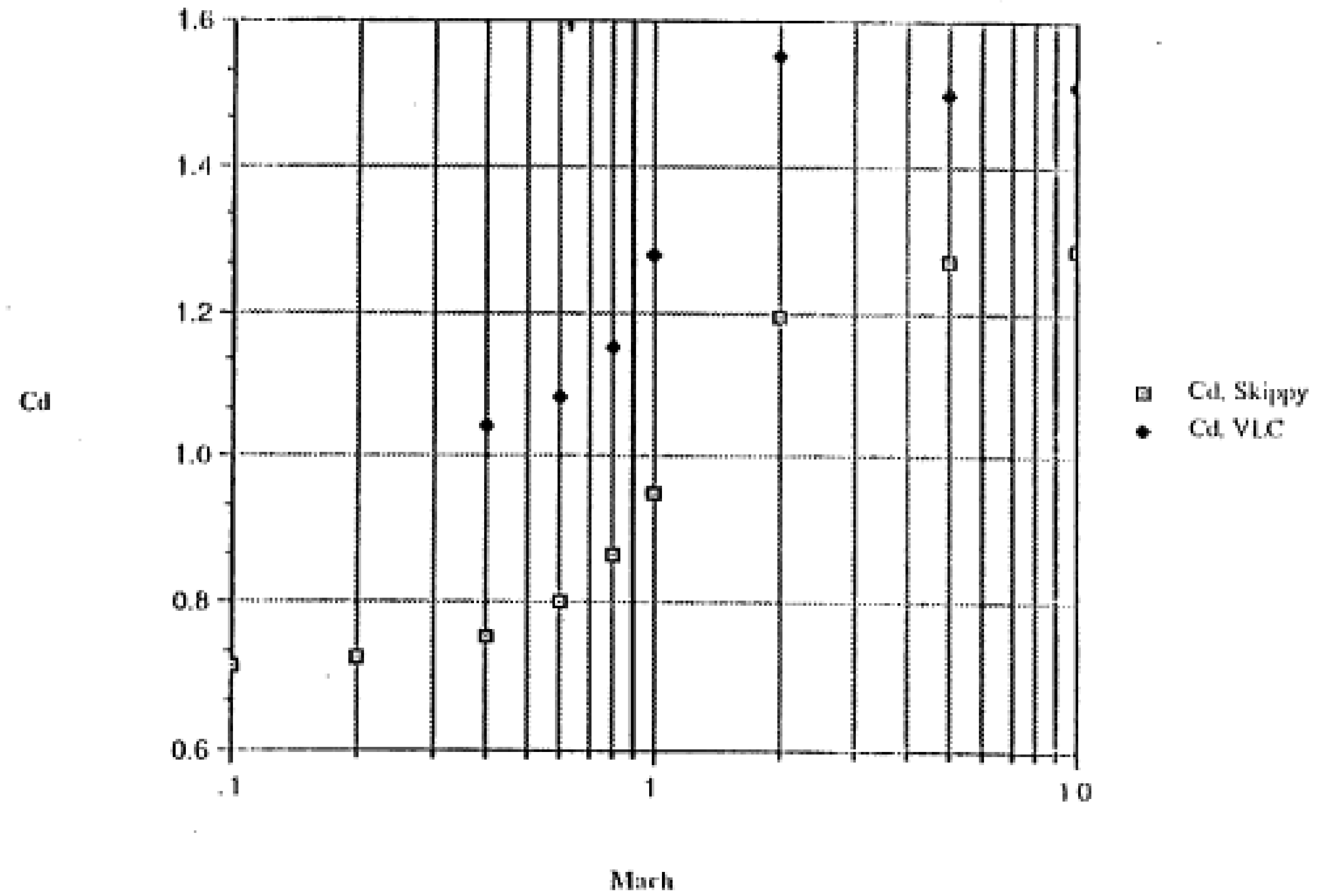


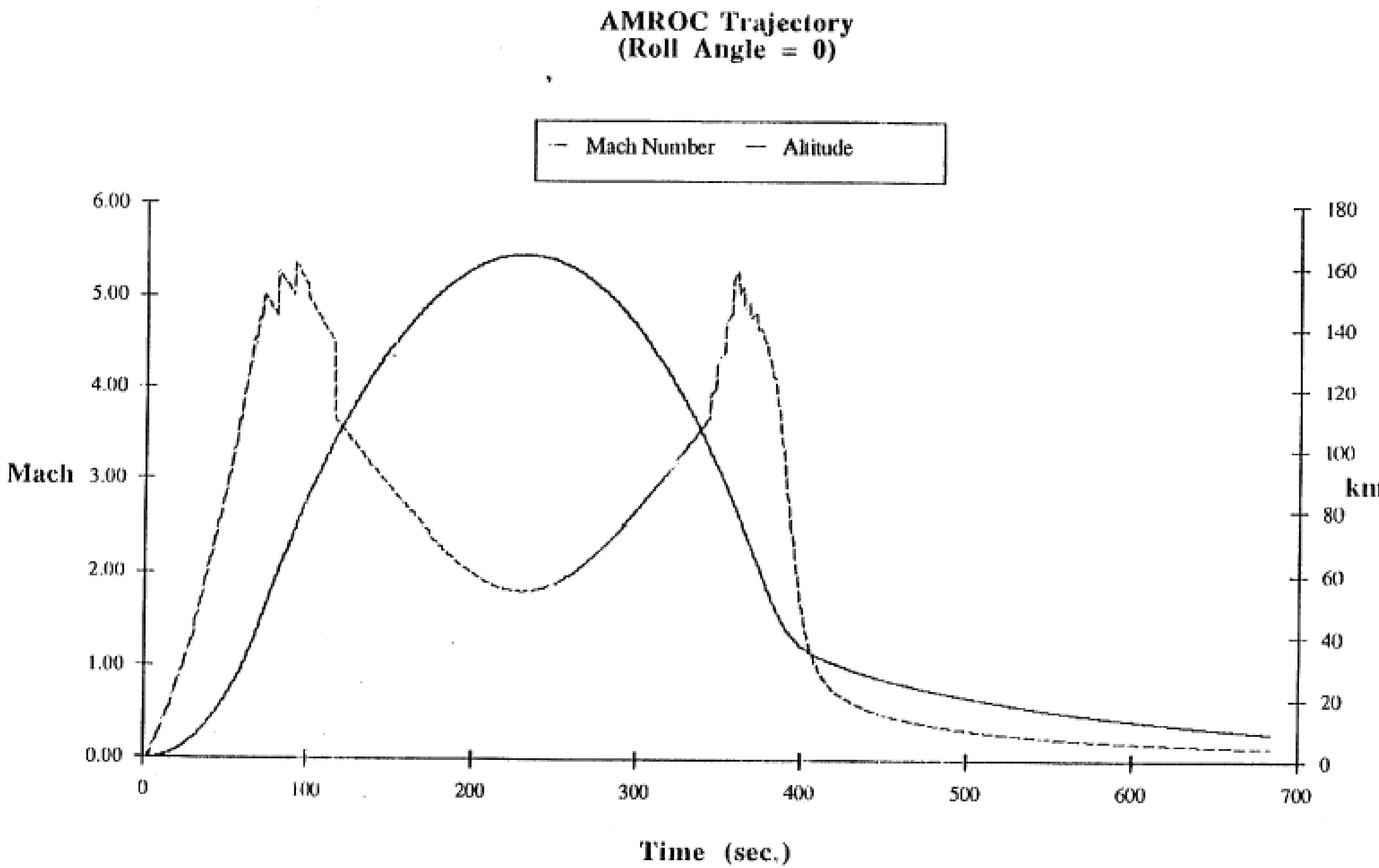
Skidbladnir in Entry Configuration
(MIT SSL)

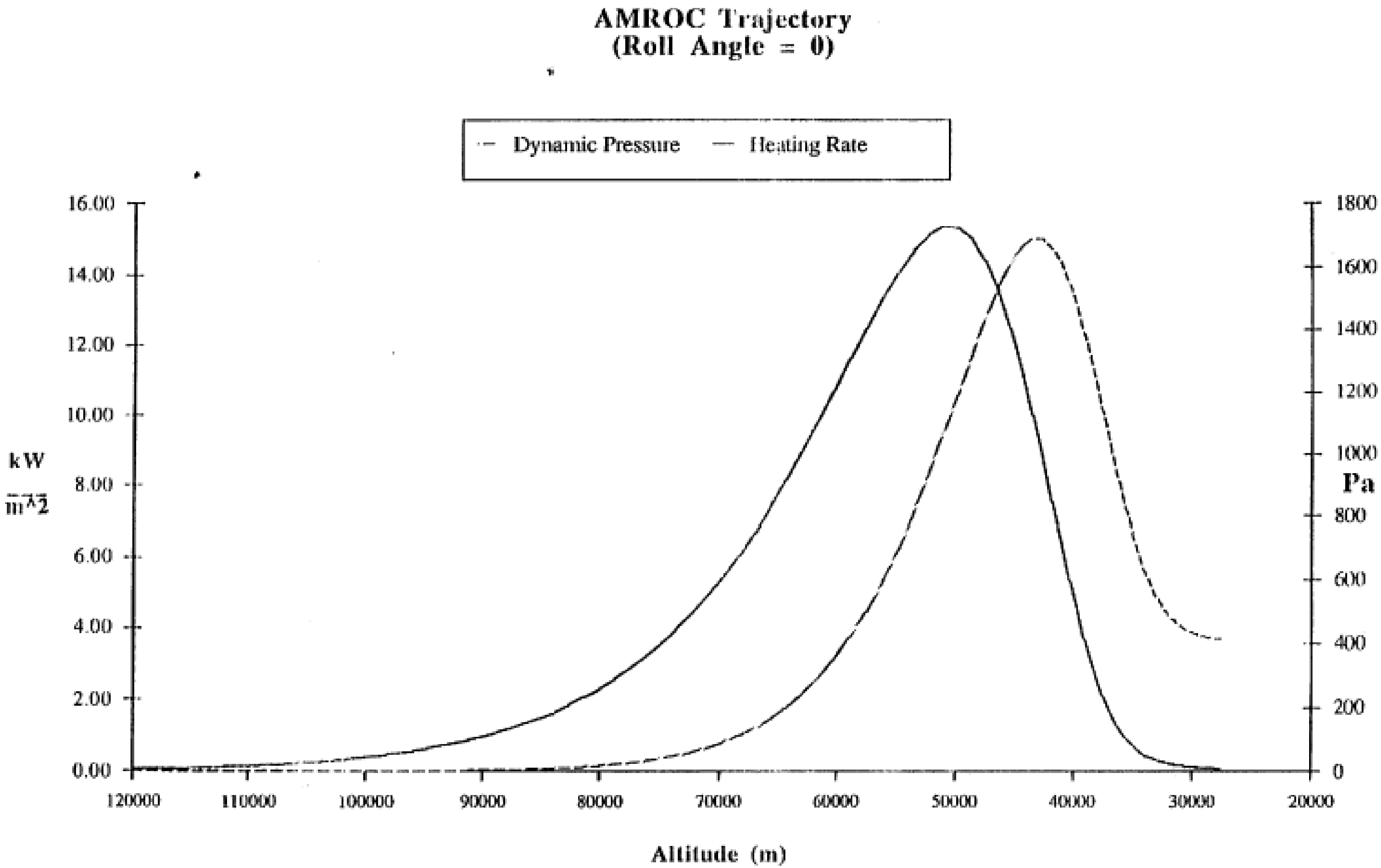


VIKING Lander in Aeroshell for Atmospheric Entry
(Martin Marietta)

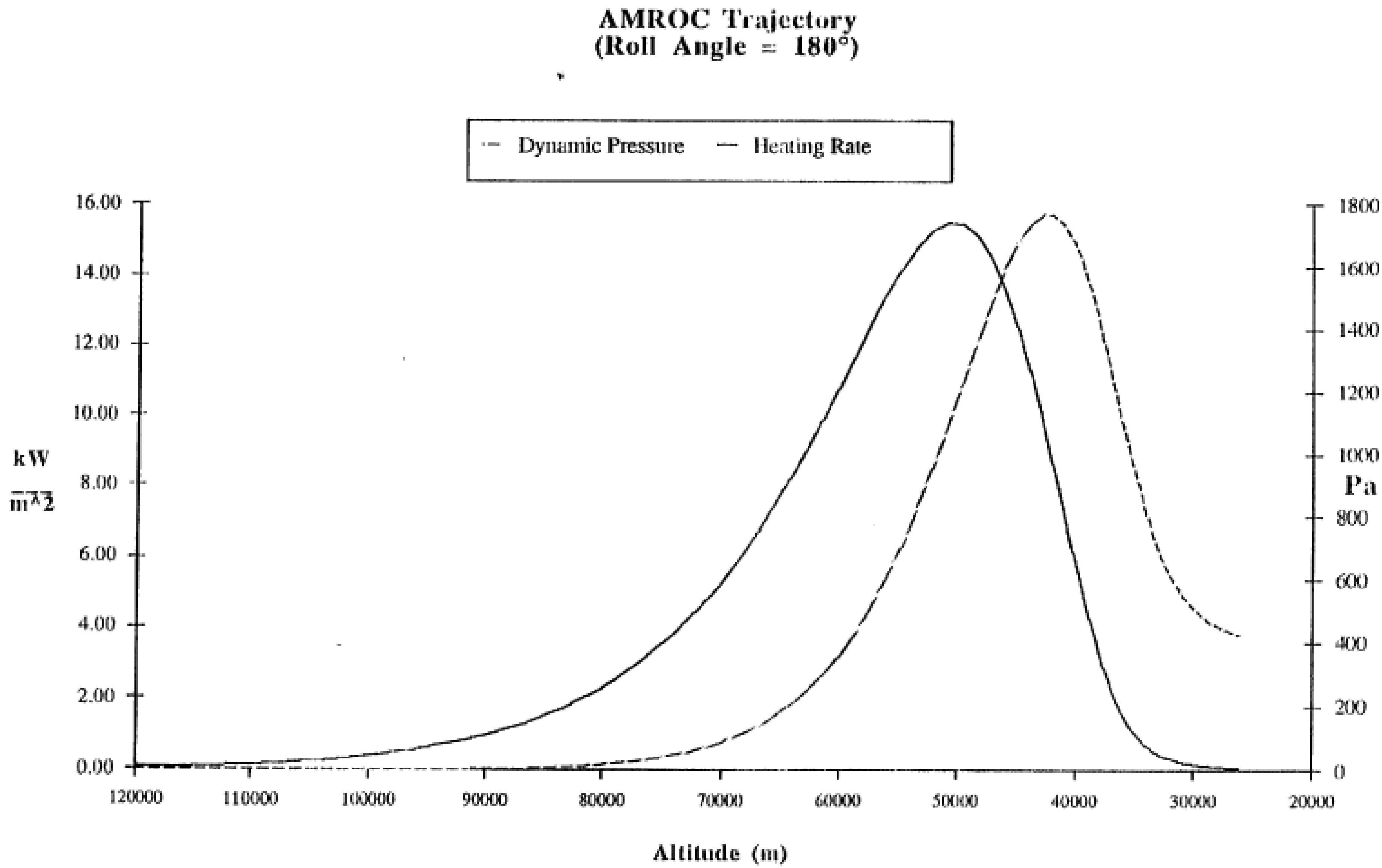
Comparison of Drag Coefficients: Parashield (Calculated) vs. Viking Lander (Wind Tunnel)




AMROC Trajectory
(Roll Angle = 0)
Mach Number
Altitude
Mach
km
Time (sec.)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
0
20
40
60
80
100
120
140
160
180
0
100
200
300
400
500
600
700



AMROC Trajectory
(Roll Angle = 0)
Dynamic Pressure
Heating Rate
kW
m^2
Pa
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1800
1600
1400
1200
1000
800
600
400
200
0
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
Altitude (m)


AMROC Trajectory
(Roll Angle = 180°)
Dynamic Pressure
Heating Rate
kW
m^2
Pa
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1800
1600
1400
1200
1000
800
600
400
200
0
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
Altitude (m)

Key Trajectory Parameters

Parameters	Best Case	Worst Case
Roll angle:	0°	180°
Max. temperature:	910° F	913° F
Max. heating rate:	15.4 W/m^2	15.5 W/m^2
Touchdown time (after deployment):	805 sec	795 sec
Downrange distance (after deploy.):	149 km	130 km
Terminal velocity:	23.0 m/sec	23.0 m/sec
Max. dynamic pressure:	1690 Pa	1770 Pa
at Mach:	3.18	3.14
Max. Mach:	5.28	5.28
Max. g's:	7.64	8.00
Total flight duration:	16:19	16:15
Total downrange distance:	229 km (143 mi)	210 km (131 mi)
Apogee:	164 km (102 mi)	164 km (102 mi)

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

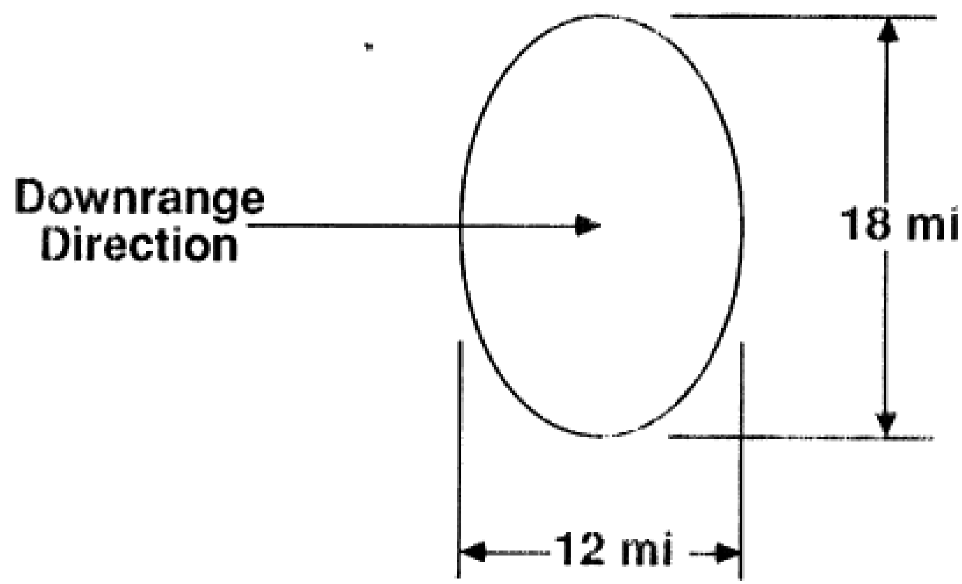
Intact capsule

Terminal Velocity ~23 m/sec (51 mph)

For water penetration of 3 m,

average deceleration is 9 g

Nominal Landing Footprint



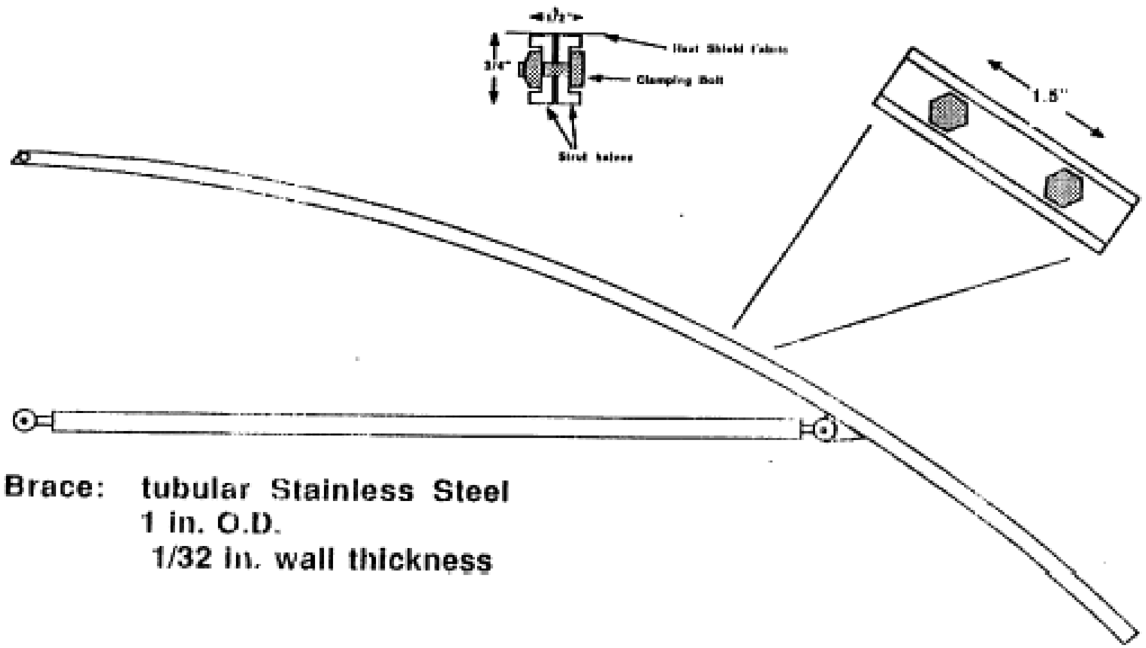
Maximum likelihood landing is at periphery of footprint

Nominal search area of 170 sq. mi.

ParaShield Structure

Strut Structural Design

Radial Strut: 303 Stainless Steel

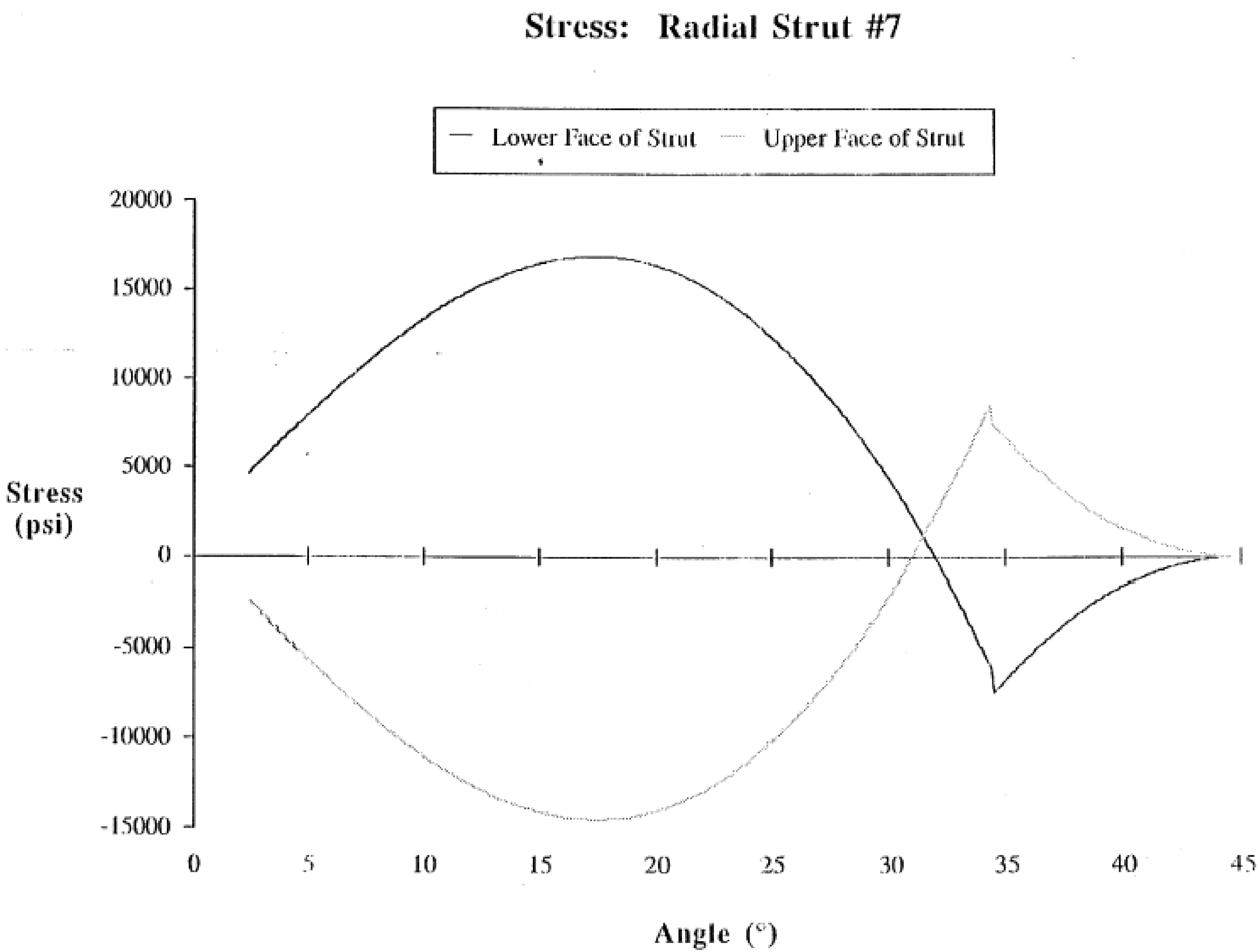


Brace: tubular Stainless Steel
1 in. O.D.
1/32 in. wall thickness

Maximum Stresses, roll angle 180°:

Brace Compression: 915 lbf./strut Buckling limit: 1930 lbf./strut

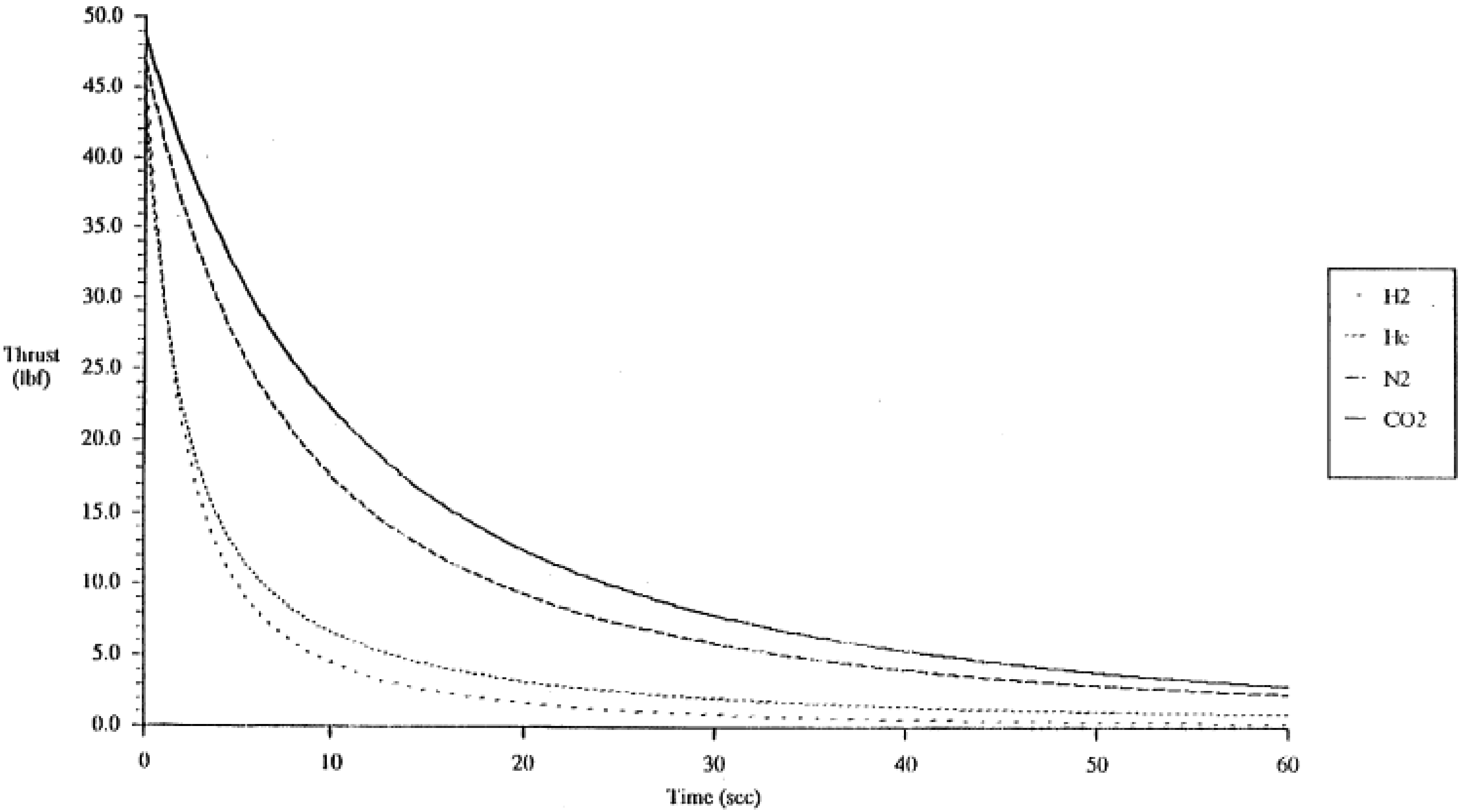
Radial Strut Bending Stress: 21000 psi Yield strength: 35000 psi



Stress: Radial Strut #7
Lower Face of Strut
Upper Face of Strut
Stress (psi)
20000
15000
10000
5000
0
-5000
-10000
-15000
0
5
10
15
20
25
30
35
40
45
Angle (°)

Attitude Control

Thrust vs. Time
(2 X 1/16" throat diameter thrusters, unregulated)

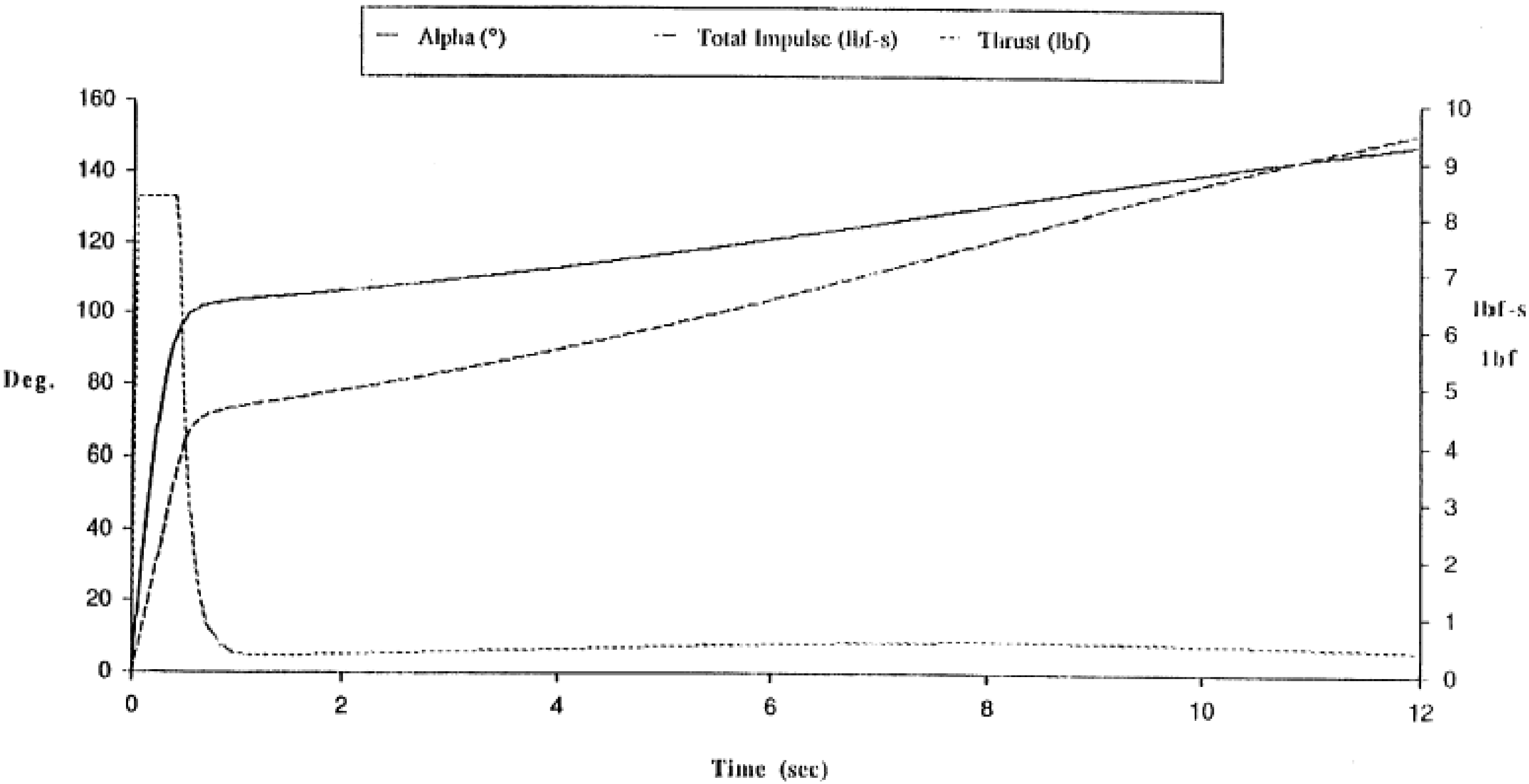


Attitude Control Propulsion

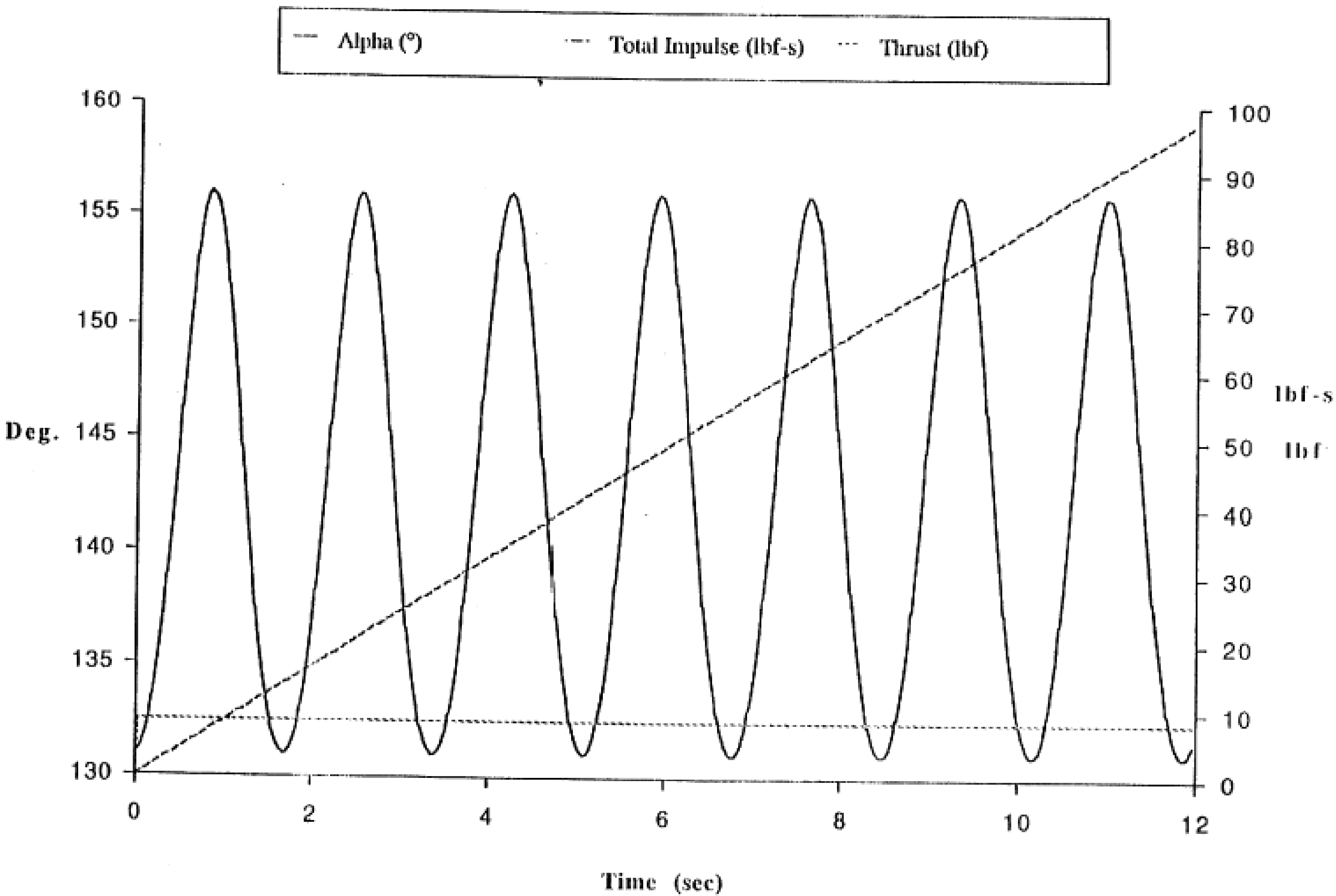
- **Requirements**
  - Damping 10 lbf-sec per axis
  - Position control 20 lbf-sec per axis
  - Total impulse requirement 90 lbf-sec
- **Assumptions**
  - Initial tank pressure 4500 psi, regulated to 125 psi
  - Tank volume 514 cu.in.
  - 2 thrusters, 0.156 in throat diameter
- **Parametric Propellent Analysis**

Propellent	Thrust (lbf)	Impulse (lbf-sec)
Hydrogen	8.15	89.6
Helium	7.65	93.6
Nitrogen	8.15	334.8
CO2	8.44	485.9

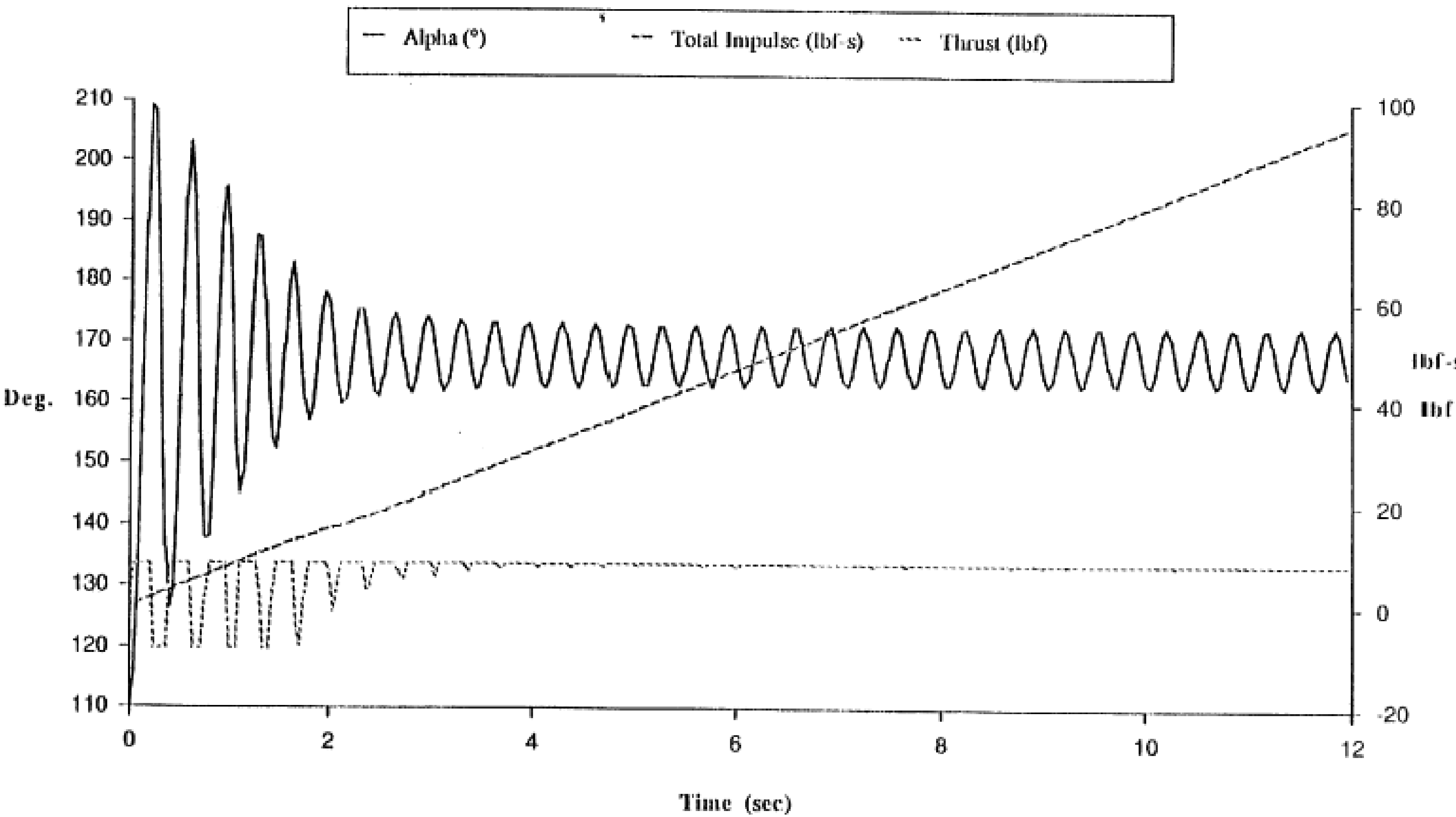
T + 245 sec., Mach 3.93, Q = 1.1 Pa
Initial Tumble Rate: 360°/sec.
Damping Control Only



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



T + 969 sec., Mach .07, Q = 391.4 Pa



Avionics

Flight Timeline

Time	Event
T – 15 min	Power up internal systems; pressurize thruster manifold
T – 120 sec	Start video camera
T – 0 sec	Launch; start master event timer; start data recording
T + 80 sec	Thrust termination
T + 144 sec	Jettison payload shroud
T + 159 sec	Detach vehicle from booster; engage attitude rate damping; start SLR camera; start mechanical deployment timer; arm ParaShield deployment
T + 174 sec	Begin nominal deployment of ParaShield
T + 184 sec	Nominal deployment of ParaShield completed
T + 220 sec	Begin contingency deployment of ParaShield
T + 230 sec	Contingency deployment of ParaShield completed
T + 345 sec	Encounter sensible atmosphere; engage attitude control
T + 370 sec	Disengage attitude control; engage attitude rate damping
T + 975 sec	Deploy recovery beacon
T + 980 sec	Touchdown

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

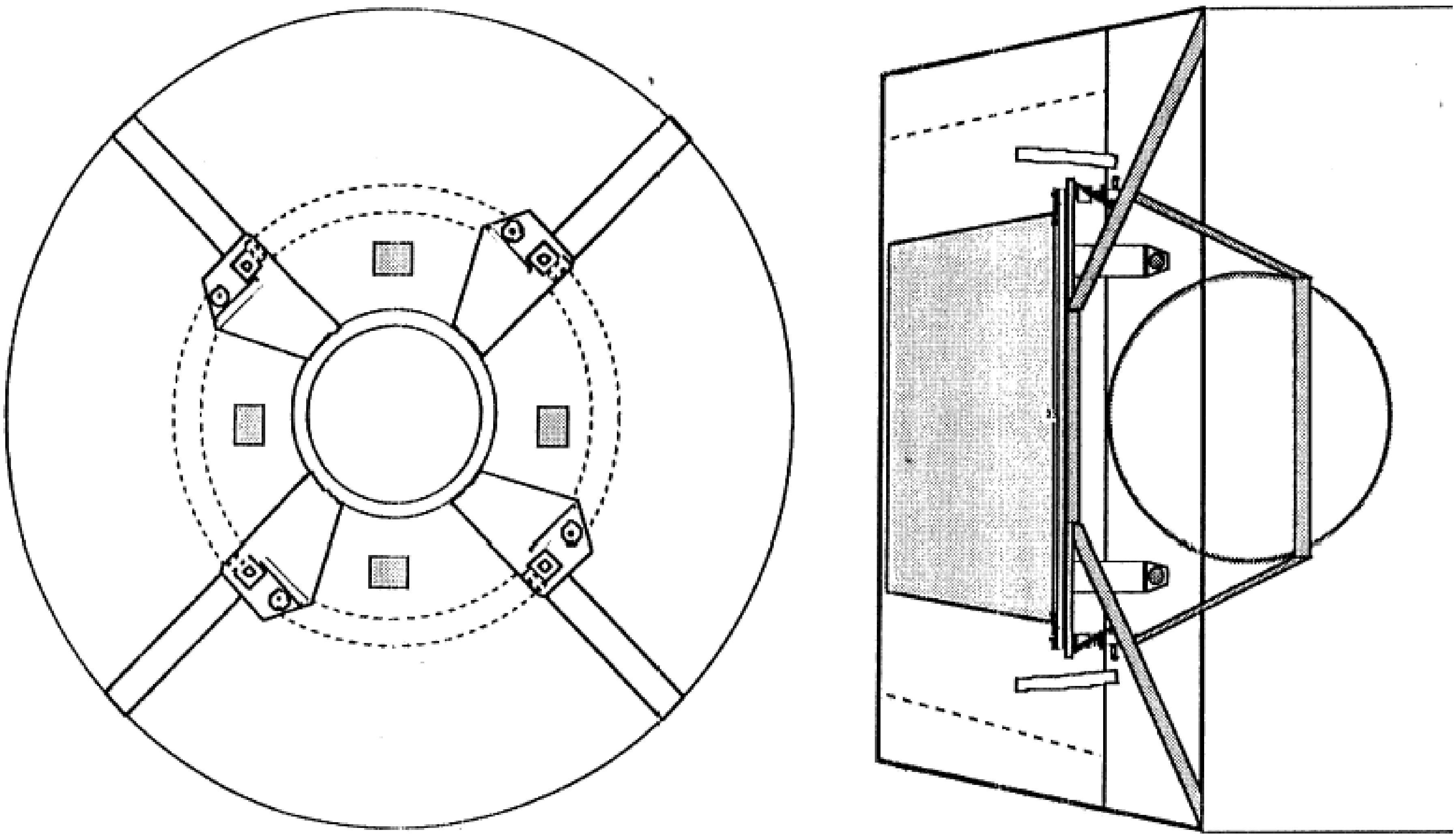
- Primary Control and Data Computer
  - Ampro 80286 single-board (AT clone)
  - Coded in C and Assembler
  - Program stored in EPROM
  - Data recorded in EAROM
  - Total data capacity 128Kx8
- Distributed Redundant Data Computers
  - F86HC11 microcontroller boards
  - Coded in Forth
  - Program and data stored in nonvolatile SRAM
  - Total data capacity 16Kx8 each
- Master Event Timer
  - Master reference clock bused to all processors
  - Synchonized 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



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

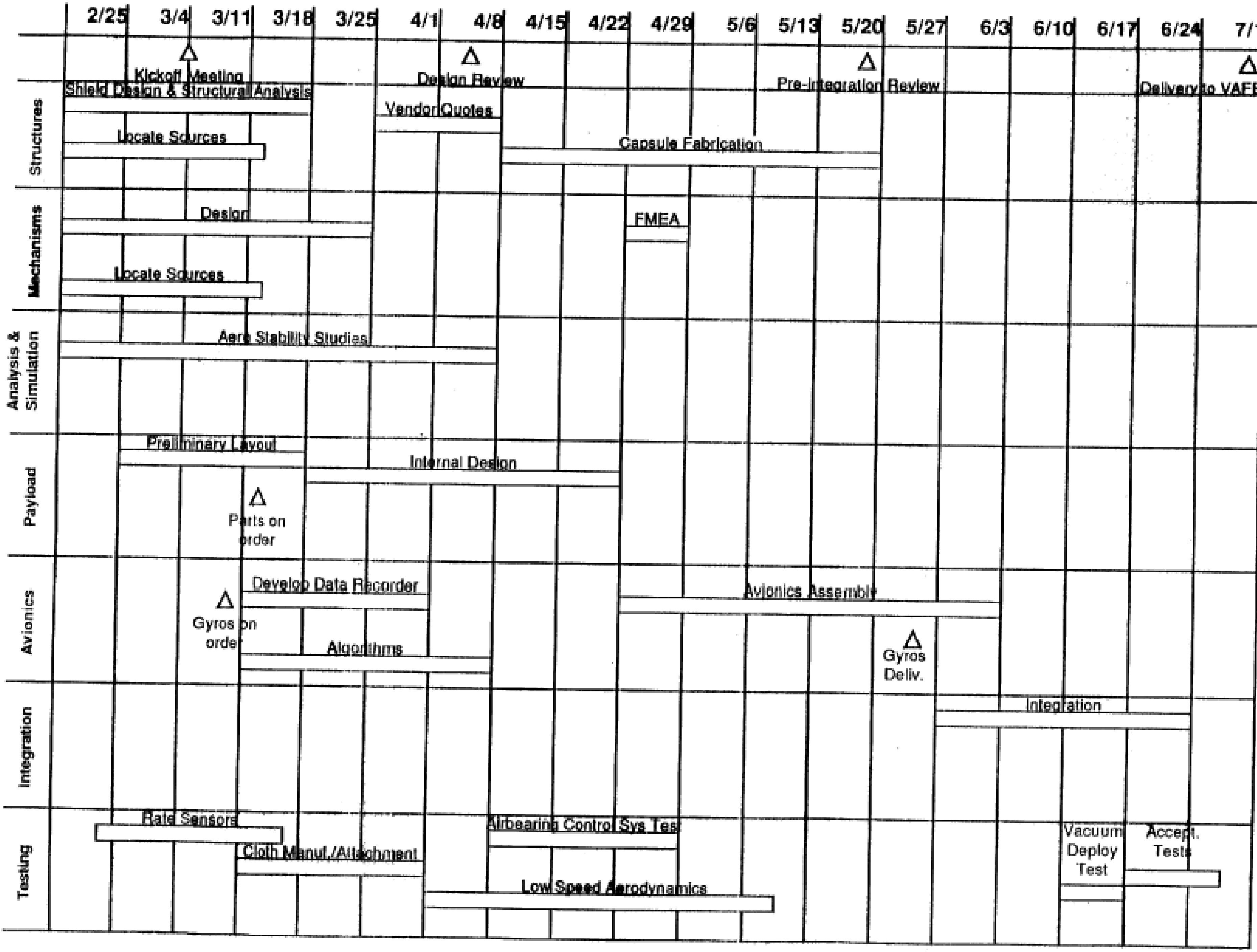
System monitoring until launch

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

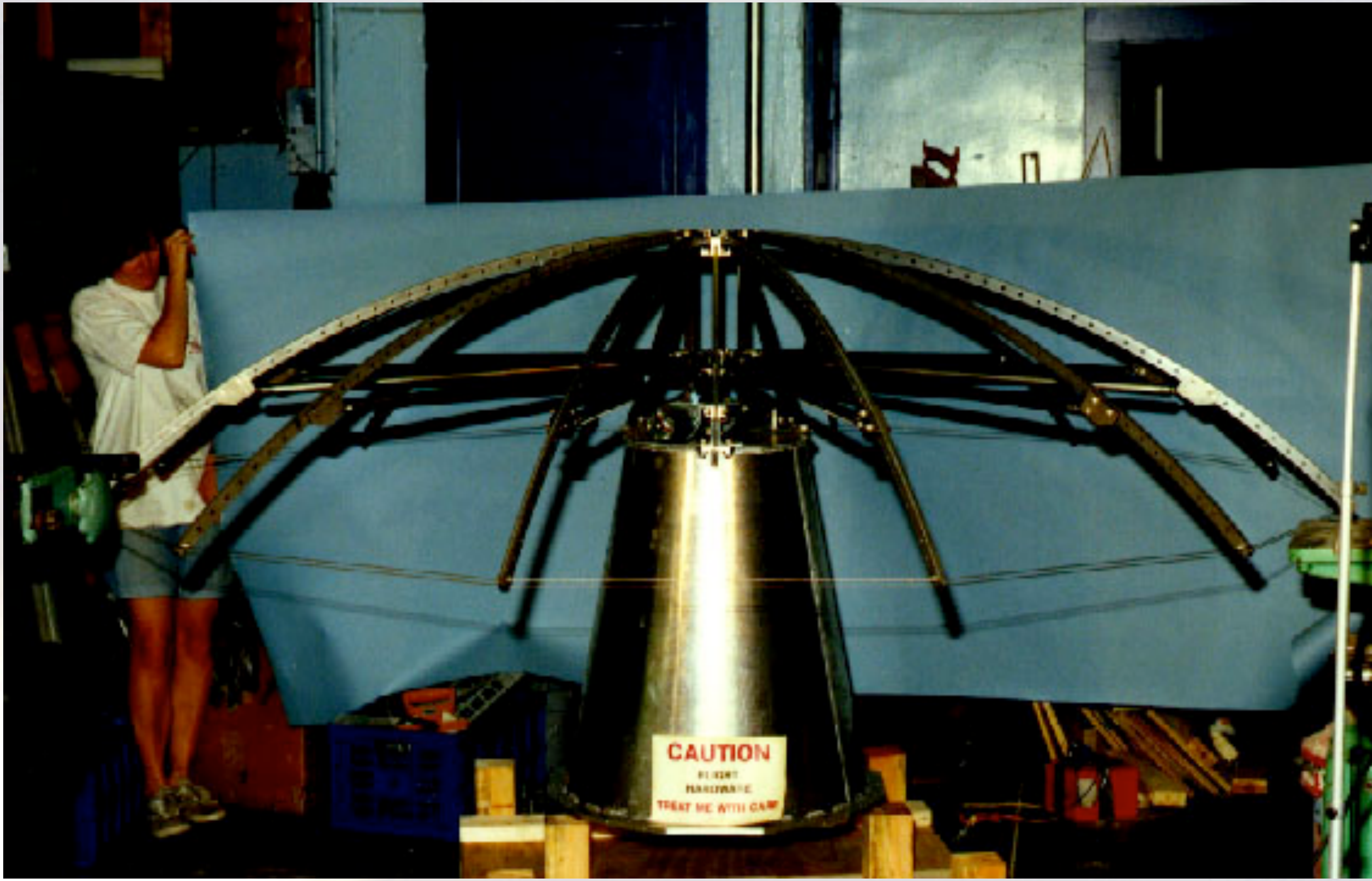


2/25
3/4
3/11
3/18
3/25
4/1
4/8
4/15
4/22
4/29
5/6
5/13
5/20
5/27
6/3
6/10
6/17
6/24
7/1
Kickoff Meeting
Design Review
Pre-Integration Review
Delivery to VAFB
Structures
Shield Design & Structural Analysis
Vendor Quotes
Locate Sources
Capsule Fabrication
Mechanisms
Design
FMEA
Locate Sources
Analysis & Simulation
Aero Stability Studies
Payload
Preliminary Layout
Internal Design
Parts on order
Avionics
Develop Data Recorder
Avionics Assemble
Gyros on order
Algorithms
Gyros Deliv.
Integration
Integration
Testing
Rate Sensors
Airbearing Control Sys Test
Vacuum Deploy Test
Accept. Tests
Cloth Manul./Attachment
Low Speed Aerodynamics

Summary

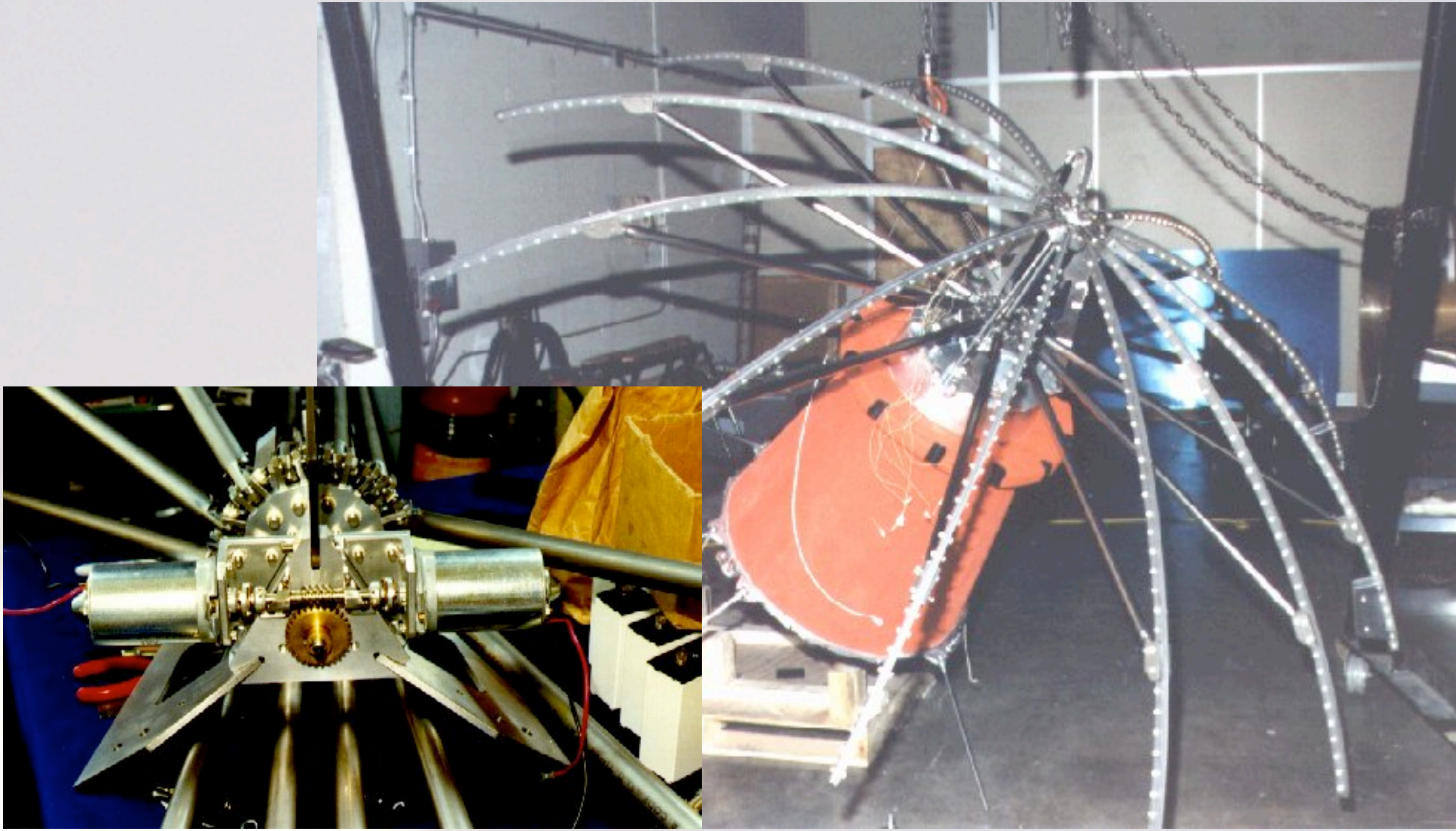
- Designs and analyses complete enough to begin general procurement and fabrication
- Detailed analyses indicate ParaShield concept will meet or exceed original performance expectations
- Resolution of primary interface issues (mechanical and electrical) expected from this trip
- Major remaining concerns 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



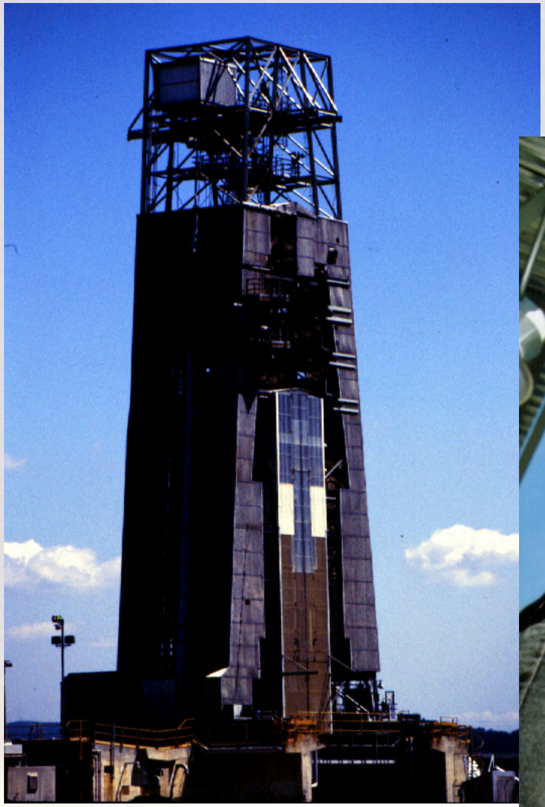
The Skidbladnir Development Team

Shield Structure and Deployment



ParaShield Stowed and Deployed

Launch Vehicle Integration

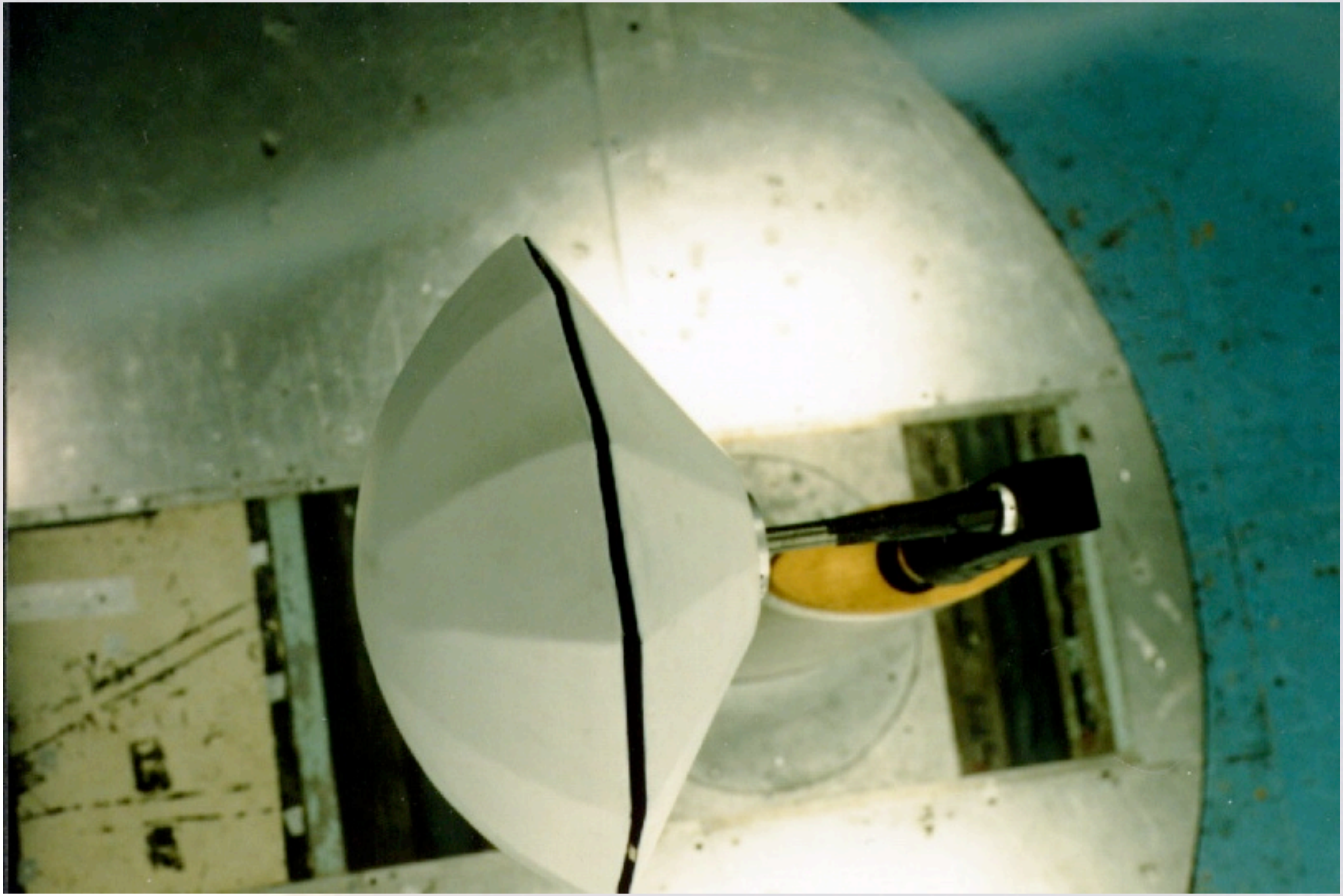


October 5, 1989 - T+2 sec

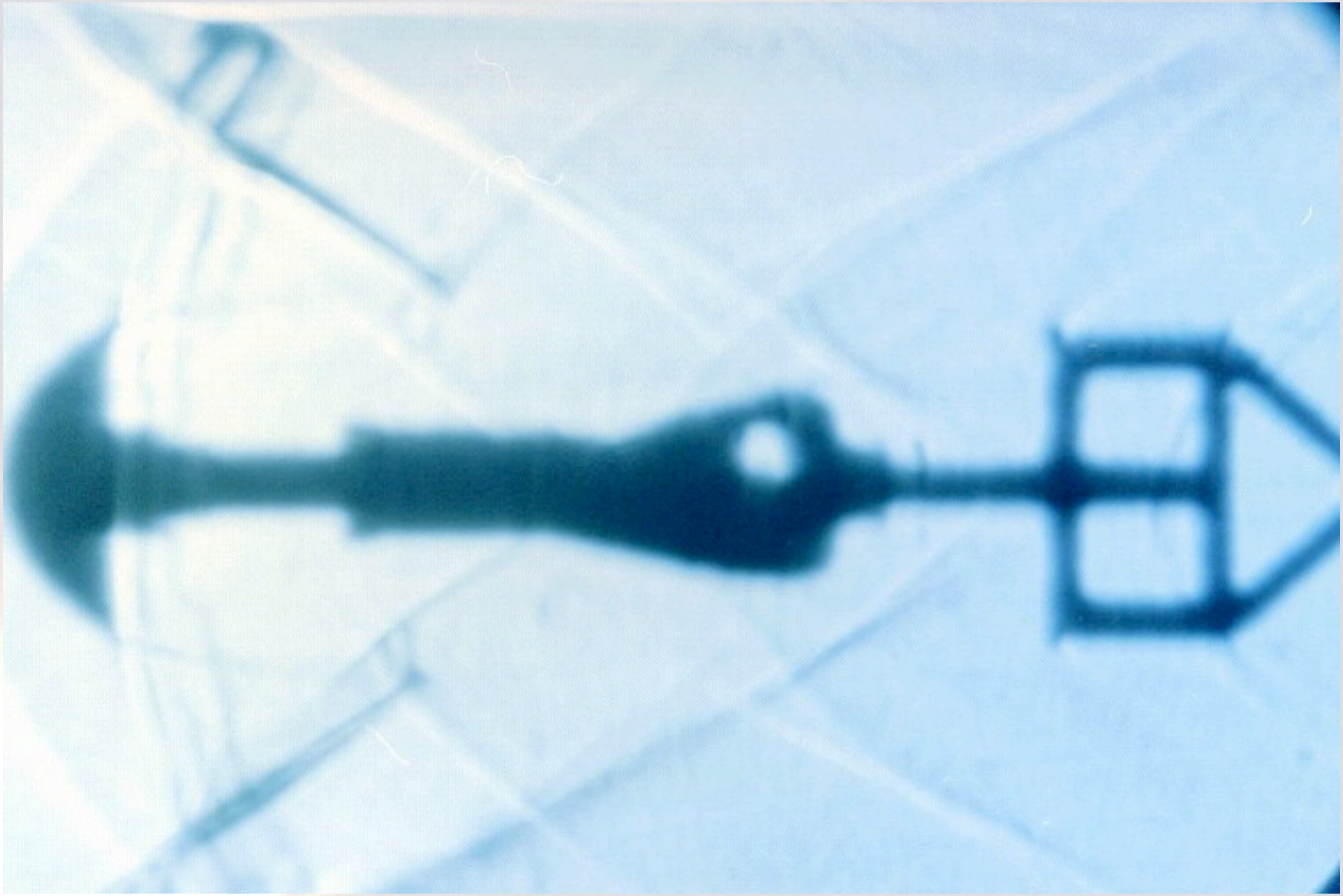
October 5, 1989 - T+60 sec

October 6, 1989 - Aftermath

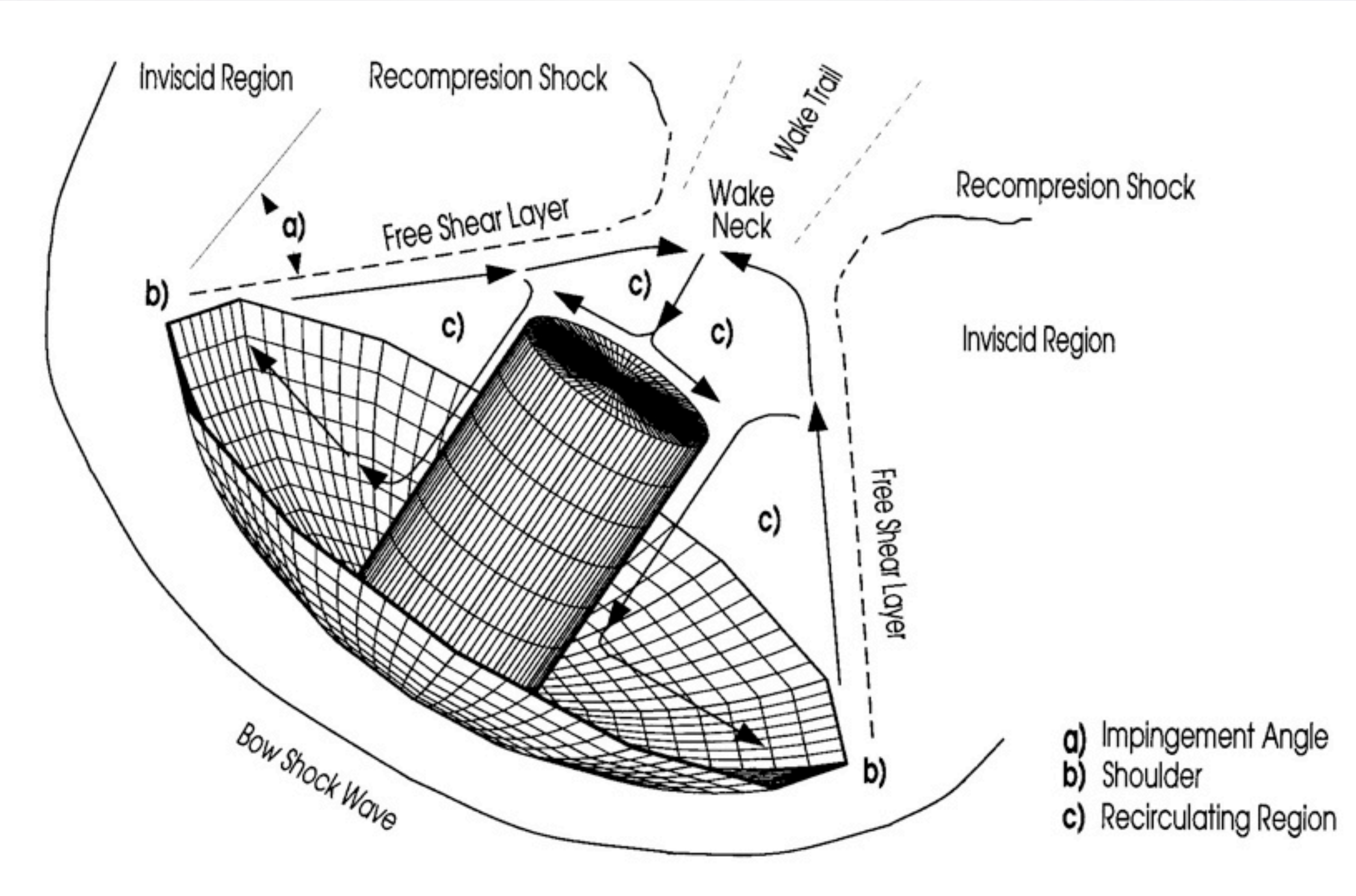
ParaShield in GLM Wind Tunnel



Schlieren Supersonic Flow Visualization

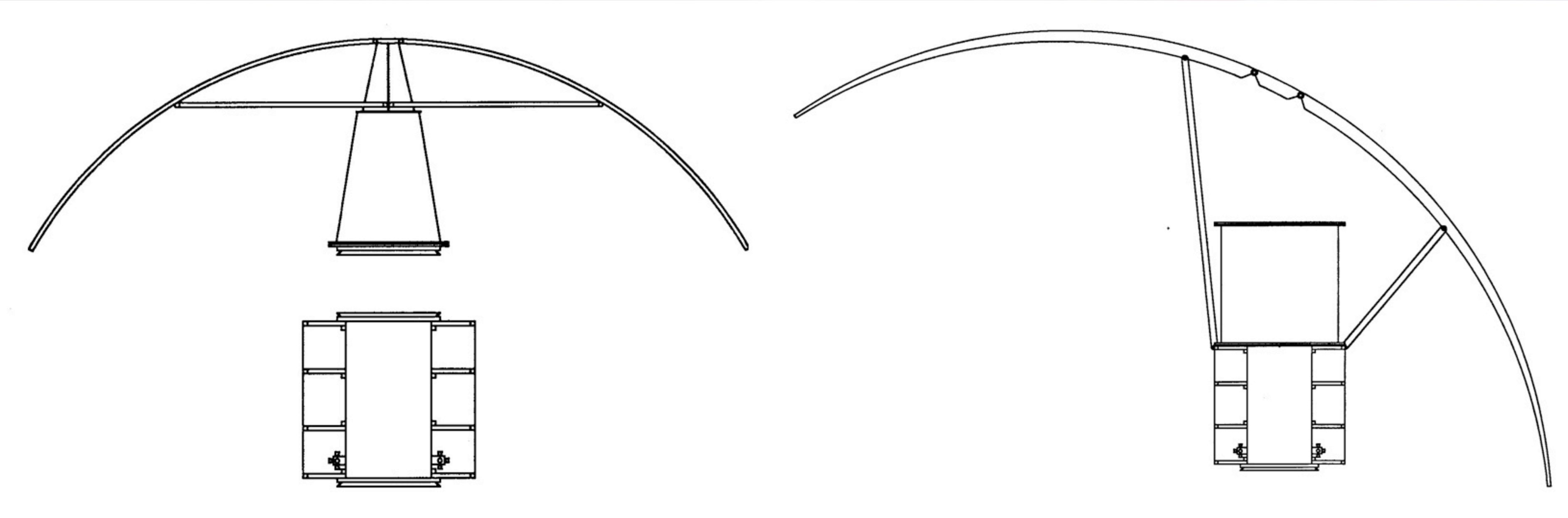


CFD Model

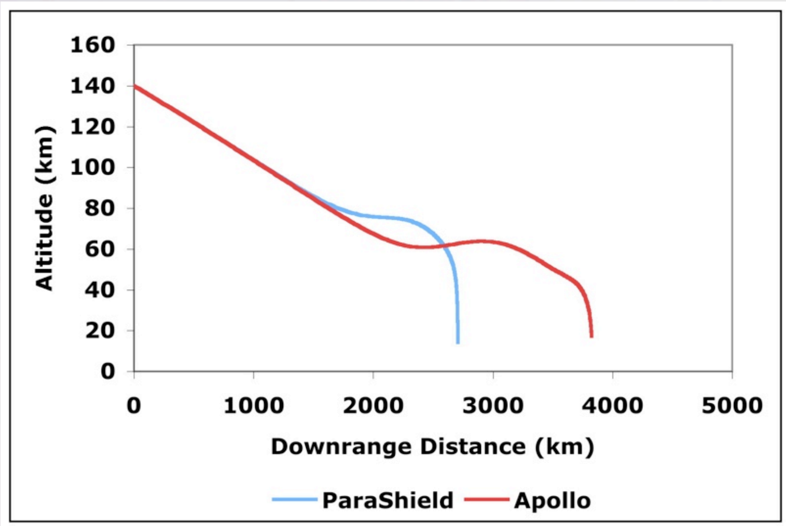


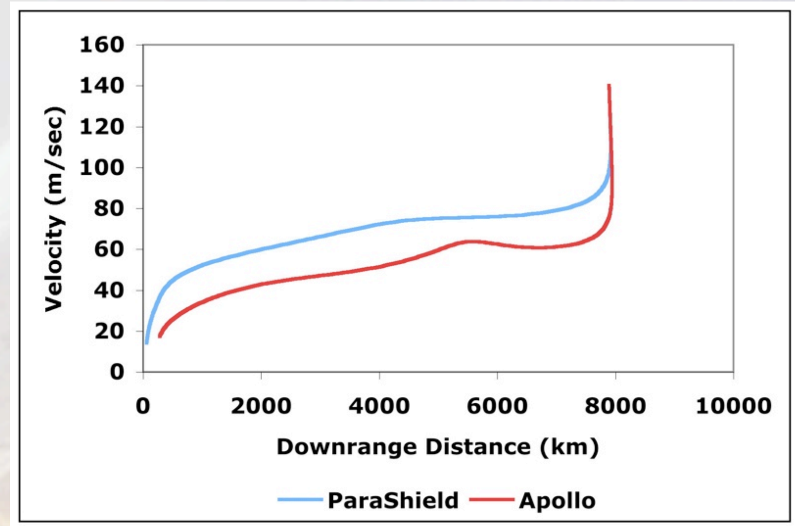
Inviscid Region
Recompresion Shock
Wake Trail
Wake Neck
Recompresion Shock
Free Shear Layer
a)
b)
c)
c)
c)
c)
Inviscid Region
c)
Free Shear Layer
Bow Shock Wave
b)
a) Impingement Angle
b) Shoulder
c) Recirculating Region

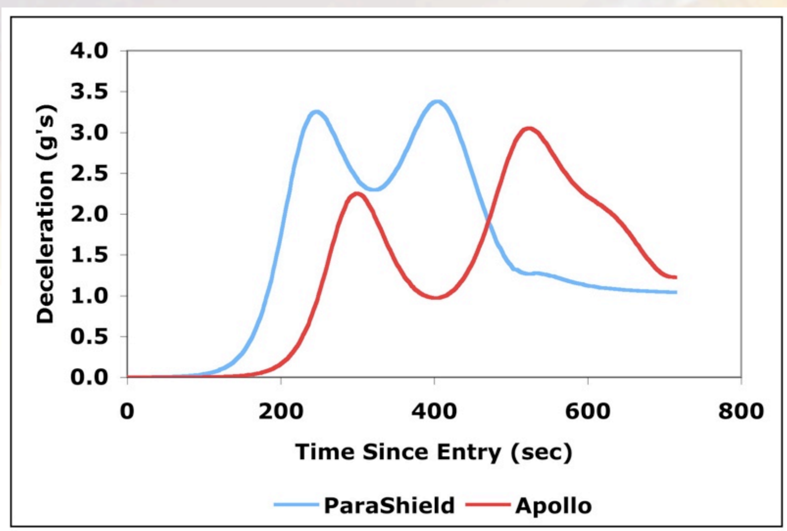
Configurations for Orbital Flight Test

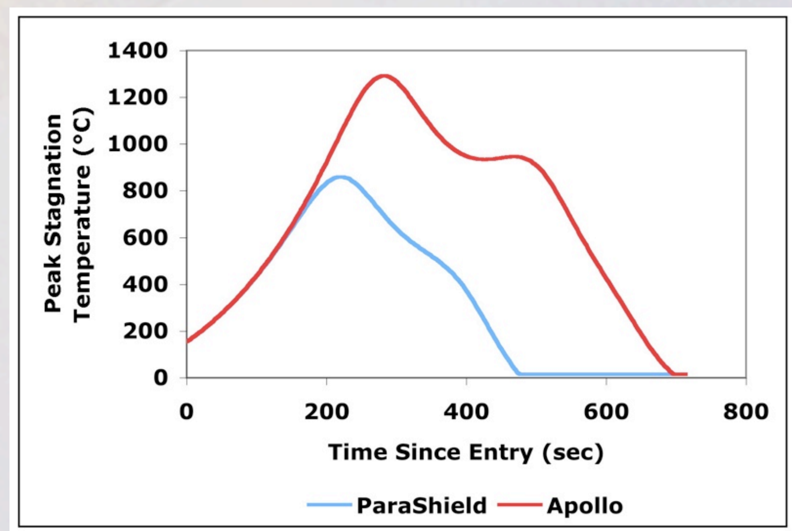


ParaShield for ISS Crew Rotation Mission

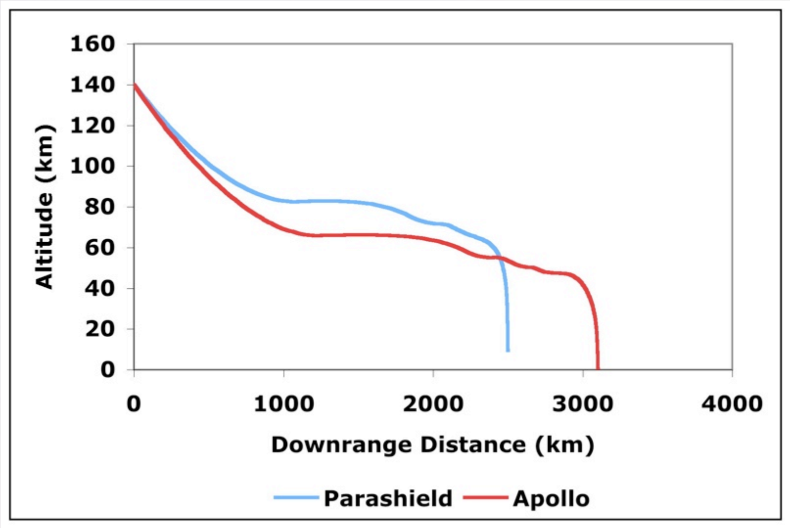


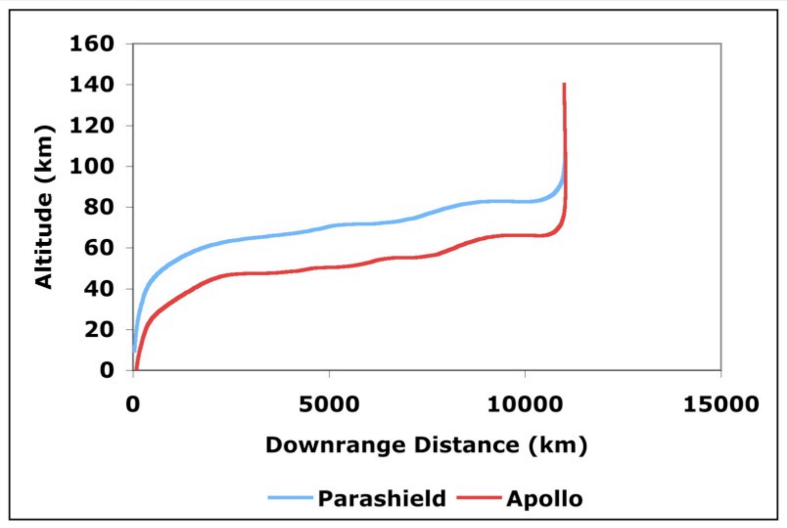


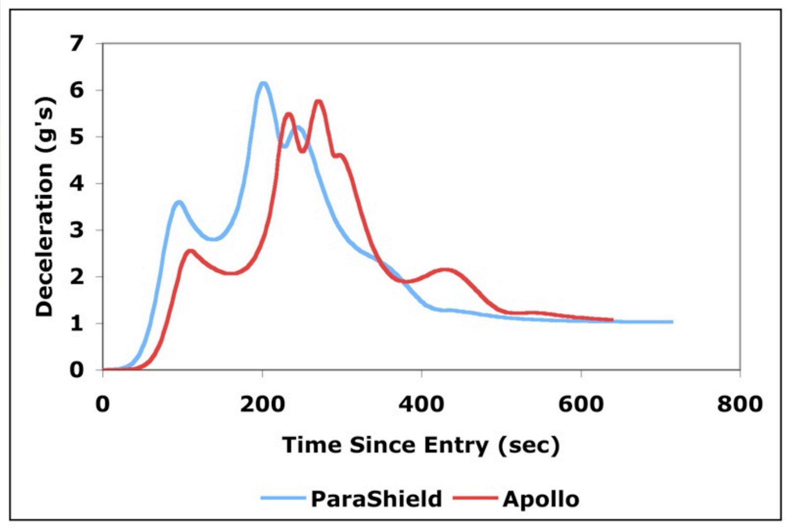


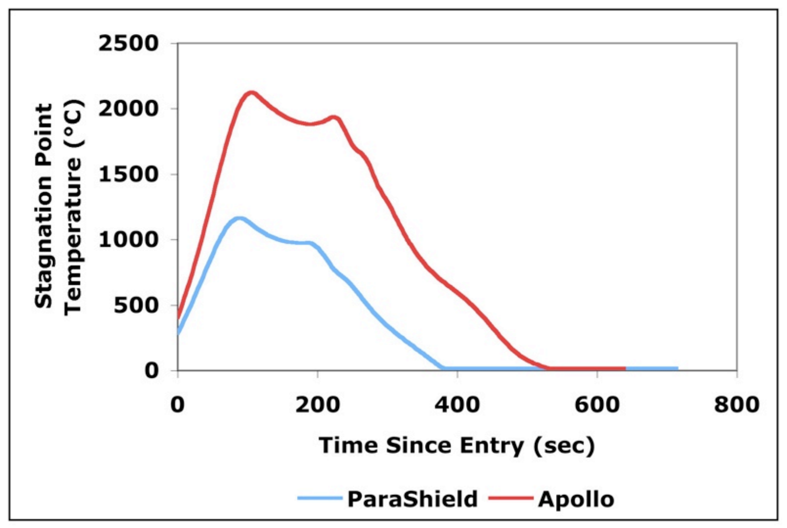


ParaShield for Human Lunar Return

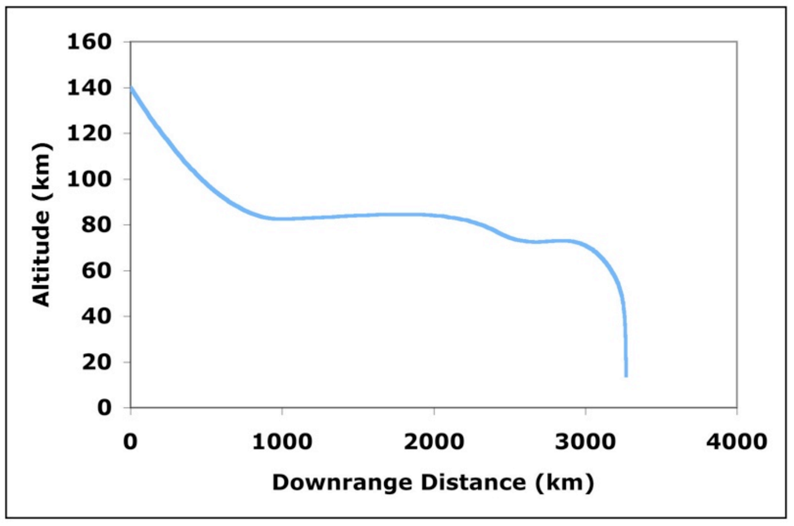


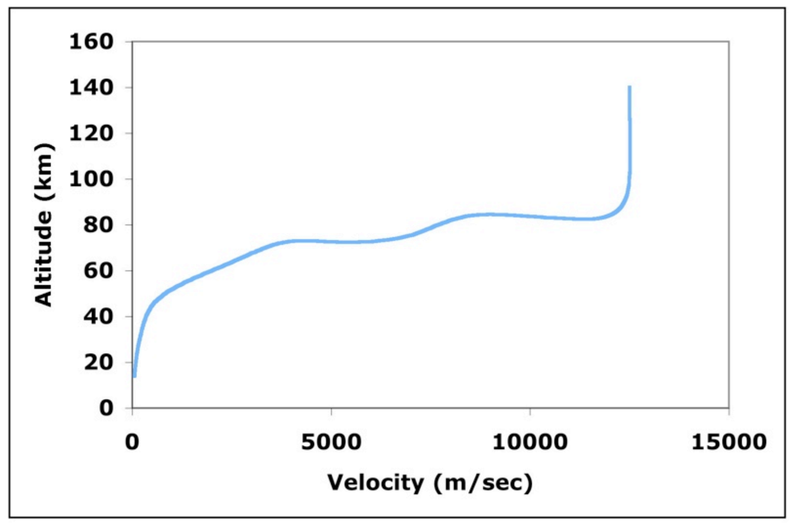


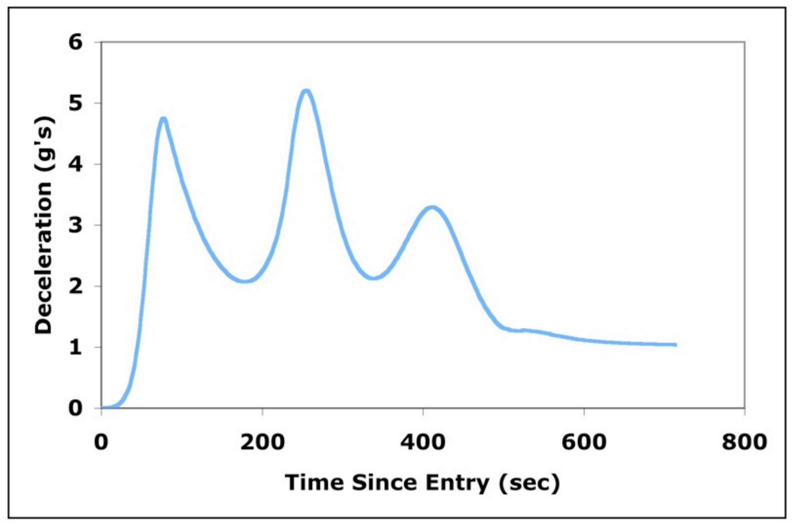


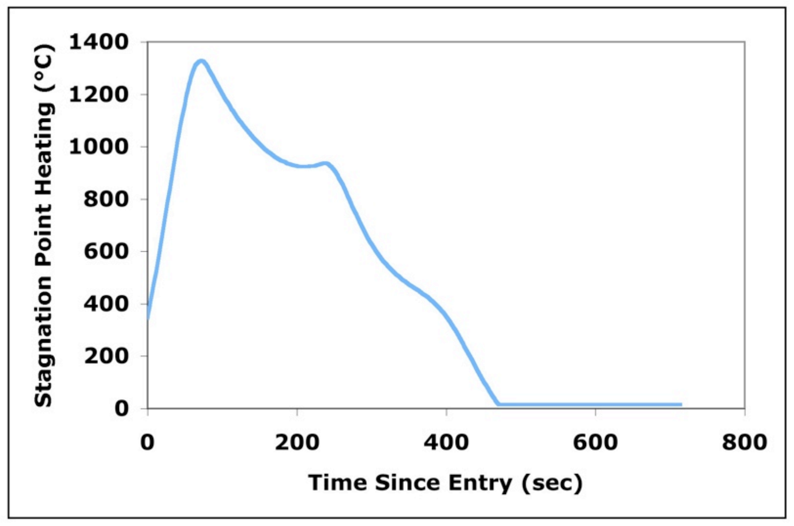


ParaShield for Human Mars Return









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