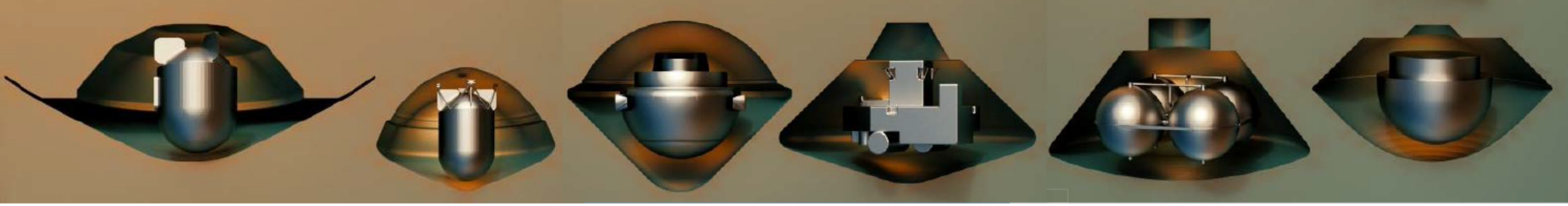
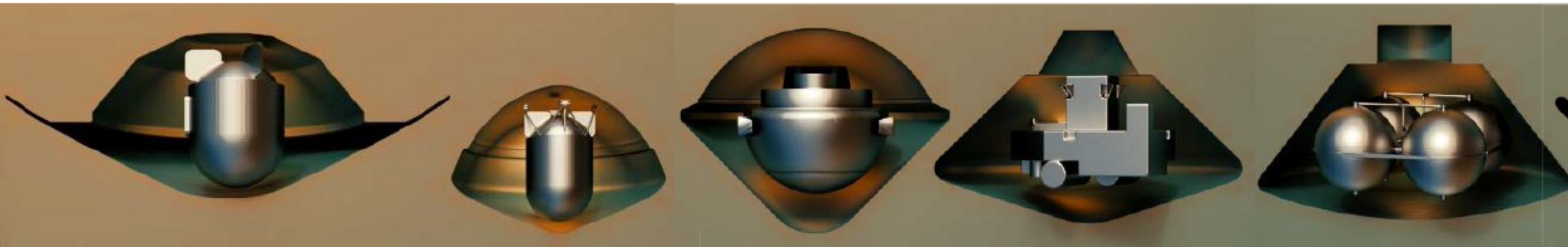


Entry, Descent, and Landing Systems Short Course

Subject: Supersonic Decelerators

Authors: Ian Clark, Mark Adler
Jet Propulsion Laboratory,
California Institute of Technology

International Planetary Probe Workshop 10
June 15-16, 2013, San Jose, California



Overview

- Introduction
- Types and Classification
- Historical Review
- Supersonic Parachutes
- Supersonic Inflatable Aerodynamic Decelerators
- Rigid Deployable Aerodynamic Decelerators

Introduction

- In the beginning, there was drag, and it was good… for a while
- Beginning in late 1950's, early 1960's, a need developed to decelerate at higher altitudes, higher Mach numbers, and higher dynamic pressures than was possible
  - Commonality of supersonic jets, development of sub-orbital and orbital rockets, and development of ICBM payloads introduced need to augment drag at supersonic conditions
- Deployable structures explored as alternative shapes to provide needed deceleration

$$D = \frac{1}{2}\rho V^2 C_D A$$

- Why deployable?
  - Packaging constraints in launch vehicle fairings
  - Aerodynamic shape modification

Classification

Supersonic aerodynamic decelerators generally fall into three primary categories:

- Parachutes
- Inflatable Aerodynamic Decelerators
  - Trailing
  - Attached
- Rigid Deployable Aerodynamic Decelerators

Functions

- Supersonic decelerators typically used to augment drag and bridge deceleration in hypersonic phase (via rigid heatshields) and subsonic terminal decelerators

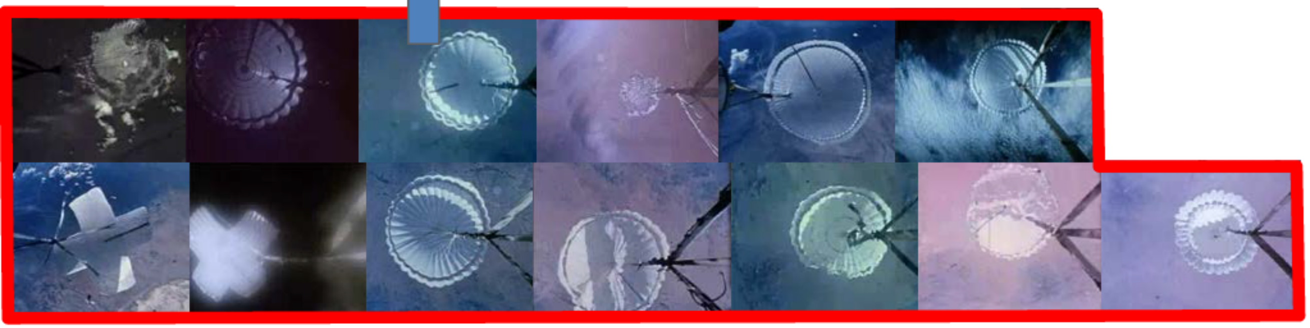
- When used as drag devices, supersonic decelerators primary functions are to
  - Improve payload ratios
  - Improve timeline margins
  - Increase landing altitudes
  - Provide for staging or reconfiguration

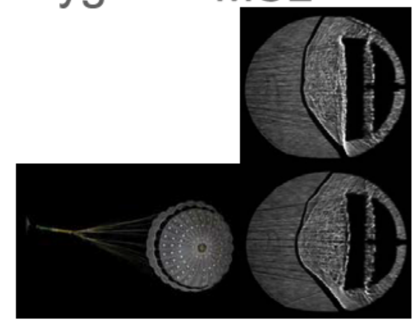
- Additional key functions include
  - Improving stability
    - Trailing decelerators generally damp vehicle oscillations and can mitigate dynamic instabilities
    - Attached decelerators shift vehicle center of pressure further back, improving static stability margin
  - Lift augmentation
    - Attached, rigid or inflatable decelerators can be used to provide additional reference area while maintaining moderate L/D's

Decelerator Historical Development

Viking 1 & 2

Genesis Stardust
Pathfinder Phoenix
MER Huygens MSL

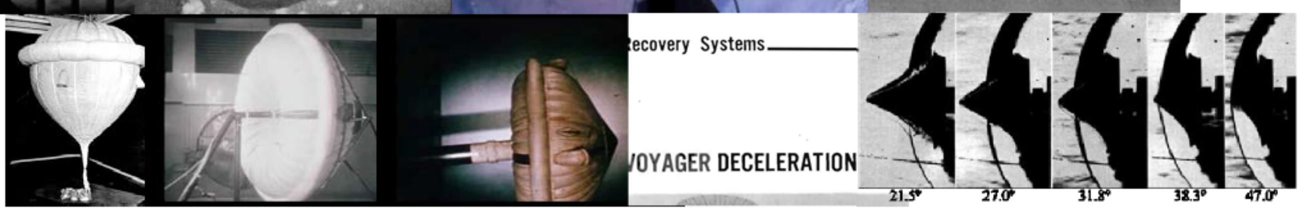


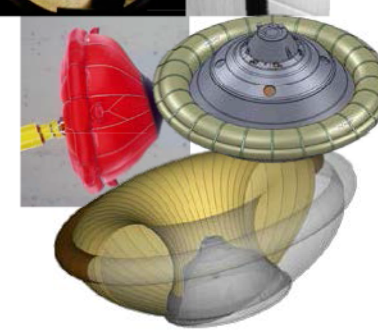


PEPP/SPED/SHAPE/BLDT

1960 | 1970 | 1980 | 1990 | 2000 | 2010

ADDPEP | Viking Develop. | PAIDAE | IRVE/HIAD/LDSD/ADEPT





Gemini Ejection

Met. Rocket

Munitions

Supersonic Parachutes

- Initial development of supersonic decelerators focused on parachutes

- Quickly observed violent fluctuations associated with aerodynamic/structural coupling
  - Supersonic wakes highly unsteady
  - Concave parachute geometry susceptible to pressure variations from unstable detached bow shock

- Subsequent efforts focused on studying effects of geometric porosity (holes/gaps in canopy) and porosity distribution on opening reliability, drag, and canopy stability

- Application generally limited to Mach numbers < ~2.7-3.0
  - Decreasing drag performance with Mach number
  - Increased instabilities with Mach number
  - Aerothermal heating and material limitations with temperature

Source: AIAA 2008-6217

Typical Applications

- Planetary Probes
  - Predominantly used at Mars in moderate Mach number (e.g. < 2.2) and dynamic pressures (< ~800 Pa)

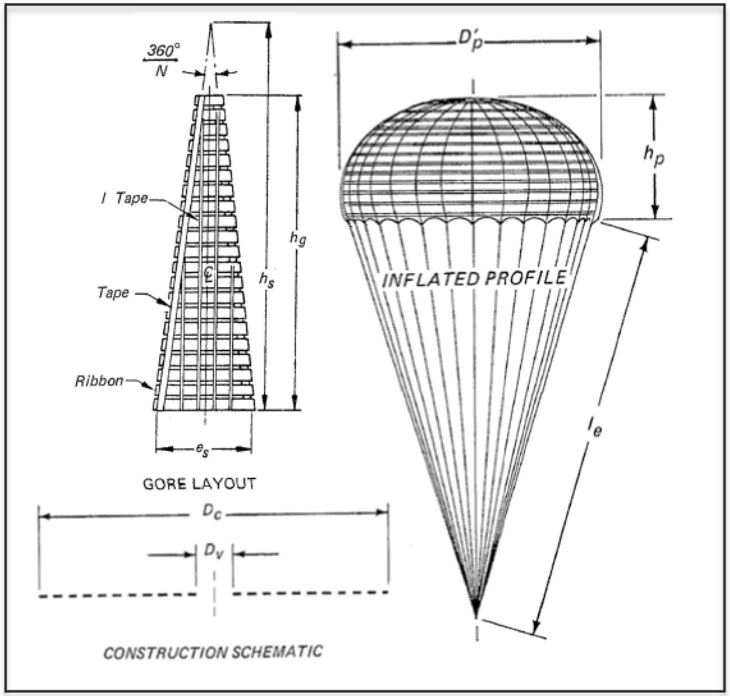
		Parachute		Approx. Deploy Conditions	
Destination	Mission	Configuration	Nom. Diameter D_0 (m)	Mach Number	Dynamic Pressure (Pa)
Mars	Viking 1	Disk-Gap-Band	16.15	1.1	321
	Viking 2	Disk-Gap-Band	16.15	1.1	378
	Pathfinder	Disk-Gap-Band	12.5	1.57	585
	MER Spirit	Disk-Gap-Band	14.1	1.77	725
	MER Opportunity	Disk-Gap-Band	14.1	1.77	750
	Phoenix	Disk-Gap-Band	11.8	1.7	490
	MSL Curiosity	Disk-Gap-Band	21.35	1.75	494
Titan	Huygens (Pilot)	Disk-Gap-Band	2.59	1.49	317
	Huygens (Main)	Disk-Gap-Band	8.31	1.41	289

- Munitions deceleration
  - High dynamic pressure, moderate Mach number
- Ejection seat stabilizers
- Drogues (stability augmentation)

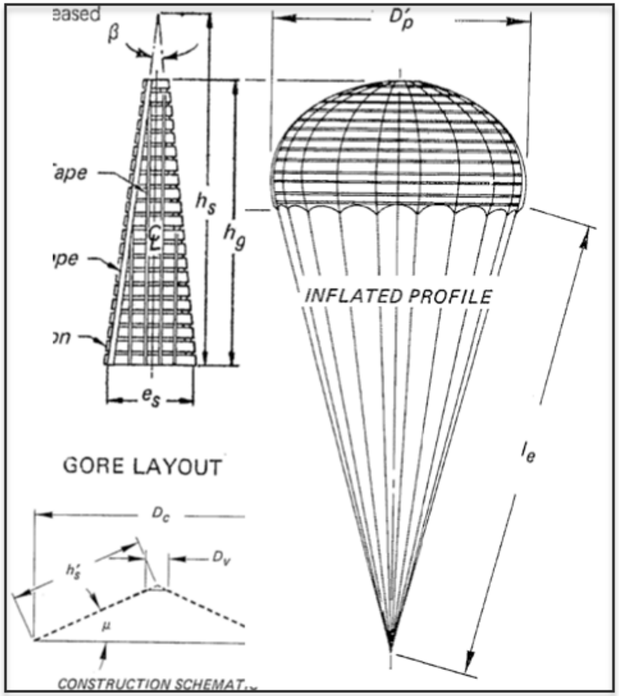
Common Configurations - Ribbon

- Slotted canopy design with good distributed porosity
- Simple construction of overlapping tapes and ribbons allows for durability and use in very high load environments
- Typically good stability but decreased drag vs. other canopy configurations
- Several derivative configurations with different inflated geometries

Flat Ribbon



Conical Ribbon



Hemisflo

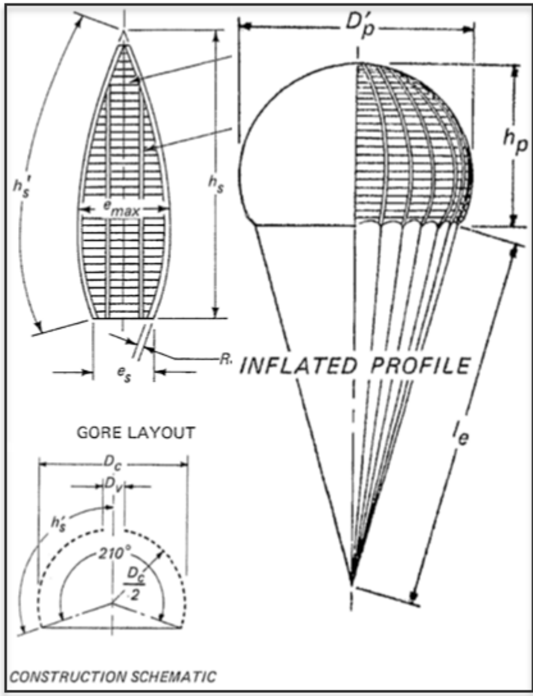
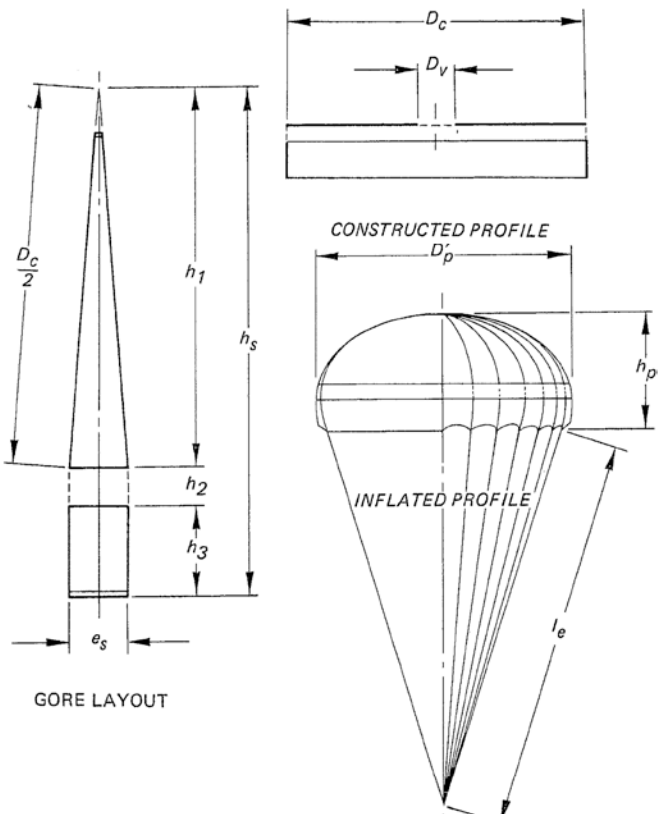


Image Source: AFFDL-TR-78-151

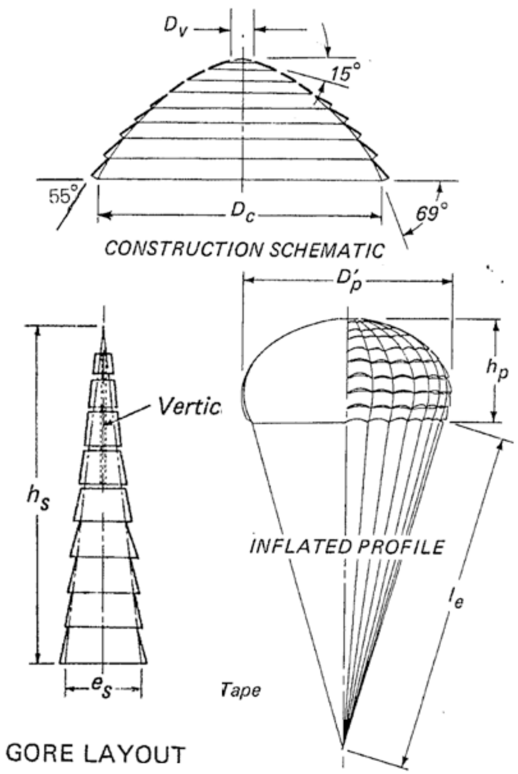
Common Configurations – Disk-Gap-Band

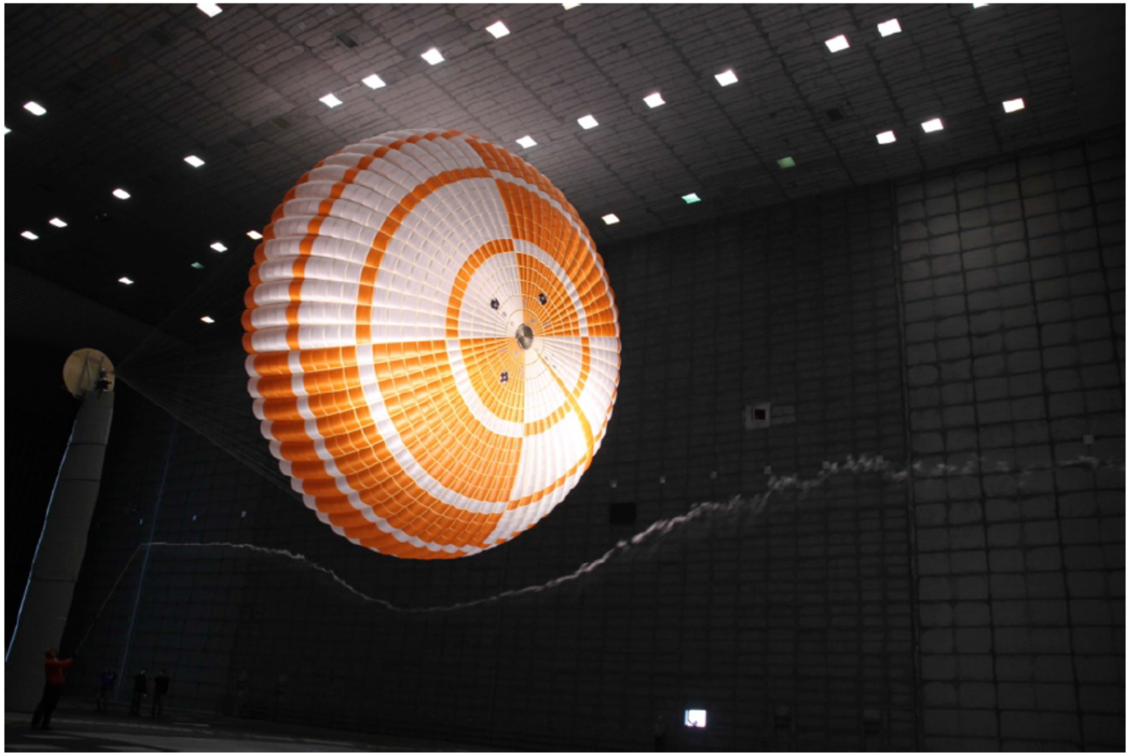
- Simple construction based on a flat disk and band design
- Originally developed as parachute for high-altitude, low-density meteorological soundings
- Has been primary supersonic decelerator for planetary probes since Viking
- Variations have used different length gaps and bands for stability augmentation



Common Configurations – Ringsail

- Construction based on rows of rings and sails (rings with fullness)
- Primarily used as a subsonic parachute, limited testing at supersonic conditions
  - Extensive use in manned space program, primary parachute for Beagle 2 probe
- Require porosity modifications (e.g. gaps) for supersonic and low-density use





Supersonic Parachute Performance

- Usage of supersonic characterized by large fluctuations in shape and drag

Supersonic Parachute Performance

- Usage of supersonic characterized by large fluctuations in shape and drag

BLDT Drag variation with Mach number

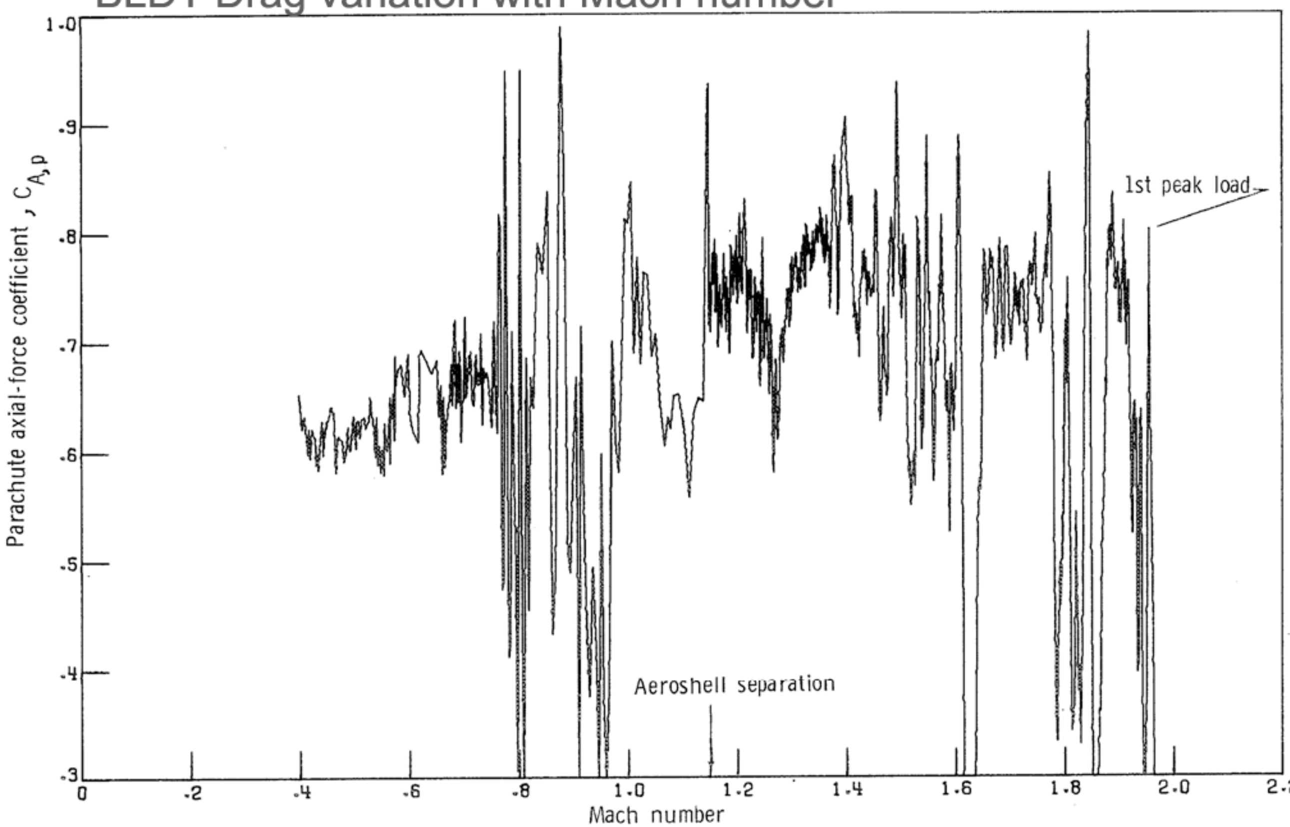


Figure 19.- Variation of AV-4 parachute axial-force coefficient with Mach number from accelerometer data.

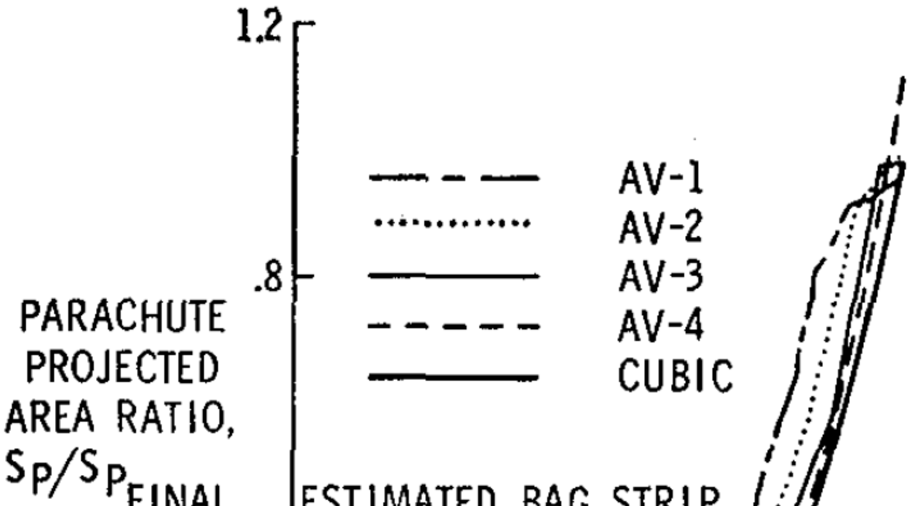
Source: NASA TN D-7734

Supersonic Parachute Performance

- Drag coefficients characterized by decrease with increasing Mach number
- C_D a strong function of geometric porosity, trailing distance, and forebody type (blunt vs. slender)

Increasing Mach Number	Decreased drag, increased areal oscillations
Increasing Geometric Porosity	Decreased drag, improved stability
Forebody Diameter	Decreased drag with blunt forebodies
Increasing Trailing Distance	Increased drag and stability

Characteristic DGB drag curve



Source: AIAA 1973-457

Inflatable Aerodynamic Decelerators

Overview

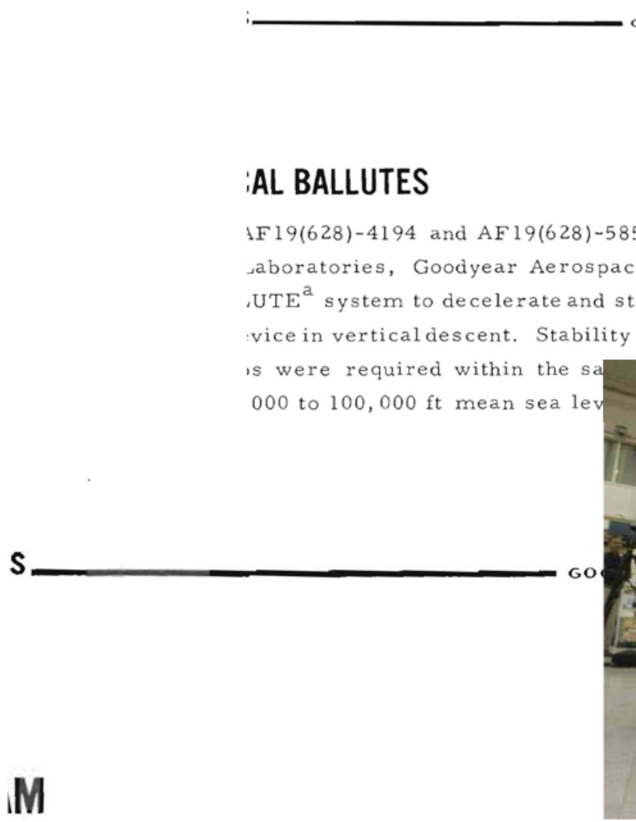
- Shape maintained by a (mostly) closed, pressurized body
- Often termed “ballutes” in the literature

Primary Functions

- Drag or aerodynamic augmentation
- Stability

Taxonomy

- Entry (hypersonic) vs. Supersonic
- Trailing vs. Attached



AL BALLUTES

AF19(628)-4194 and AF19(628)-585
aboratories, Goodyear Aerospace
UTE[a] system to decelerate and sta
vice in vertical descent. Stability
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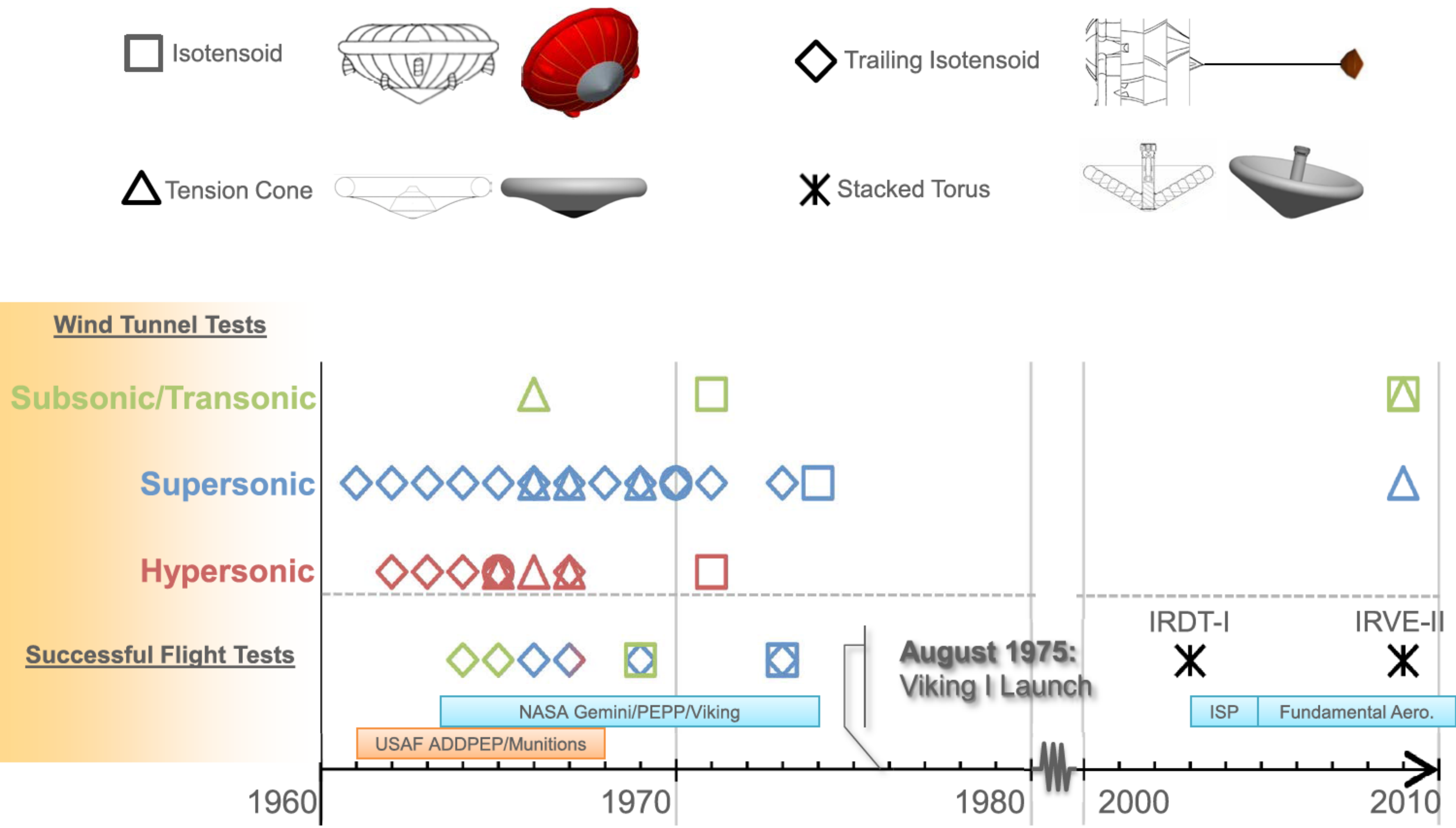
000 to 100,000 ft mean sea lev

S

M

IAD Development History



SIAD Overview

- Deployed intra-atmospherically, generally after peak heating and deceleration has occurred
  - Typical application is to provide drag augmentation earlier in the trajectory for staging to another decelerator (parachute) or terminal descent system

- Rapidly deployed and inflated using either on-board pressurization system or ram-air inlets, or both

- Environments governed by moderate to low heating (~ 1- 5 W/cm^2) and rapid deployment

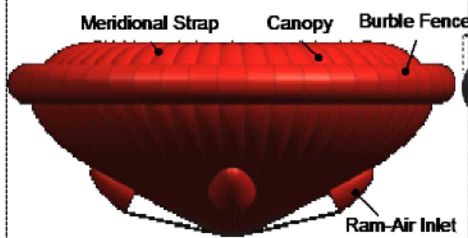
- Generally fabricated from woven or braided materials (e.g. Vectran, Kevlar, and Technora)

Foremost SIAD Configurations

Graphic source:
NASA TM X-1773

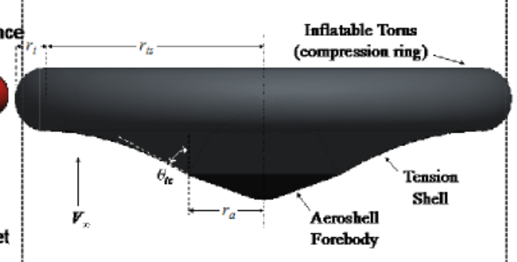
Trailing Isotensoid

- "Isotensoid" refers to structural theory by which shape is derived
- Often called a "Ballute" in the literature
- Inflated through ram-air inlets
- Vast majority of documented test data is for this IAD configuration



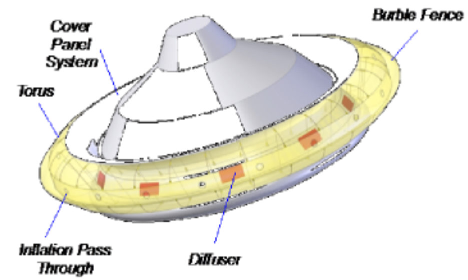
Attached Isotensoid

- Extends isotensoid theory to attached configurations
- Motivated by mass reduction and improved aerodynamic drag performance
- Subsonic tests up to 11 m in diameter



Tension Cone

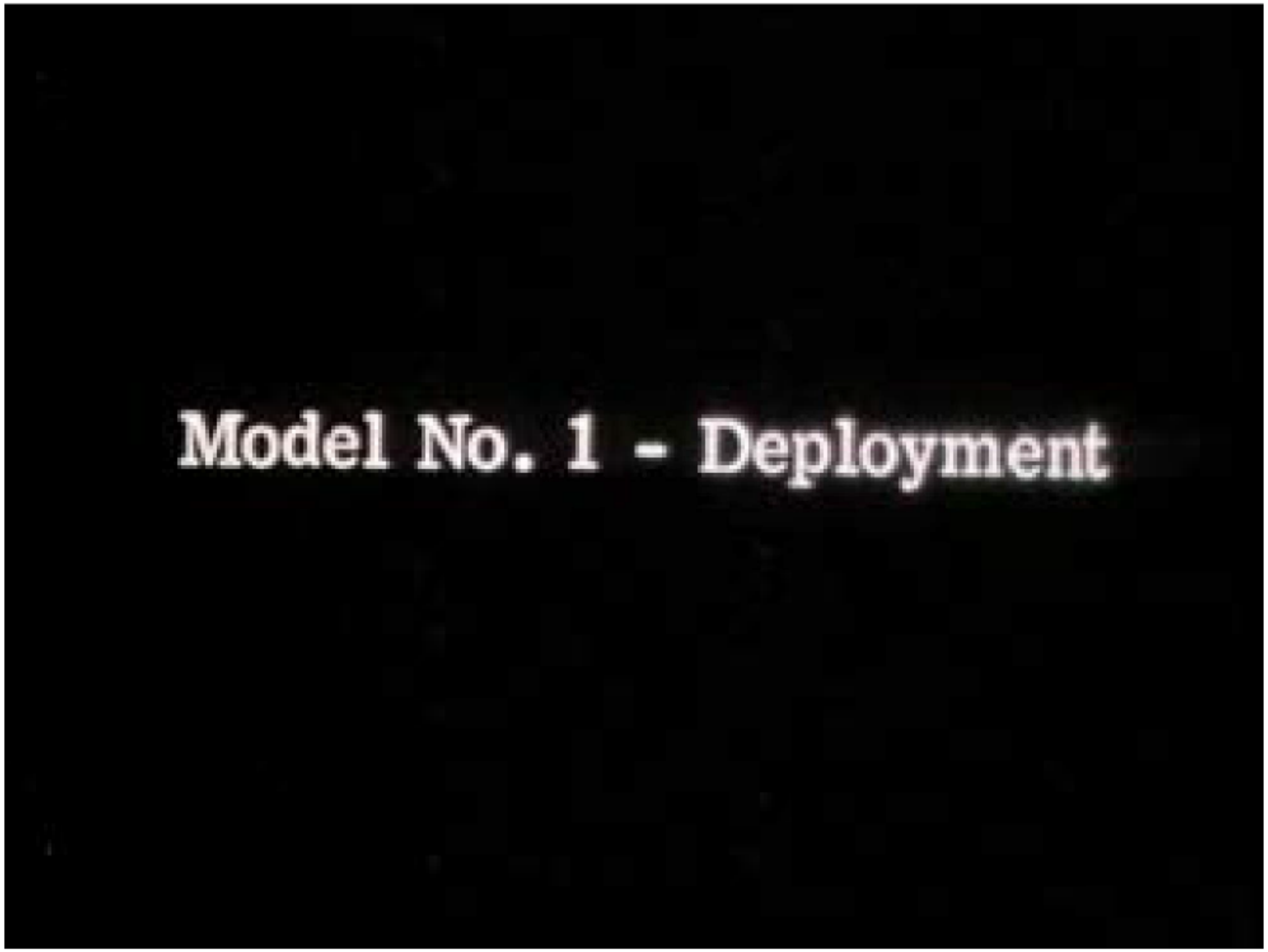
- Shell of revolution with only tensile stresses under axisymmetric aerodynamic loading
- Inflated compression ring holds tension shell shape



Attached Torus

- Single torus integrated with the entry vehicle
- Presence of burble fence improves aerodynamic stability

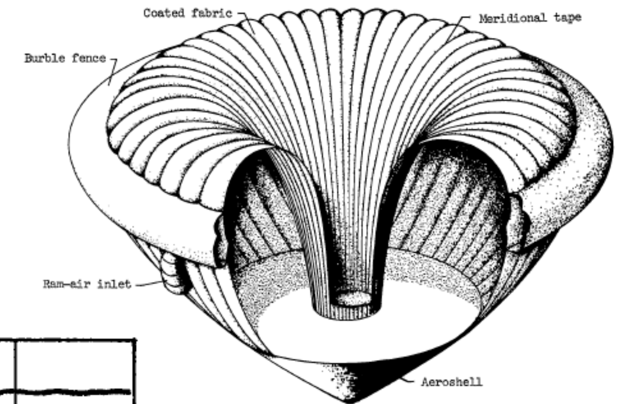
Attached Isotensoid Deployment

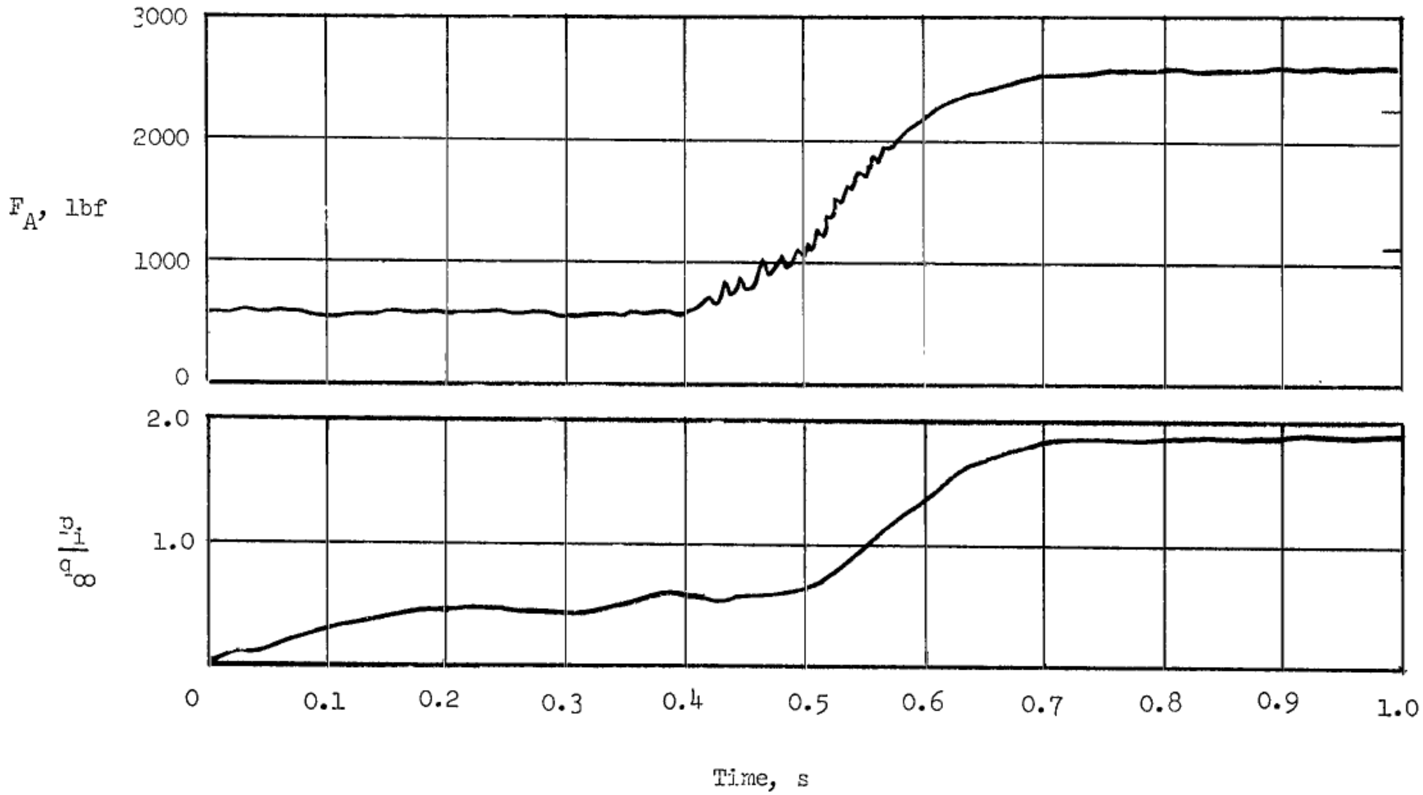


Deployment and Inflation

Mach 3.0

q_∞: 5.6 kPa





Source:
NASA TN D-5840

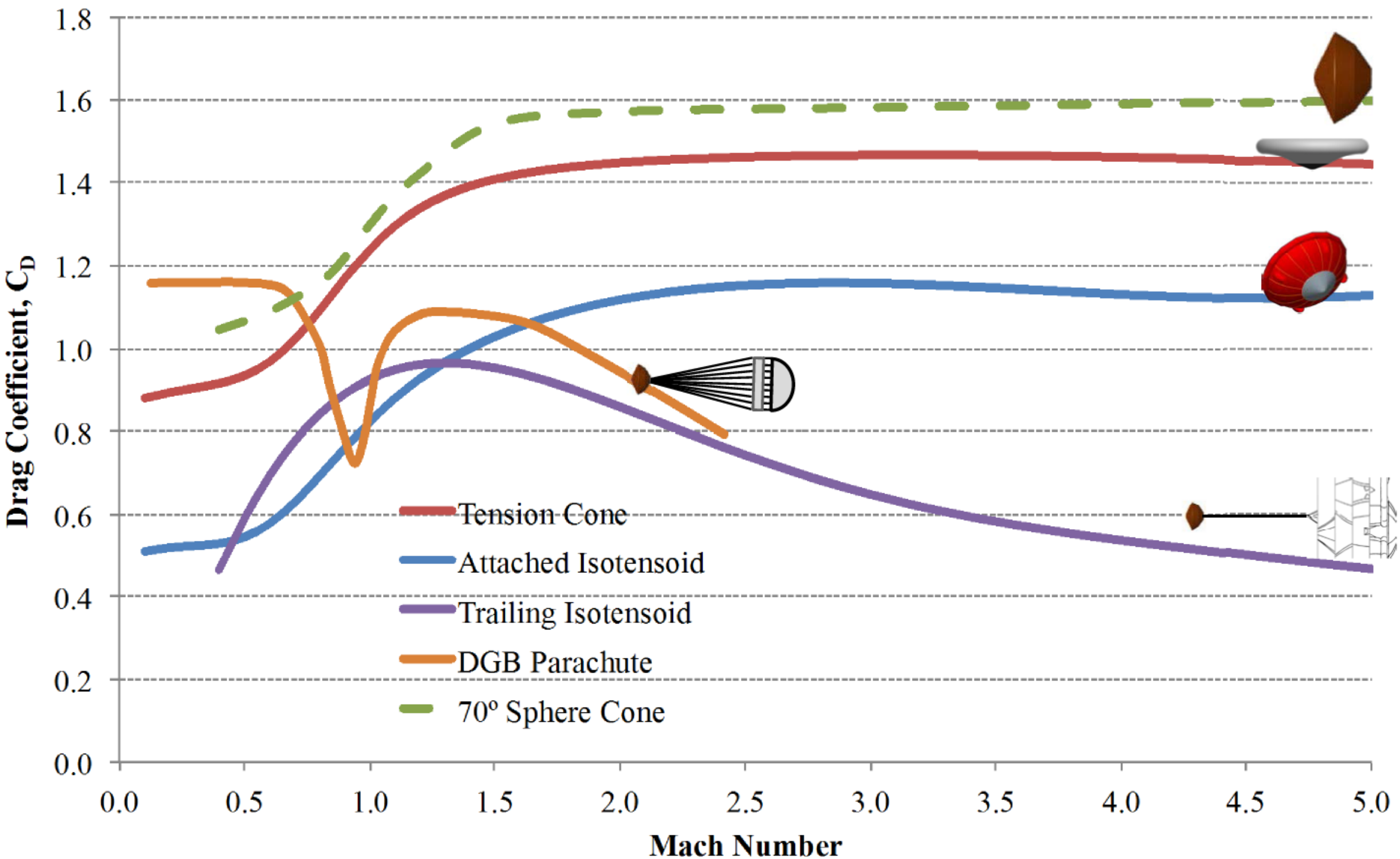
Trailing Isotensoid Deployment

Attached Torus Deployment

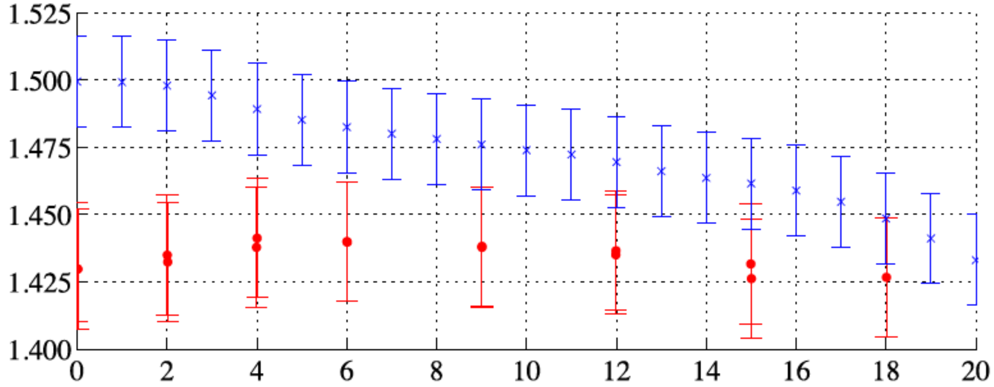
Aerodynamic Performance

- The aerodynamic performance (drag and stability) of attached SIADs is generally similar to that of a rigid blunt body
- Complexities arise as configurations grow larger or move from more rigid to more flexible geometries
  - More flexible => typically reduced static stability

Drag Comparison

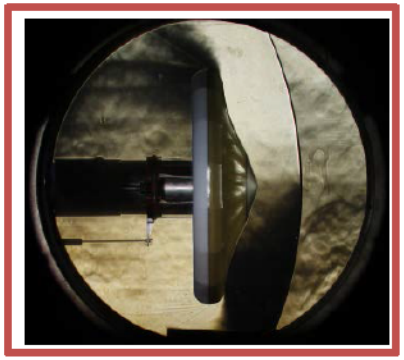


Drag & Stability (Tension Cone)



Mach 2.5
Re ~10^6

Rigid Model:
Metallic
Force & Moment



Semi-Rigid Model:
Textile Membrane
Rigid Torus

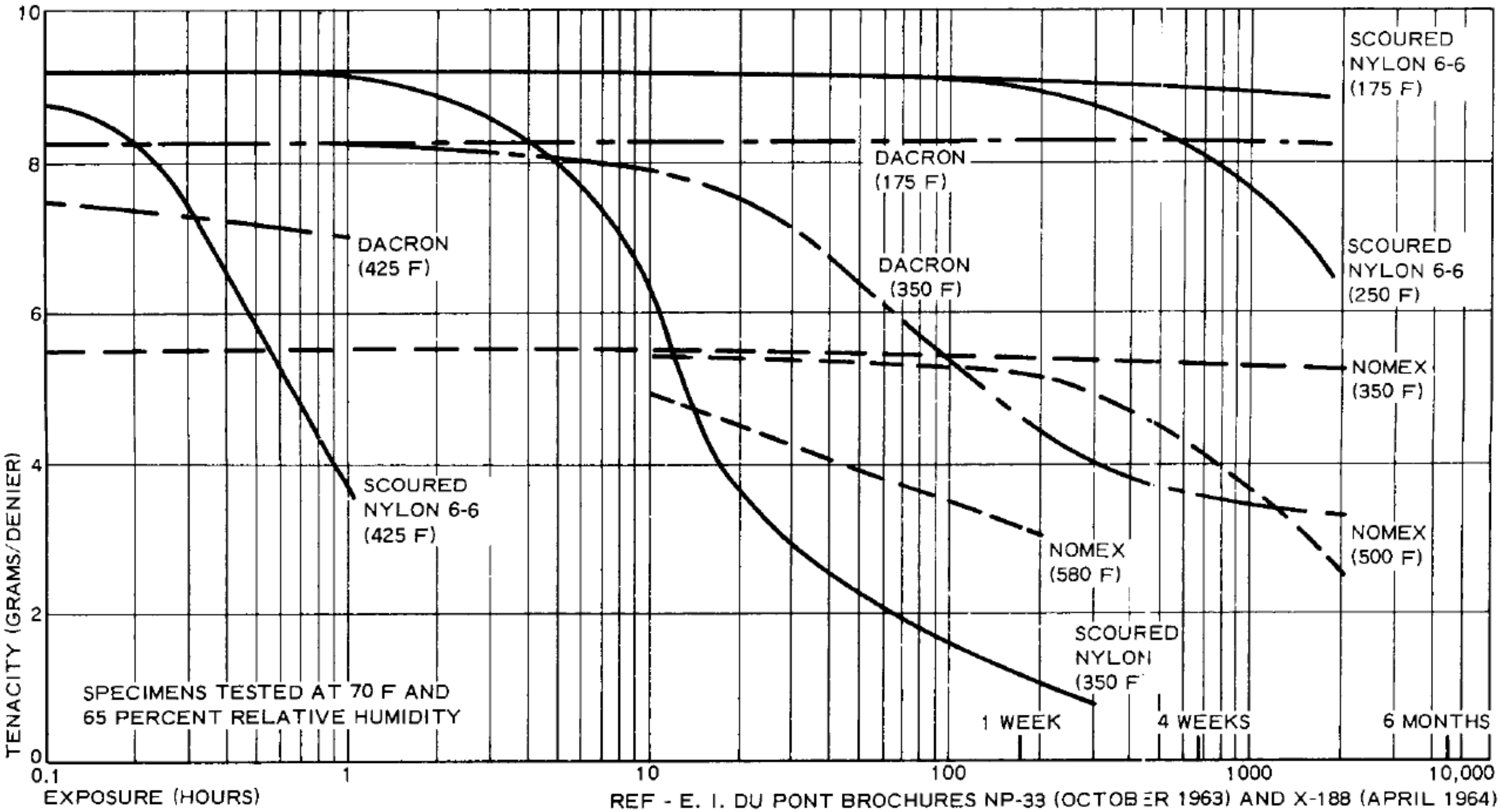
Materials

- SIADs traditionally fabricated from woven softgood materials
  - e.g. Nomex, Kevlar, Vectran

- Material performance characteristics of interest include
  - Strength: typically driven by inflation pressure stresses of article
  - Thermal performance: Small, O(1 W/cm^2), heating can still lead to temperatures of 300 ºC or above
  - Fatigue behavior: stowage and deployment exposes material to concerns regarding flex-cracking

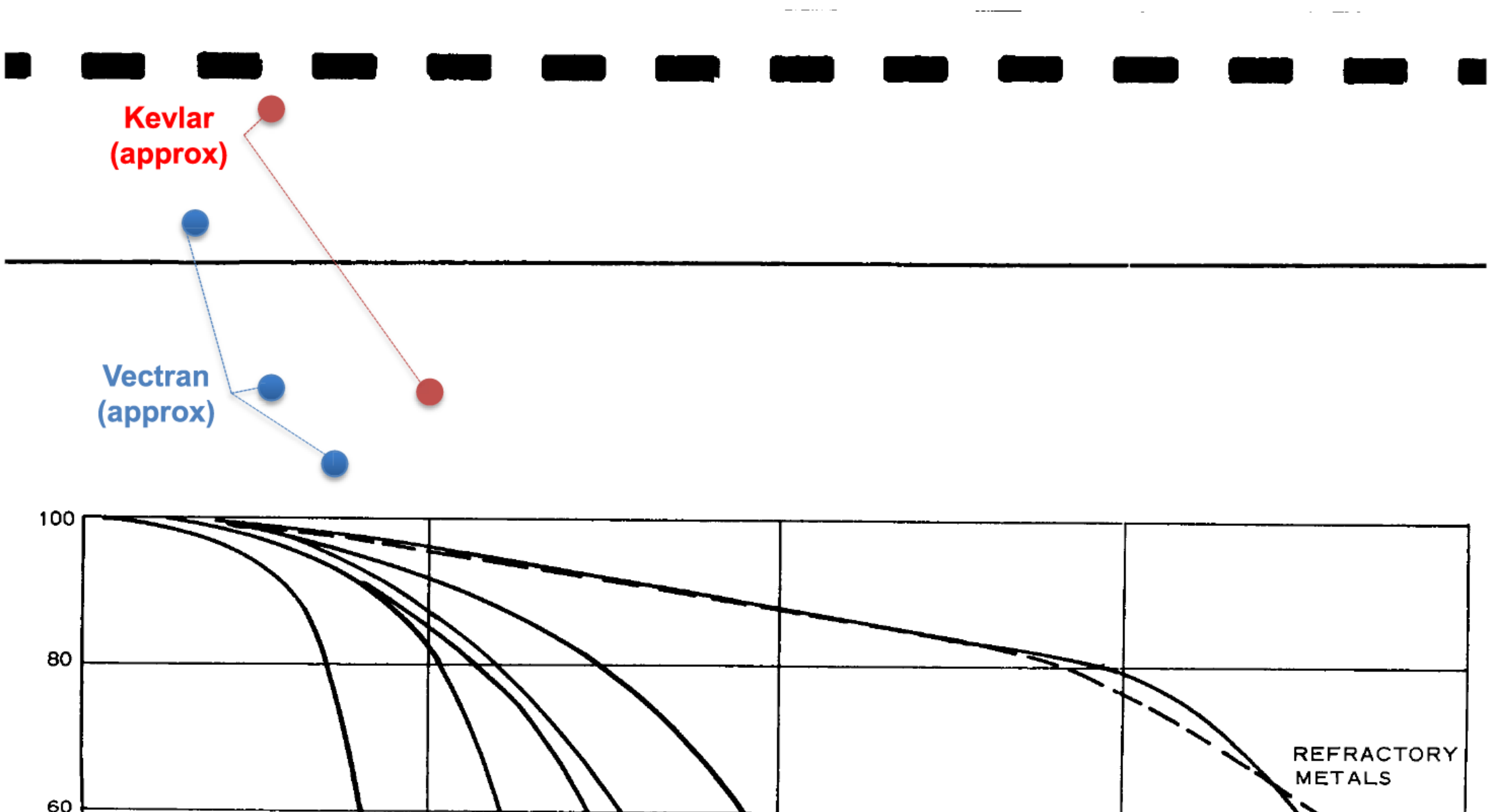
- SIAD softgoods often coated to reduce material permeability or provide better thermal performance
  - e.g. Silicone, Urethane, or more exotic coatings like Dynatherm

Materials: Thermal Performance



Source: NASA CR-79496 (GER-12842)

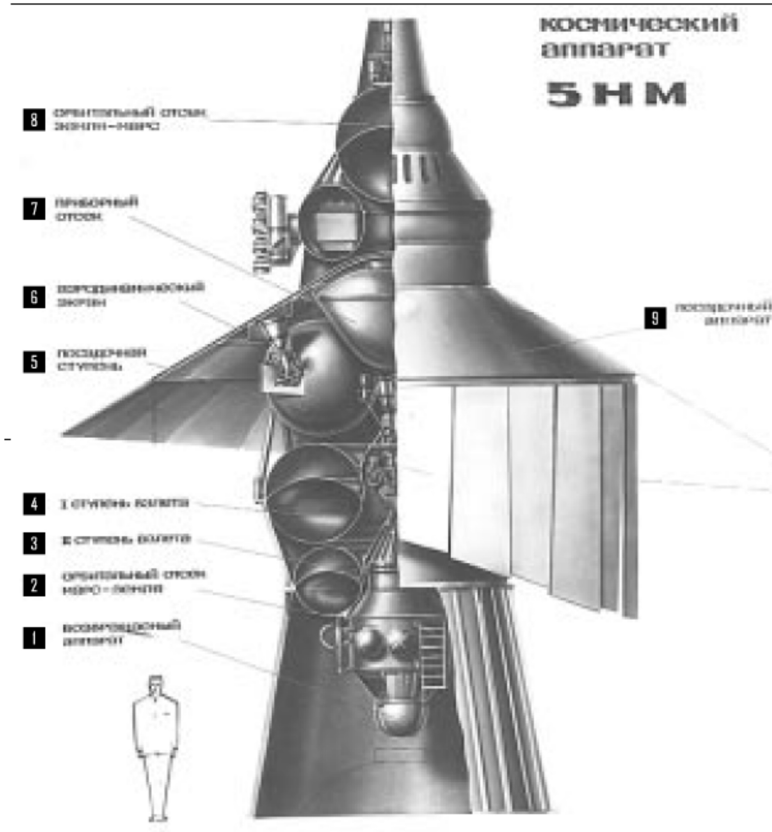
Materials: Thermal Performance



Source: NASA CR-79496 (GER-12842)

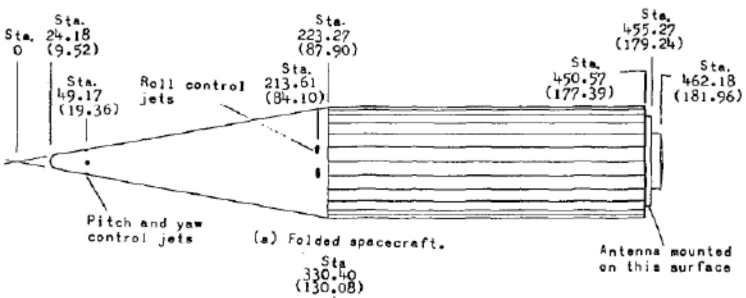
Rigid Deployable Decelerators

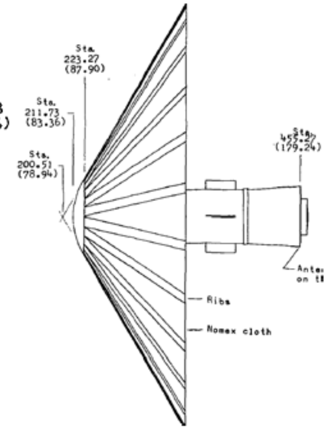
- Concepts branch across flight regimes (supersonic and hypersonic)
- Historically are thought to be more massive than inflatable decelerators
  - Limited data of relevant configurations to compare against
- In theory, provides much better scaling and ease of development



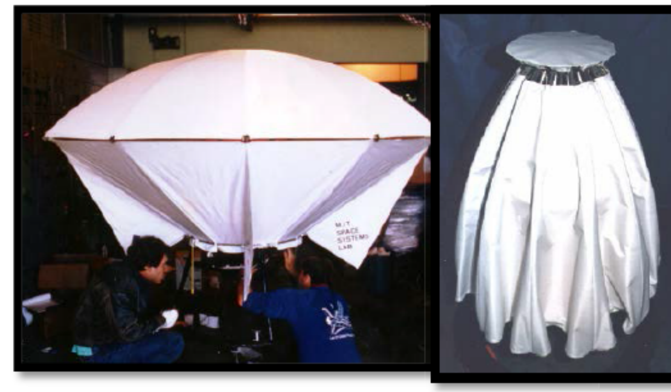
Source: NASA NP-1999-06-251-HQ

Often Proposed, Seldom Implemented

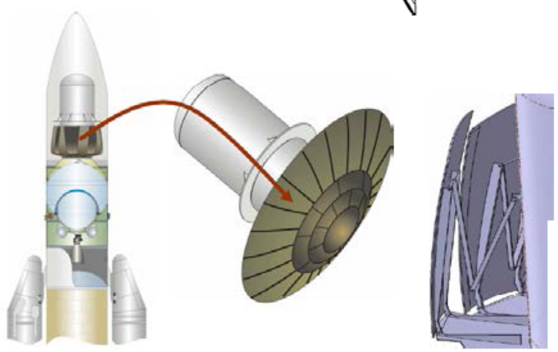




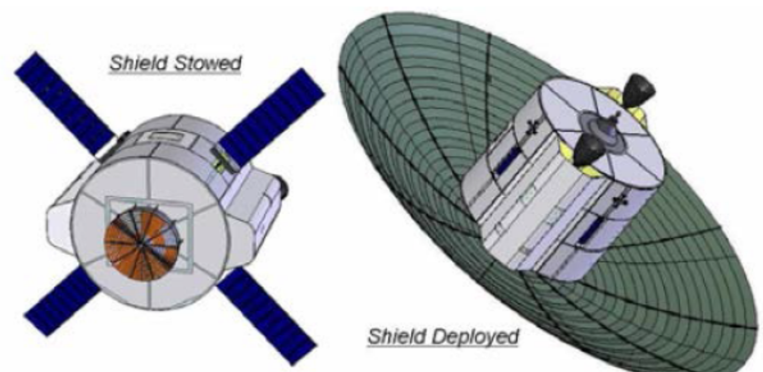
SPED, NASA LaRC, 1972



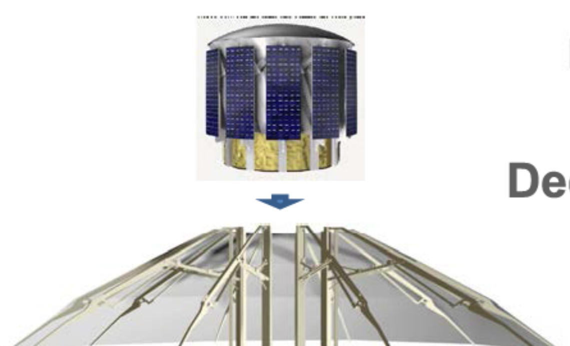
Parashield, MIT 1988



Deployable CMC Decelerator, Astrium, AIAA ADS 2003



Phoenix, U. Maryland, IAC 2006



BREM-SAT 2, U. Bremen, AIAA Small Sat 1996

Questions