Looking Up: An SMD Technology Brown Bag Series

"The Adaptable, Deployable Entry and Placement Technology (ADEPT)"

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Outline

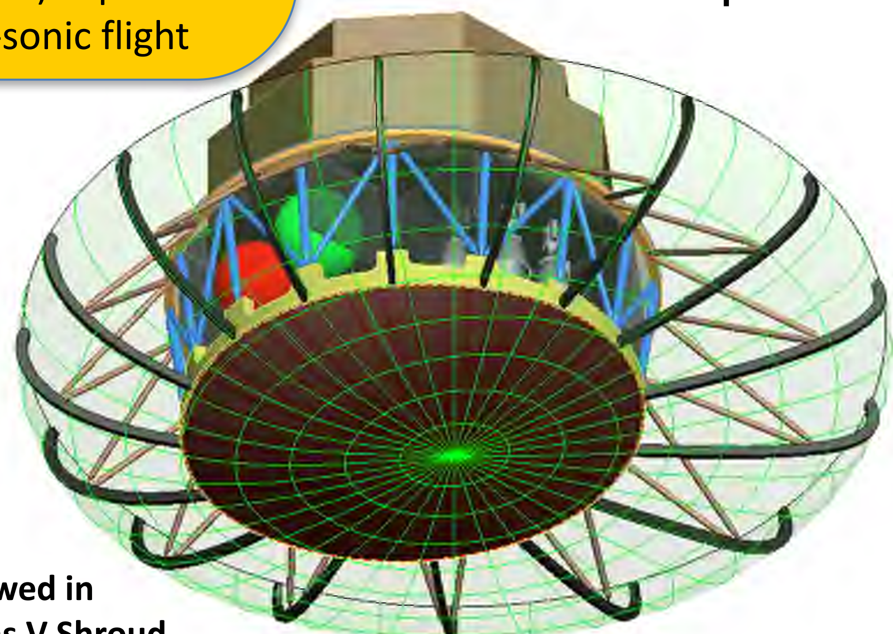
- ADEPT Technology Overview
  - What challenge is ADEPT addressing?
  - Summary of mission infusion opportunities
  - Functional description and capabilities
- ADEPT SR-1 Flight Experiment
  - Overview and Test Objectives
  - Description and Status
- Next Steps…
  - Demonstrating performance in relevant environments
  - Future mission infusion possibilities
- Summary

Adaptable, Deployable Entry and Placement Technology (ADEPT) Overview

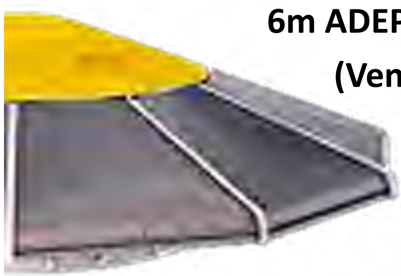
- **ADEPT is an atmospheric entry *__architecture__* for missions to different planetary bodies with atmospheres.**
  - Low ballistic coefficient entry vehicle with low L/D enables large payload (20 mT) delivery to Mars surface
  - Enables missions where entry vehicle stowed volume on spacecraft is a constraint
  - Rugged, robust system can be deployed for long durations in transit prior to entry and has damage tolerance to impact events
  - ’Open back’ deployable shape (no backshell) expected to be dynamically stable in transonic and sub-sonic flight

1m Nano-ADEPT (Mars)

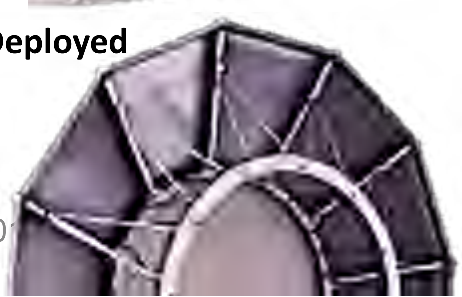
16m Lifting ADEPT Human Mars Exploration



6m ADEPT-VITaL (Venus)

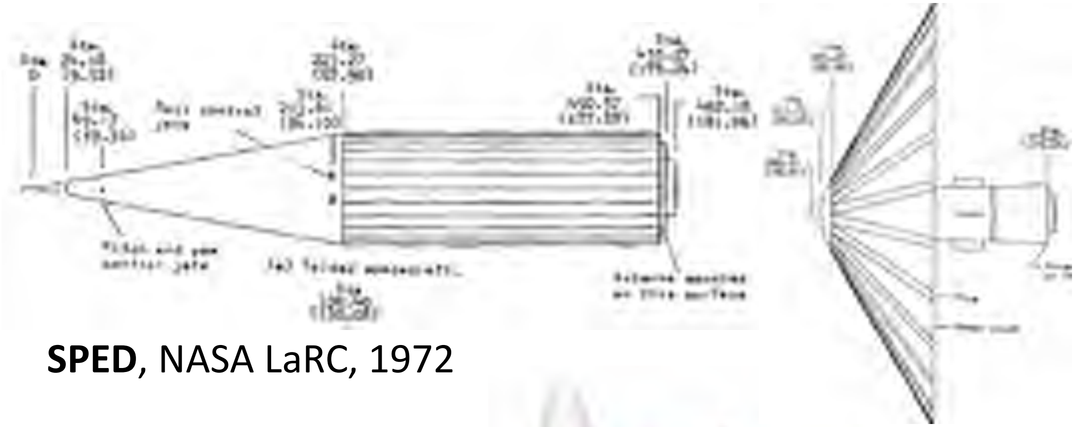


Deployed

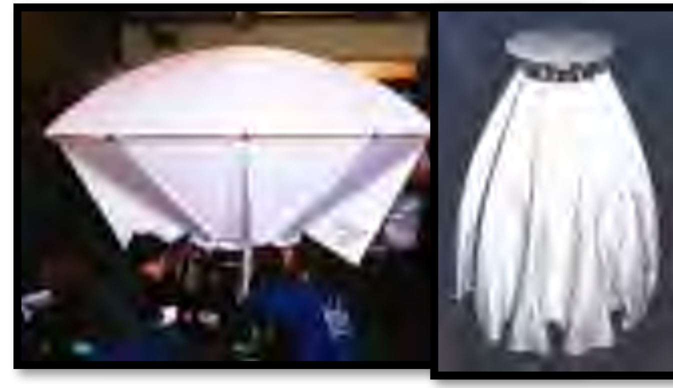


Stowed in Atlas V Shroud

Mechanically Deployables: Often Proposed, Seldom Implemented



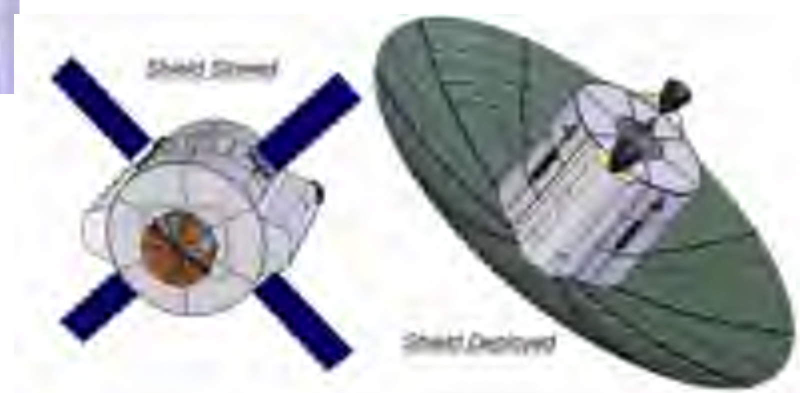
SPED, NASA LaRC, 1972



Parashield, MIT 1988

Deployable CMC Decelerator, Astrium, AIAA ADS 2003

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

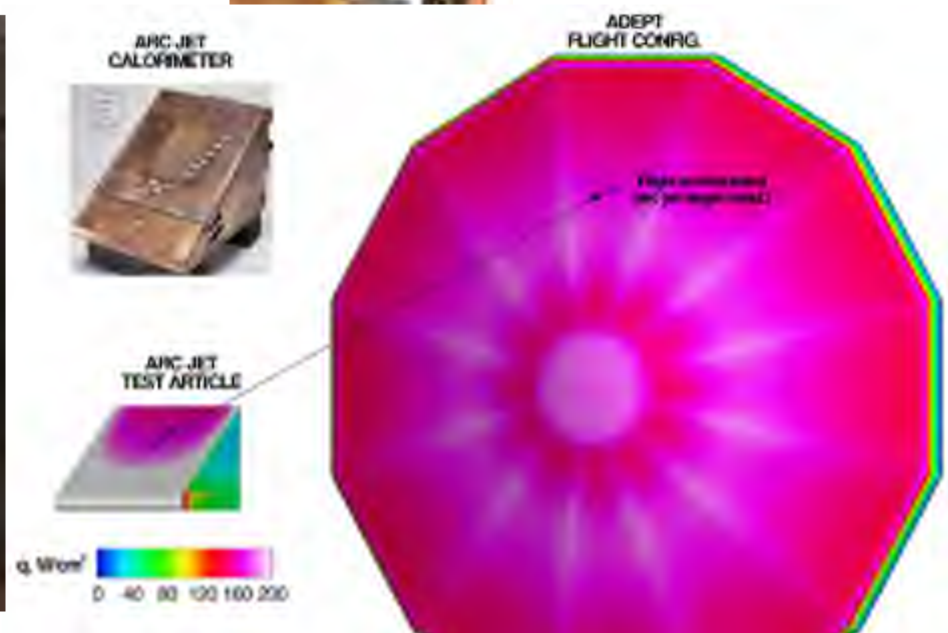


Phoenix, U. Maryland, IAC 2006

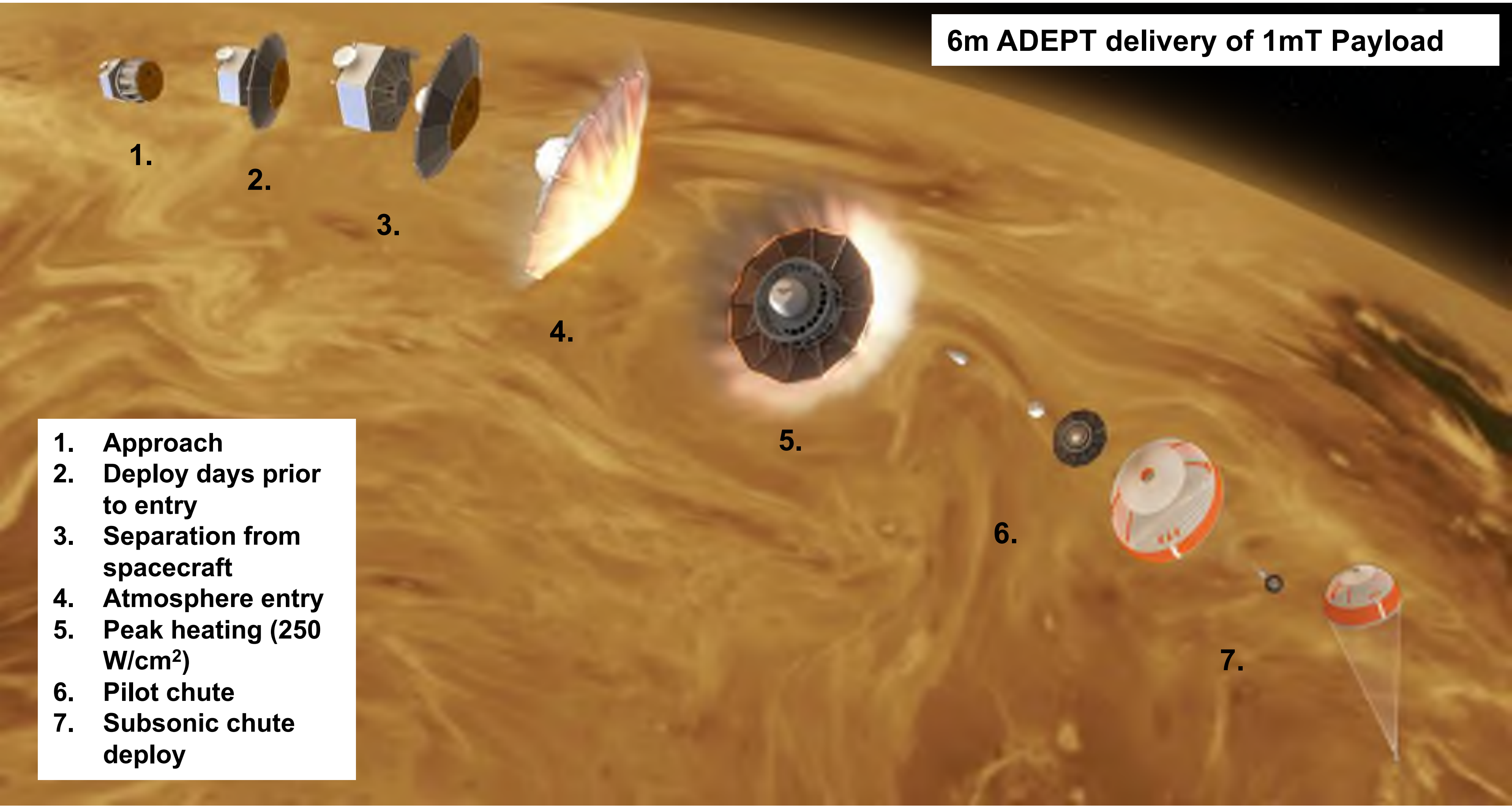
Challenge: Need flexible material that can survive high aerothermal heating experienced during hypersonic planetary entry

Key Technology Breakthrough enabling ADEPT Carbon Fabric Capability Demonstration

- **Challenge: Design and Test Flexible Material capable of high aerothermal heating while sustaining high tension loads**
  - Multi-layer 3D woven carbon fabric tested above 200W/cm^2
  - Test under combined aerothermal and mechanical loading
- **Test Results: Success!**
  - Carbon fabric able to maintain load at temperature.
  - Biaxial tension load has little impact on the rate of cloth layer loss
  - Fabric tested easily withstood a heat load of 15.7 kJ/cm^2. This is well above the 11 kJ/cm^2 expected for a Venus

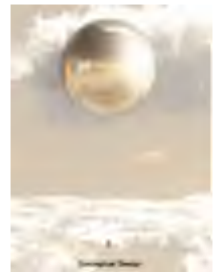


ADEPT Entry Mission
Deliver 1mT Payload to Venus surface



1m ‘Nano’ ADEPT Mission Insertion Possibilities
Small Scale -> Take Advantage of Small Packaging

Venus



Science Pull:
- Delivery of In-situ atmosphere science instruments.
- Achieve low deceleration loads for sensitive instruments

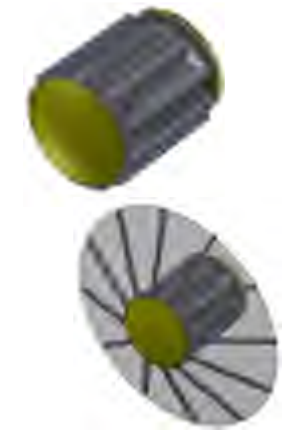
Mars

Science Pull:
- Global distribution, low cost
- Numerous landers

Dandelander (Malin SSS):
Cubesat distributed surface network concept

Earth

LEO Return: Secondary on Upper Stage, ISS Downmass or free-flyer on Super Strypi class LV



Titan

- Lifting ADEPT allows aerocapture at Titan
- Cruise flight with open-back supports RTG thermal management

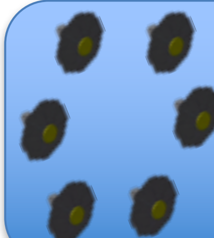
[redacted]

ADEPT 1m Mission Infusion Example: Mars Secondary Payload Network Landers

MSL Release from Cruise Stage

Interplanetary Cruise Phase:
~ 9 Months

Secondary Payload Deployment Phase:
Up to 8 Secondary ADEPT landers sequentially deployed after last TCM, no sooner than 1 week from entry interface

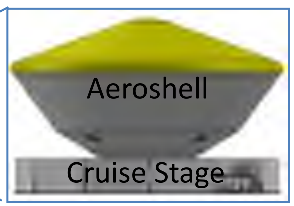


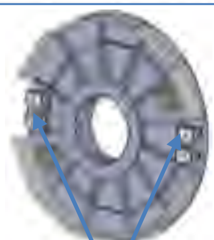
MSL EDL

Nano ADEPT Network Entry:

Ballistic Entry, β=5-50 kg/m^2
Peak heating: 40-110 W/cm^2
Heat Load: 1-4 kJ/cm^2
Peak Decel: 16-21 g
Terminal Velocity: 40-90 m/sec

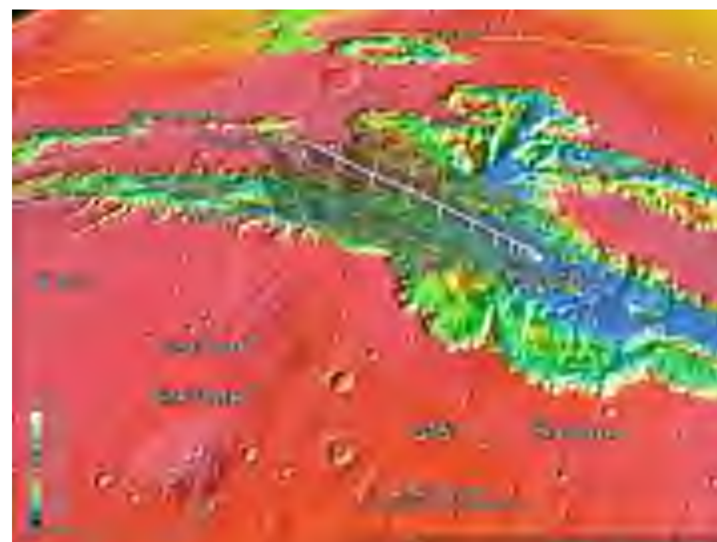
Launch
Atlas V 540





Cruise Stage Sep System Placement

Concept of sub m class ADEPT contained inside 12U Sep System



***Mission Concept from Malin Space Science Systems presented at CubeSat to Mars Workshop (CalTech Nov 20-21, 2014 https://marscubesatworkshop.jpl.nasa.gov)**

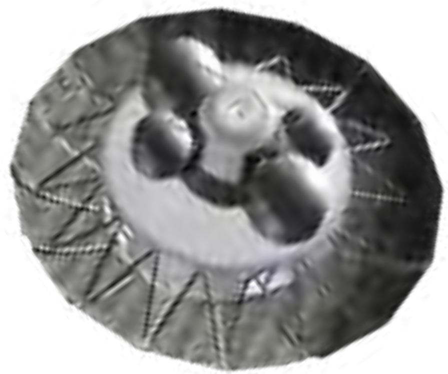
Entry Technologies Considered for Human Missions

Inflatable

HIAD – Hypersonic Inflatable Aerodynamic Decelerator

Deployable

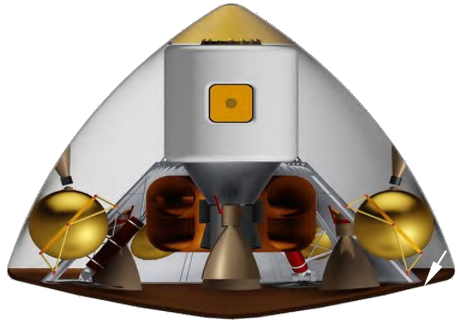
ADEPT – Adaptable Deployable Entry and Placement Technology



Mid L/D

Rigid Structure

Heritage Blunt Capsule

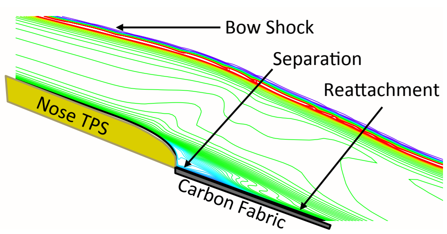


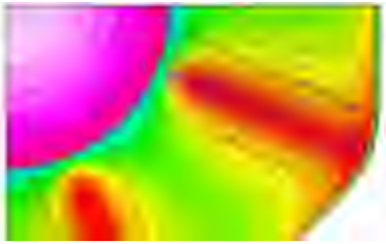
ADEPT Technology Advancement Highlights

ARC JET TEST

POST-TEST

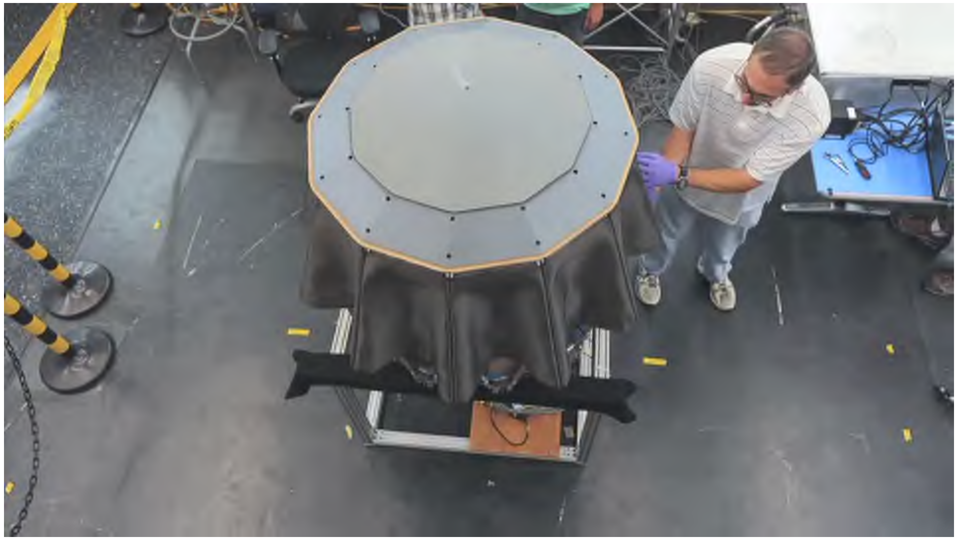
Damage Tolerance arcjet testing



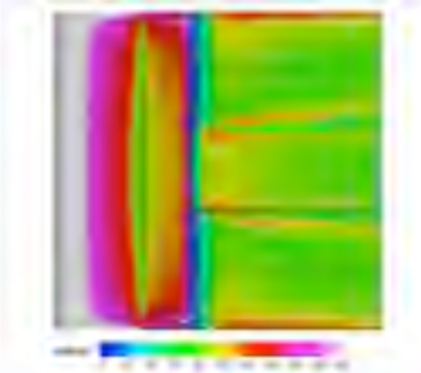


High Fidelity Flowfield Modeling of Heating Conditions

Mechanical Strength Testing of Fabric Joints



2 m Ground Test Article Deployment

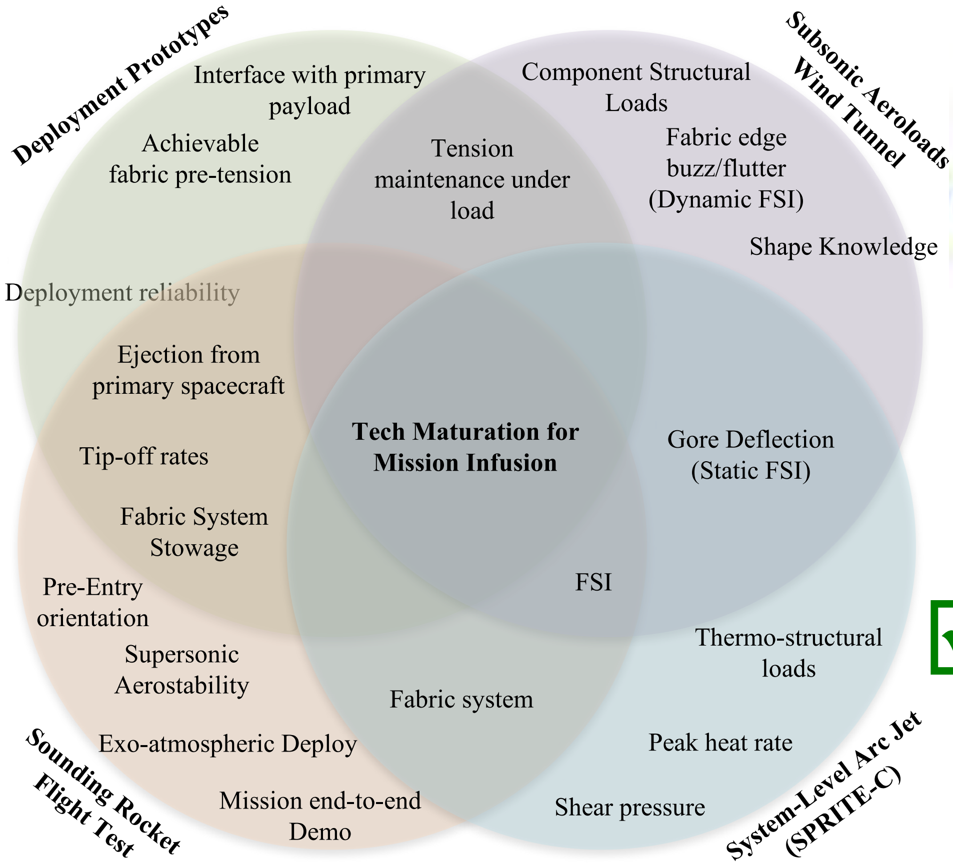


Fabric Joint Design Validated with Arcjet Testing

ADEPT Development Focus
1m ‘Nano’ Technology Maturation Strategy

Deployment Prototype Demonstrator (FY15-16)

SR-1 Sounding Rocket Flight Test (FY17-18)



7x10 Wind-tunnel Aeroloads test (FY15)

SPRITE C System level Arc-jet testing (FY15)

- **System Level testing in relevant environments, minimal component testing**

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1m ‘Nano’ Technology Maturation Strategy

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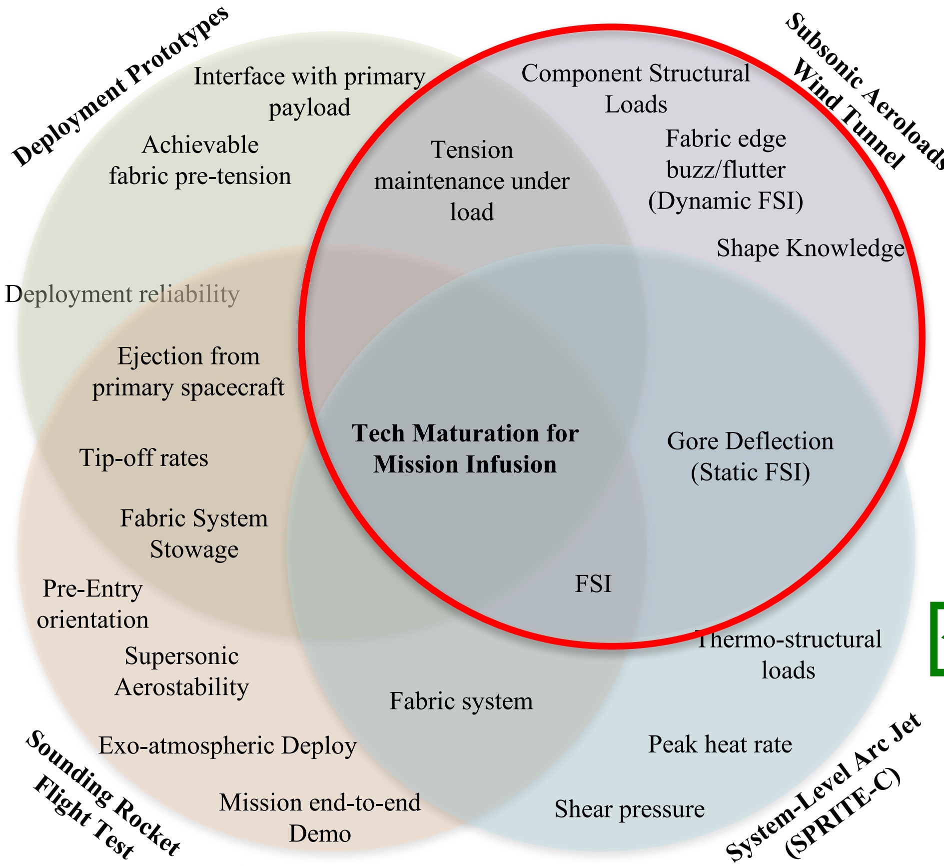


7x10 Wind-tunnel Aeroloads test (FY15)

SPRITE C System level Arc-jet testing (FY15)

- **System Level testing in relevant environments, minimal component testing**

Nano-ADEPT Aeroloads Test (FY15)

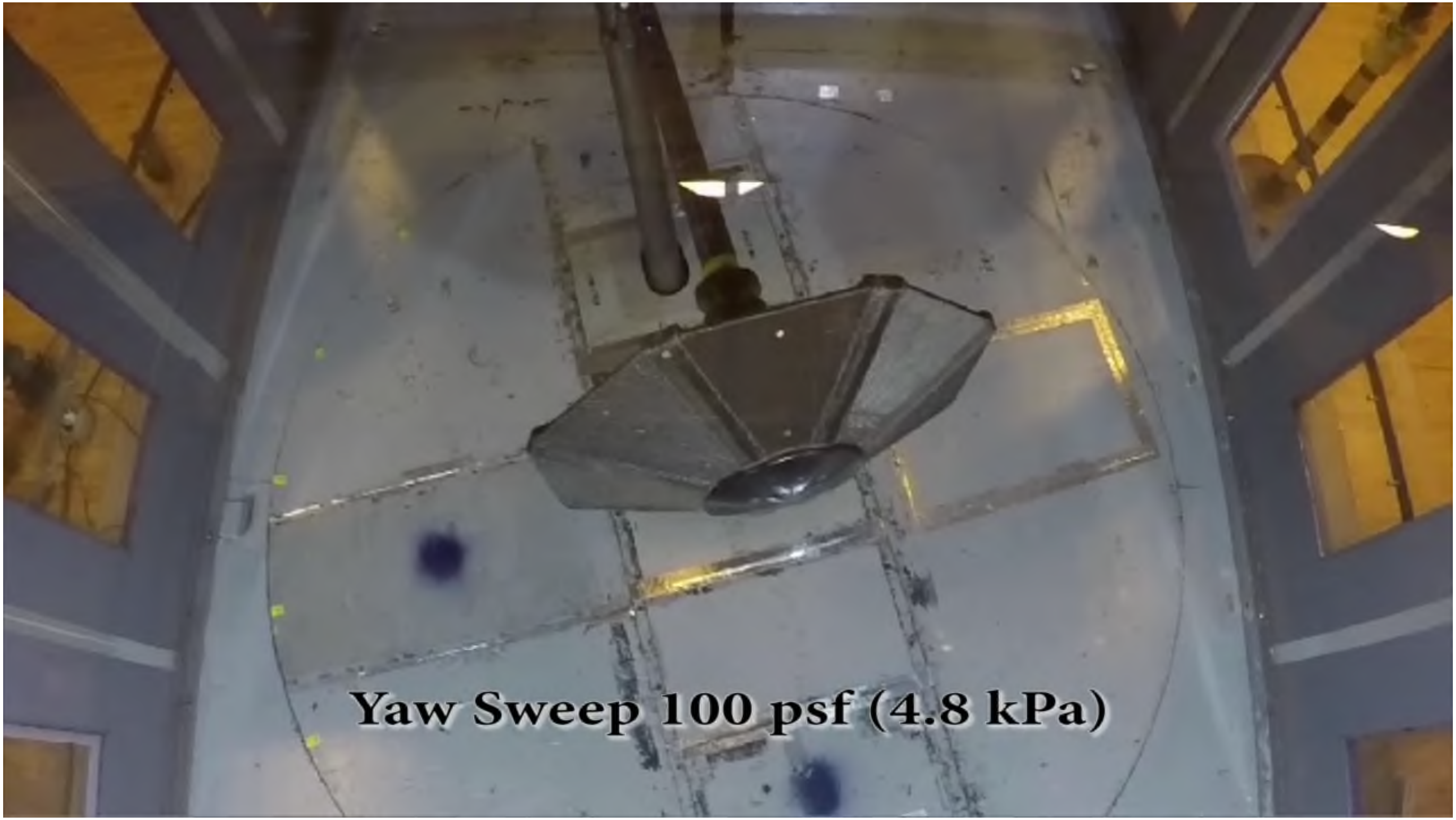
- Testing was completed in seven business days at the US Army's 7x10 Foot Wind Tunnel located at NASA Ames (27-Apr to 5-May 2015)
- Shared funding was provided through NASA STMD GCDP ADEPT program (FY15) and a NASA Ames Center Innovation Fund Award (FY14)

Test Objective	Instrumentation
Obtain static deflected shape and pressure distributions while varying pre-tension at dynamic pressures and angles of attack relevant to Nano-ADEPT entry conditions at Earth, Mars, and Venus.	Photogrammetry; String potentiometers; Outer Mold Line (OML) static pressure taps
Observe dynamic aeroelastic behavior (buzz/flutter) if it occurs as a function of pre-tension, dynamic pressure, and angle of attack.	High speed video; Strut load cells
Obtain aerodynamic forces and moments as a function of pre-tension, dynamic pressure, and angle of attack.	Internal balance

Flight-like carbon fabric skirt includes key features such as carbon yarn stitching and seam resin infusion

- **All test objectives were met.**
- **Rich data set was obtained using non-invasive instrumentation**
- **Data products and observations made during testing will be used to refine computational models of Nano-ADEPT**
- **Bonus experiment of asymmetric shape demonstrates that an asymmetric deployable blunt body can be used to generate measureable lift**

Video Highlights from 7x10 Test



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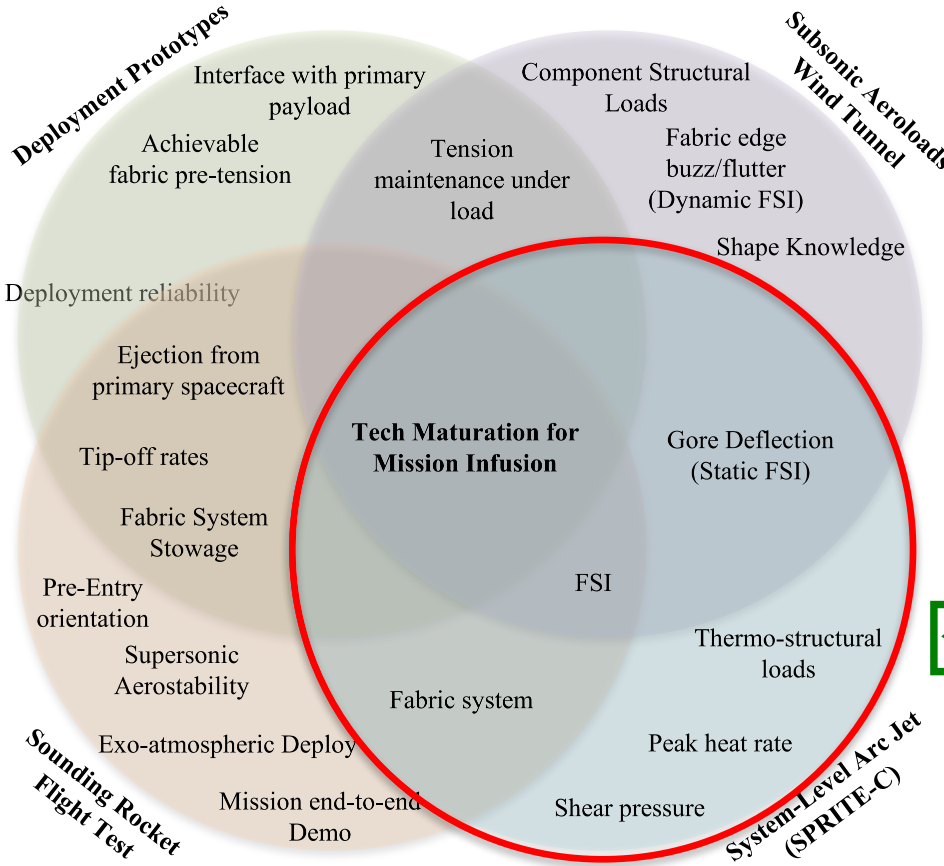
1m 'Nano' Technology Maturation Strategy

Deployment Prototype Demonstrator (FY15-16)

SR-1 Sounding Rocket Flight Test (FY17-18)



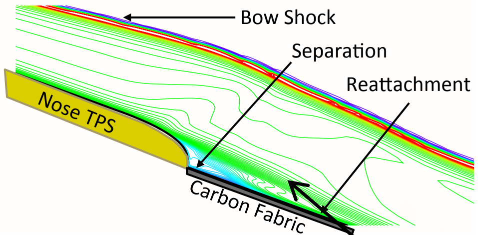
7x10 Wind-tunnel Aeroloads test (FY15)

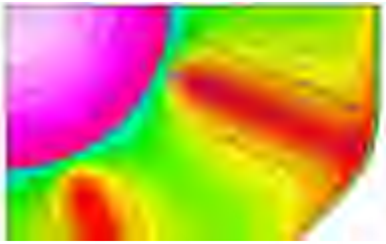
SPRITE C System level Arc-jet testing (FY15)

- **System Level testing in relevant environments, minimal component testing**

ADEPT SPRITE C Arcjet Test (Sept 2015) Design Features

FLOW FEATURES

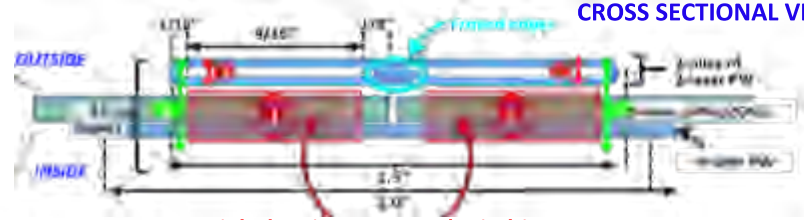




Streamlines & Heating Contours

JOINT ANATOMY

CROSS SECTIONAL VIEW



High density structural stitching

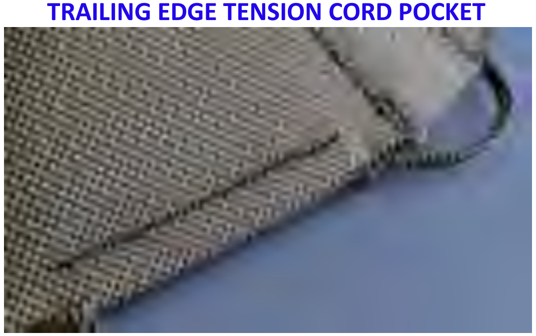
3D WOVEN FABRIC

TOP VIEW ACREAGE

JOINT SHIELDING LAYERS

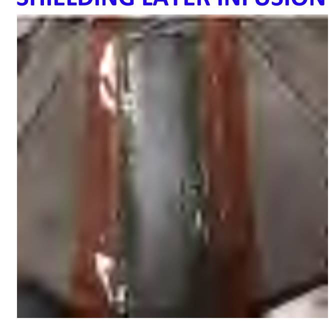
BOTTOM VIEW ACREAGE

TRAILING EDGE TENSION CORD POCKET



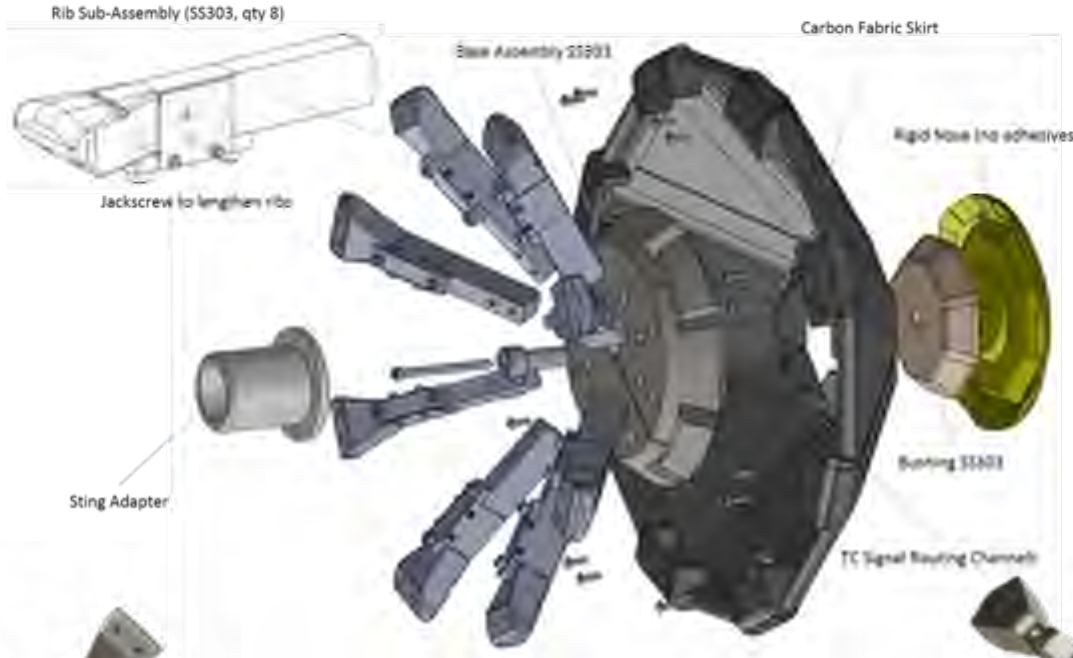
JOINT STITCHING & INSULATING LAYERS

SHIELDING LAYER INFUSION

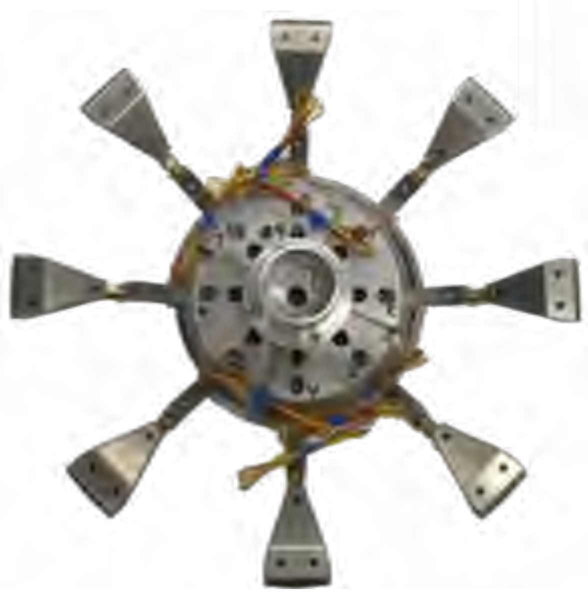


Test Article Description-Assembly

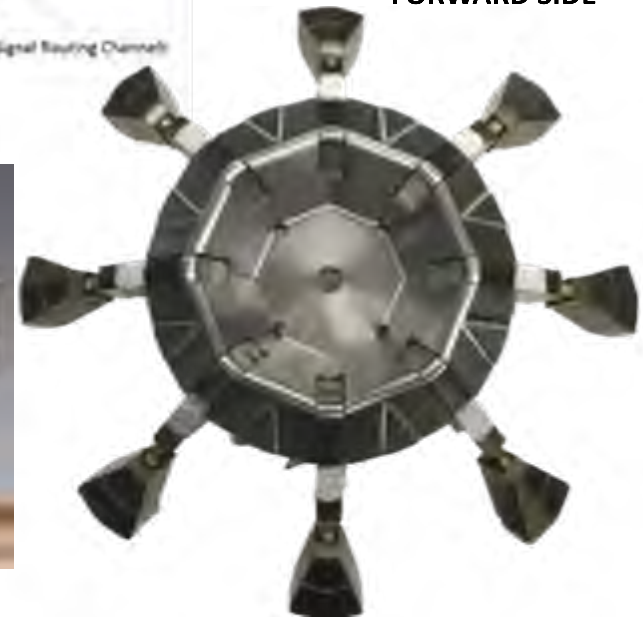
EXPLODED VIEW



AFT SIDE



FORWARD SIDE



SPRITE C Results: Test Video- C2, Condition 1

Test Article Description and Conditions

Test Article 1
Condition 1 for 60 sec

- Graphite Nose
- Six Layer C-Fabric
- Phenolic Infused Joints

Test Article 2
Condition 1 for 40 sec
Condition 2 for 40 sec

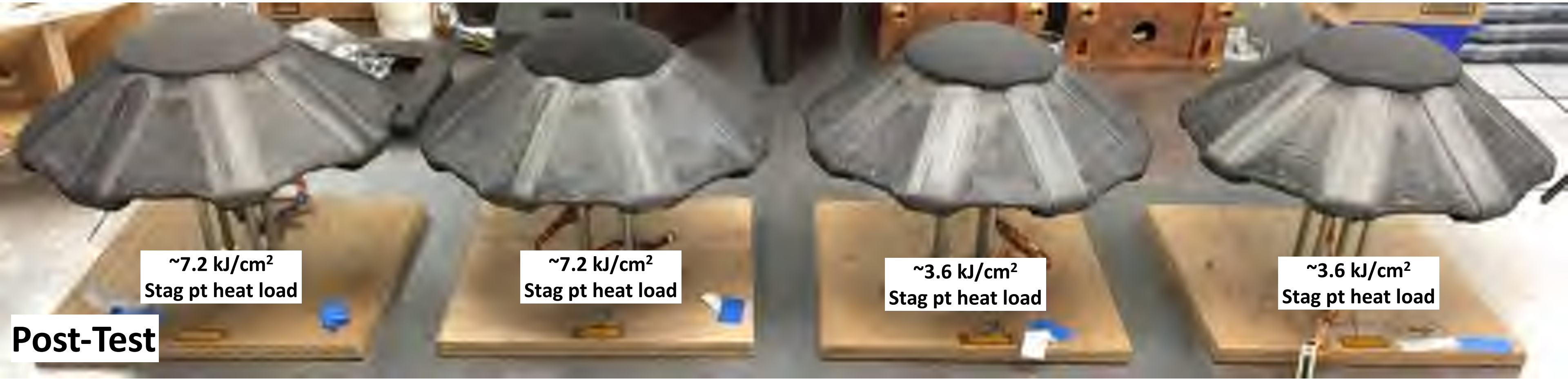
- Conformal PICA Nose
- Six Layer C-Fabric
- Phenolic Infused Joints

Test Article 3
Condition 2 for 60 sec

- Graphite Nose
- Six Layer C-Fabric
- Various Resin Infused Joints

Test Article 4
Condition 2 for 60 sec

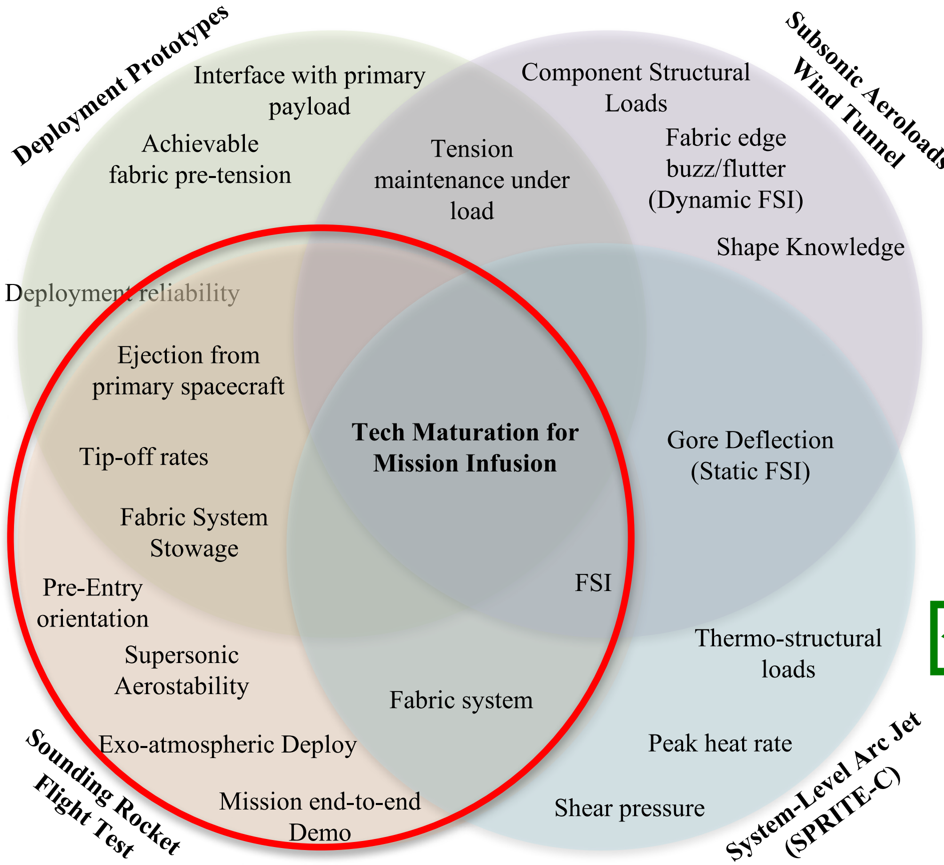
- Graphite Nose
- Four Layer C-Fabric
- Various Resin Infused Joints
- Insulating Fabric at Rib Interface



ADEPT Development Focus
1m 'Nano' Technology Maturation Strategy

Deployment Prototype Demonstrator (FY15-16) ☑

SR-1 Sounding Rocket Flight Test (FY17-18) ☐

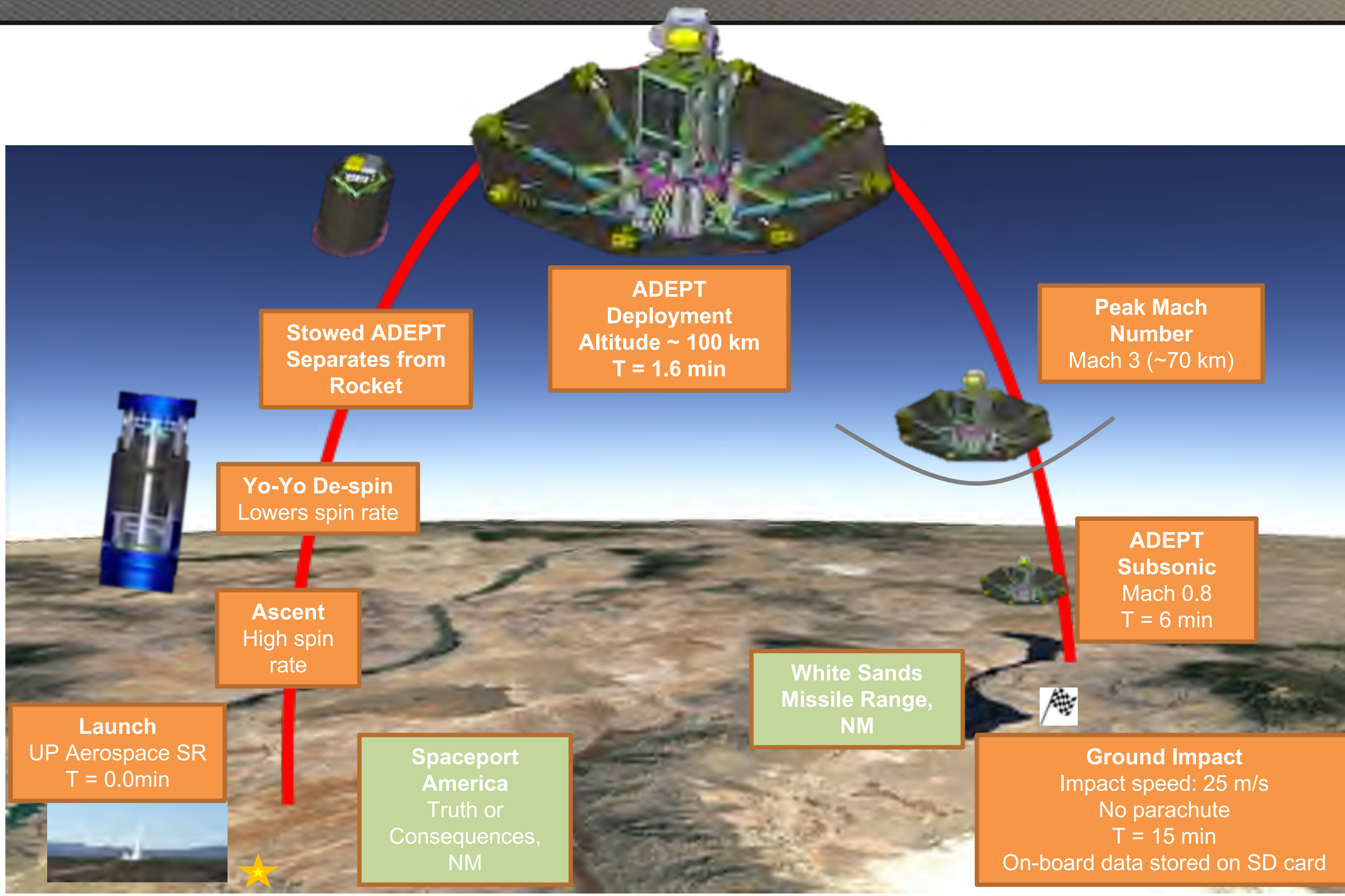


☑ **7x10 Wind-tunnel Aeroloads test (FY15)**

☑ **SPRITE C System level Arc-jet testing (FY15)**

- **System Level testing in relevant environments**
- **GCD approved (Aug 2016) SR-1 Sounding Rocket Flight Experiment**
  - **Demonstrating exo-atmospheric deployment and supersonic stability**
  - **Aggressive schedule: 1 year between PDR and Launch!**

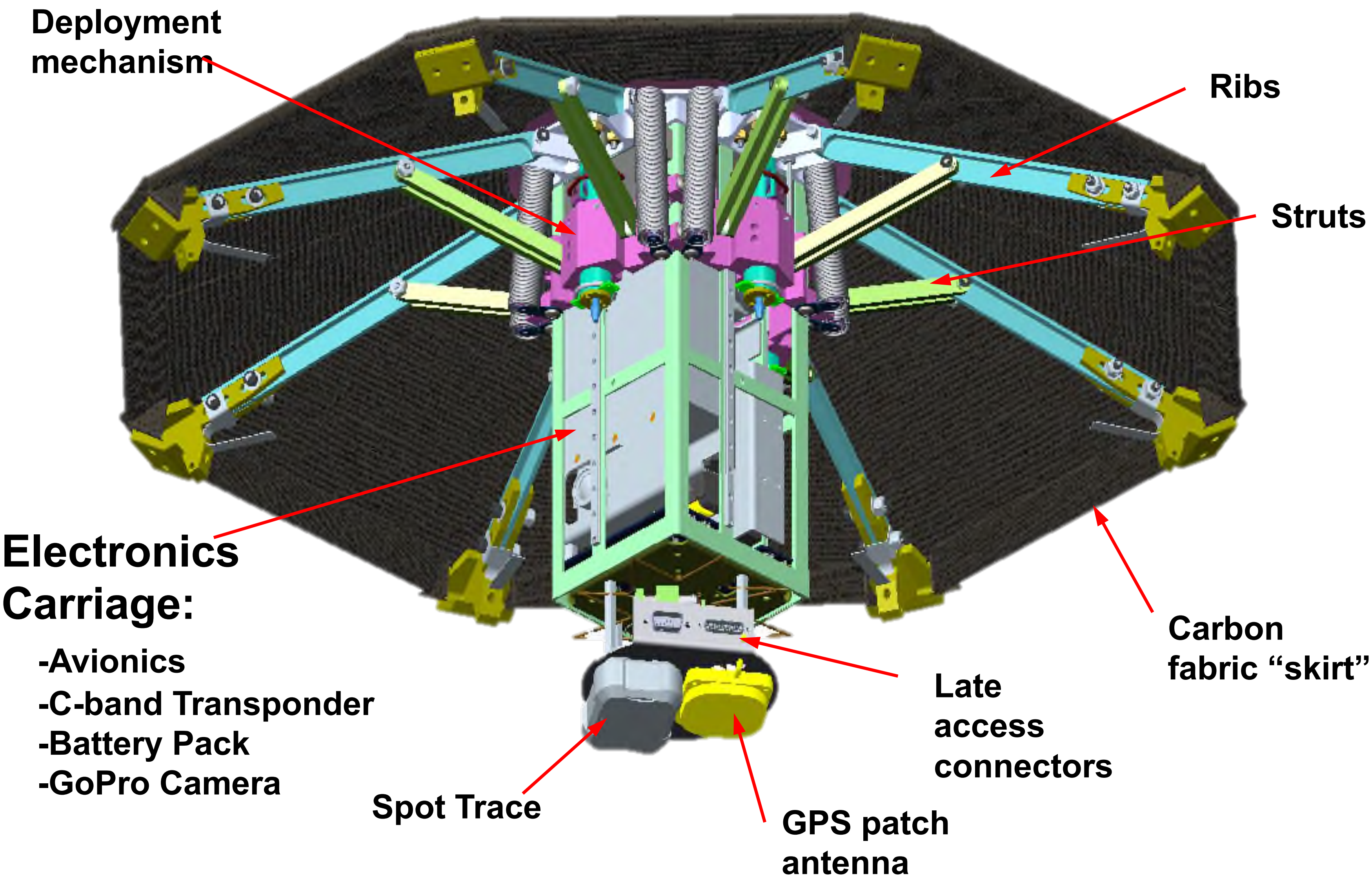
SR-1 Flight Experiment Overview



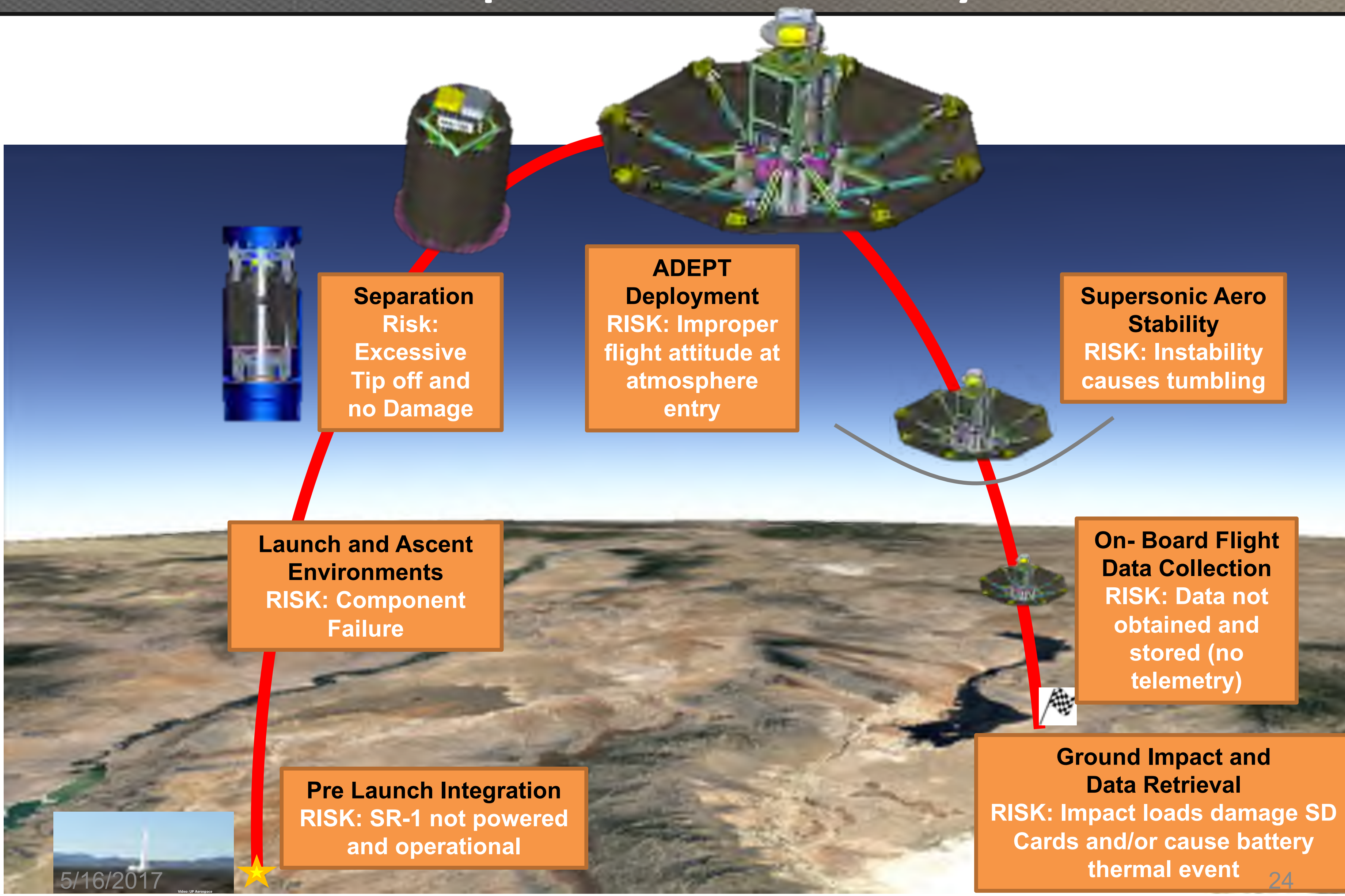
Key Performance Parameter 1: ***Exo-atmospheric deployment to an entry configuration***
Key Performance Parameter 2: ***Demonstrate Aerodynamic stability without active control***

SR-1 Animation movie

SR-1 Layout and Subsystems

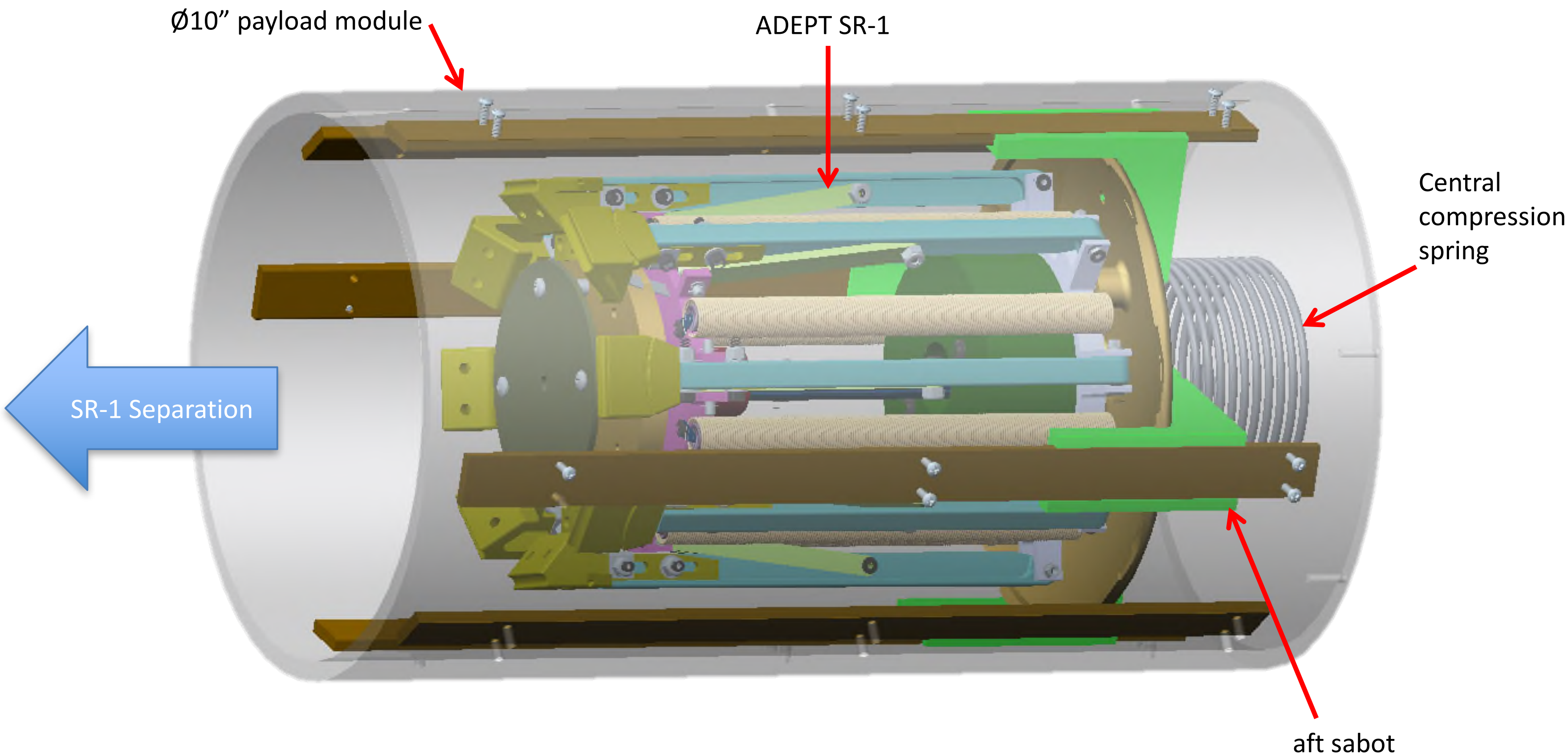


SR-1 Flight Experiment
Development Tests driven by Risks

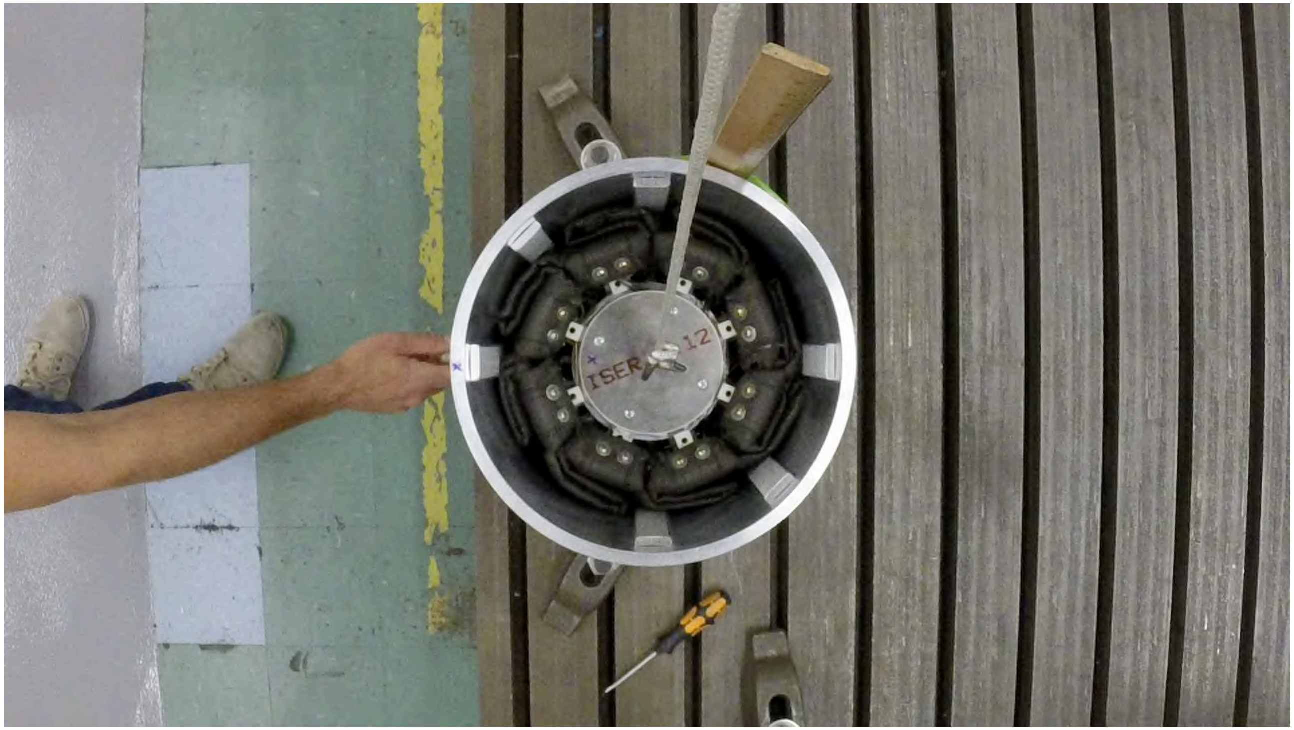


SR-1 Design Status: Separation System

- **The SL-10 separation system has been adapted for SR-1 and prototyped**



SR-1 Simple Separation Test

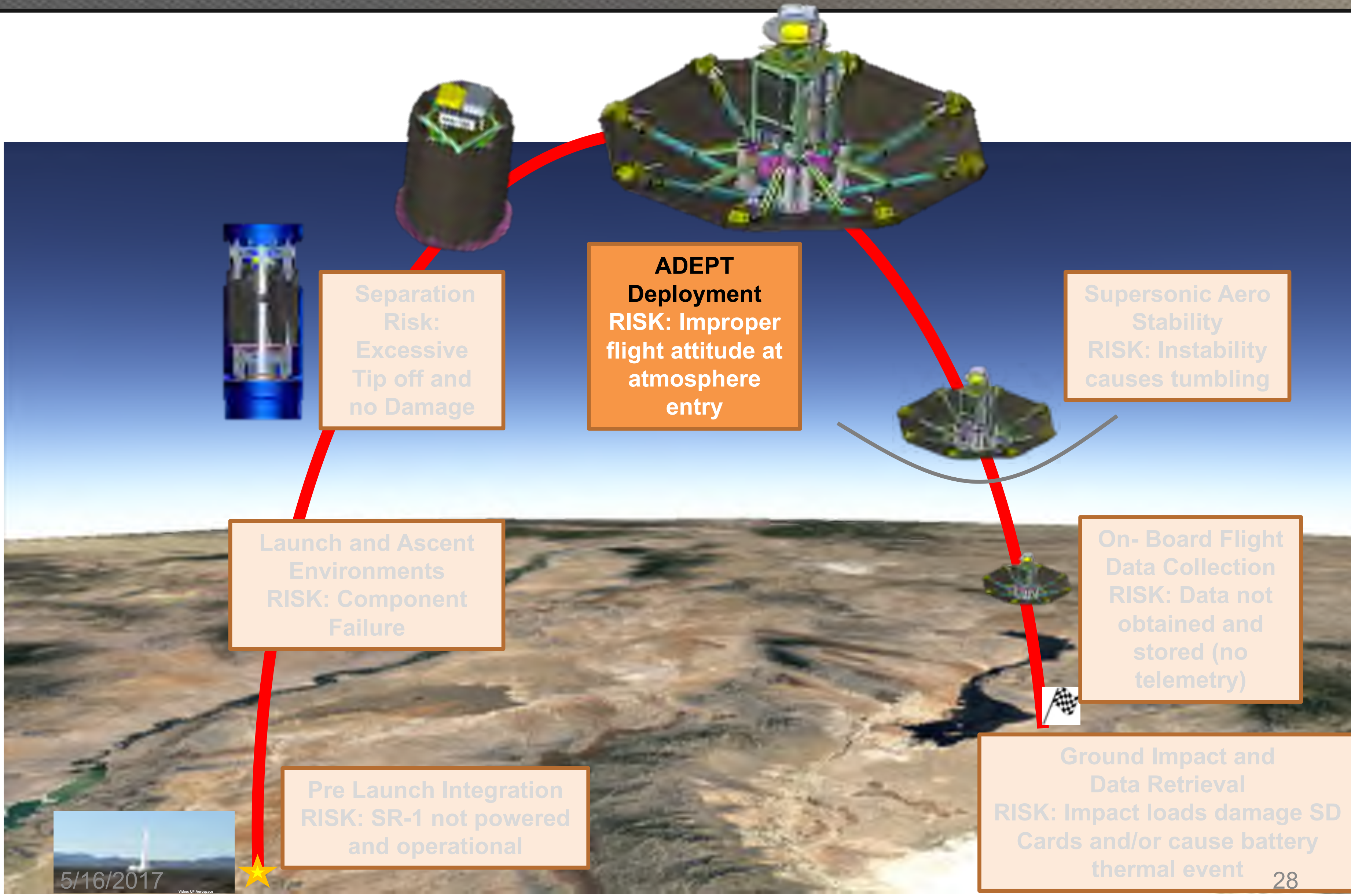


Stowed Fit Check & Separation Demonstration

Long duration stowage test

- ADEPT SR-1 stowed for 85 days to assess long duration storage

SR-1 Flight Experiment
Development Tests driven by Risks

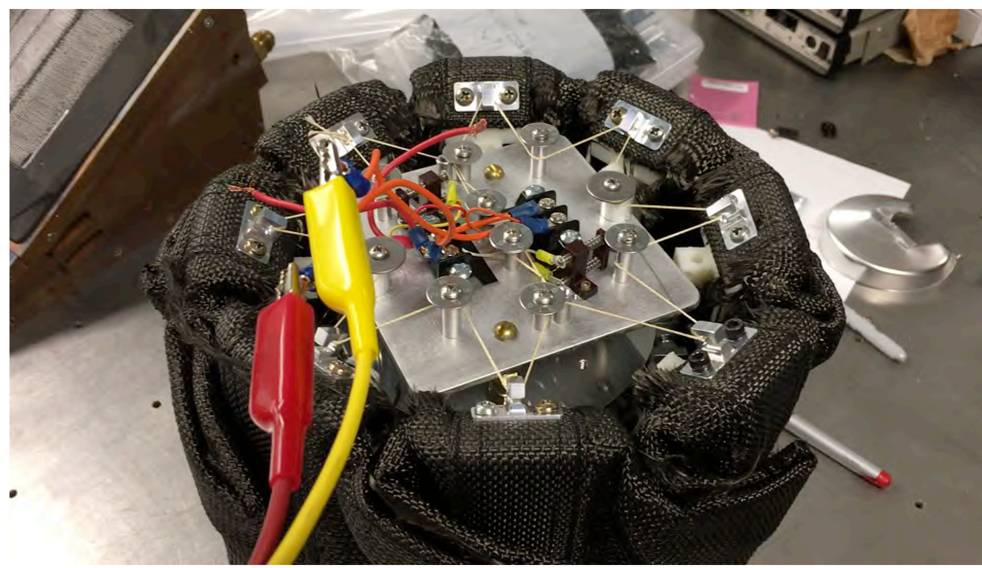


Deployment System (Rib release)
Test results

- Vectran cable **<u>retains</u>** rib tips in stowed state
- A separation sensor in the nose cap detects when ADEPT is ejected from the payload module.
- Sensor activates Ni-Chrome burn wire, which cuts through Vectran cable.
- SR-1 spring-actuated deployment occurs immediately after Vectran cable has been cut.
- Burn wire tested in vacuum chamber equivalent to 100K ft altitude.
- Cut time was repeatable 4.5 seconds at 1.6 amps. (Temperature was 66°F)

Ni-Chrome burn wire
(2X for redundancy)

Vectran cable



SR-1 Flight Experiment
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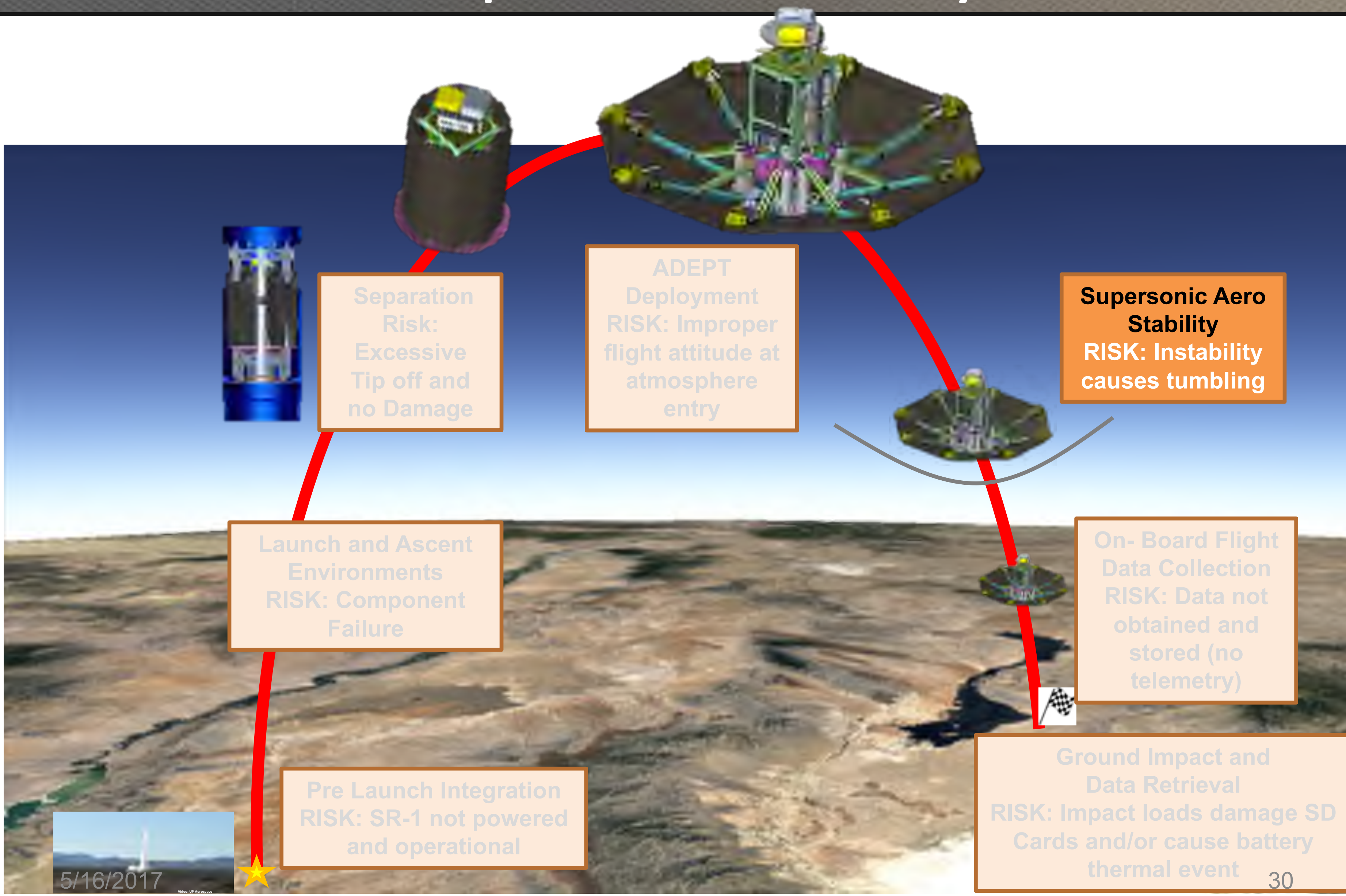
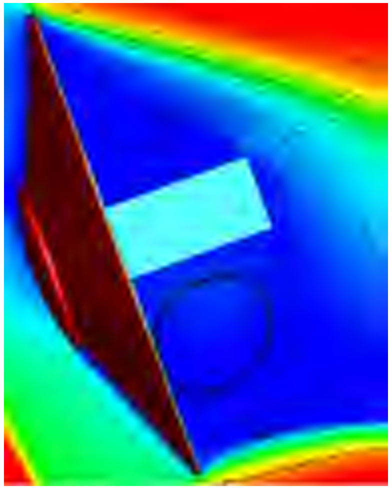
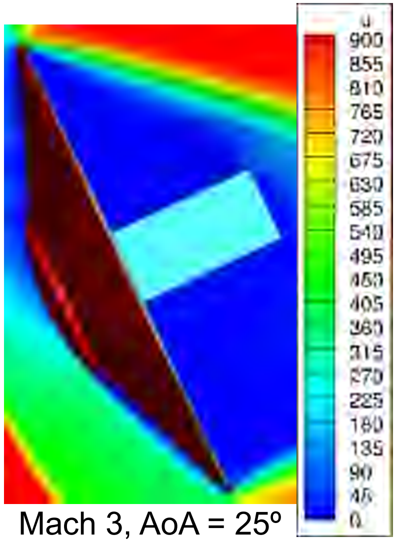


Vehicle Length Limitation

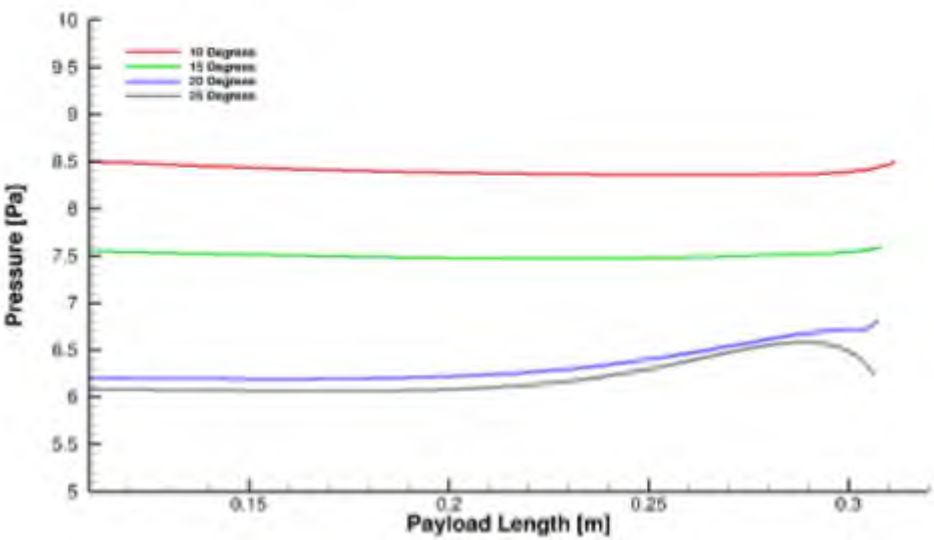
- **The maximum vehicle length is constrained by the need to avoid impingement with the high-speed flow as it expands in the wake**
  - Aerodynamic interaction with shear layer could cause unpredictable flight dynamics
  - No "payload heating" concerns with SR-1, but need to avoid any impingement for DRM traceability
- **This need puts severe limitations on the volume available for instrumentation**
  - Most volume is already consumed by crushable mass, C-Band transponder, and AVA
- **Current vehicle length: 0.32 m (nose tip to aft end)**
  - Payload configuration is getting close to the shear layer at this angle of attack and is feeling some effects from the higher velocity flow
  - Magnitude of induced forces are an order of magnitude lower than forebody
  - <u>Recommendation to limit vehicle length to 0.32 m</u>



Mach 3, AoA = 20º



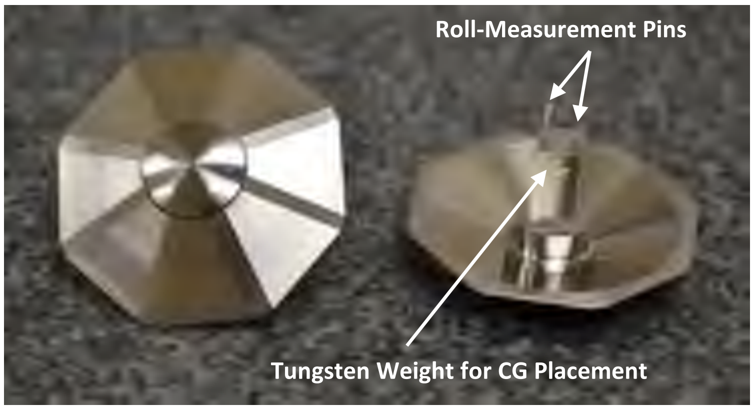
Mach 3, AoA = 25º



ADEPT SR-1 Ballistic Range Test

- Objective: obtain free-flight dynamic data at supersonic speeds (Mach 1.2-Mach 3.0)
- Test data informs a decision on Center of Mass location for SR-1, a mitigation step for top project risk

ADEPT SR-1 Ballistic Range Models



ADEPT SR-1 Model and Sabot

HFFAF Test Section Exterior

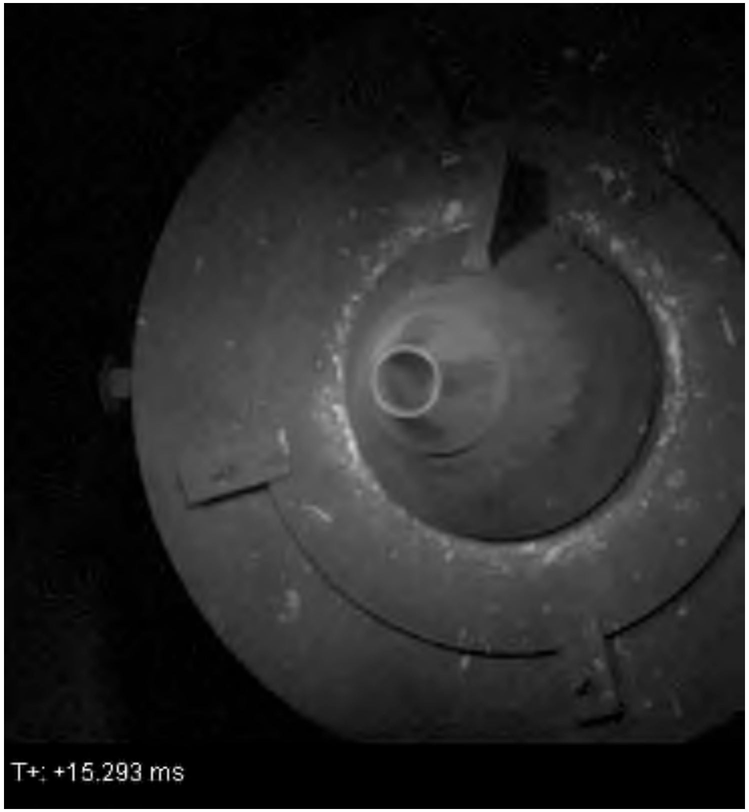
HFFAF Features

- Enclosed, controlled-atmosphere test section, 24 m (75 ft) long
- 16 orthogonal-view digital shadowgraph stations, spaced every 1.524 m (5 ft).
- High-speed video cameras to record launch and sabot separation characteristics.
- Various hypervelocity and supersonic launchers.

Overcoming Challenges in Ballistic Range

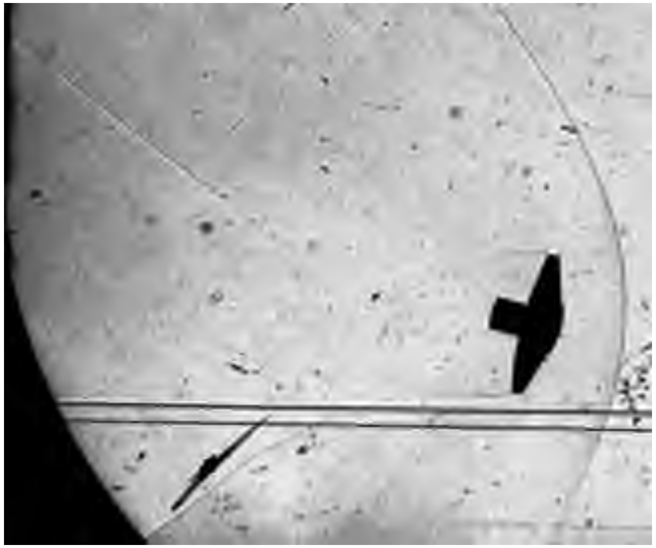
- ADEPT SR-1 shape presented new challenges to Ballistic Range facility

Clean sabot separation!



Preliminary Ballistic Range Test Results

- 15 total shots were performed
  - 11 calibration shots
  - 4 "for credit" shots
- Mach at mid-range of "for credit" shots: 1.225, 1.208, 1.493, 2.245
- *Preliminary* results:
  - The vehicle is dynamically unstable at low angle of attack (typical of blunt body entry vehicles)
  - Limit cycle oscillation amplitude is ~25º at Mach 2.2
  - In general, observed dynamic behavior supports moving CG forward to x/D=0.15 from current nominal location (x/D = 0.17) in order to improve stability for SR-1

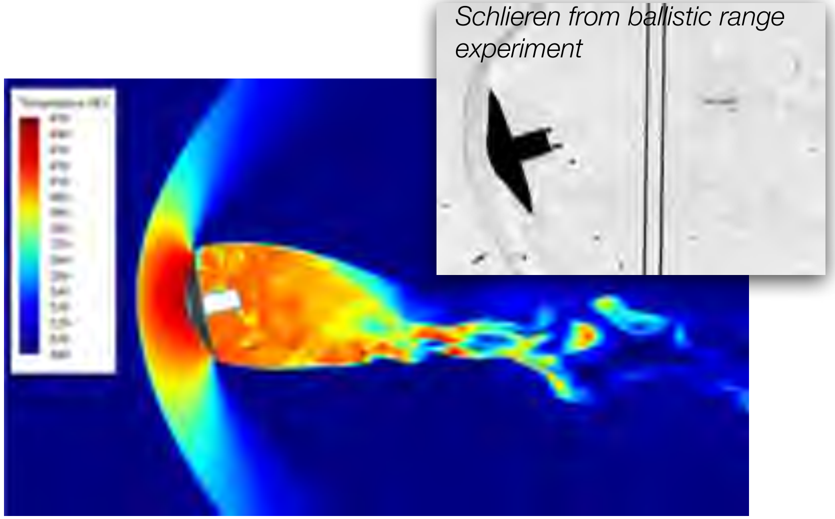


Mach 1.50, -13.7º angle of attack

Mach 2.58, 19.2º angle of attack

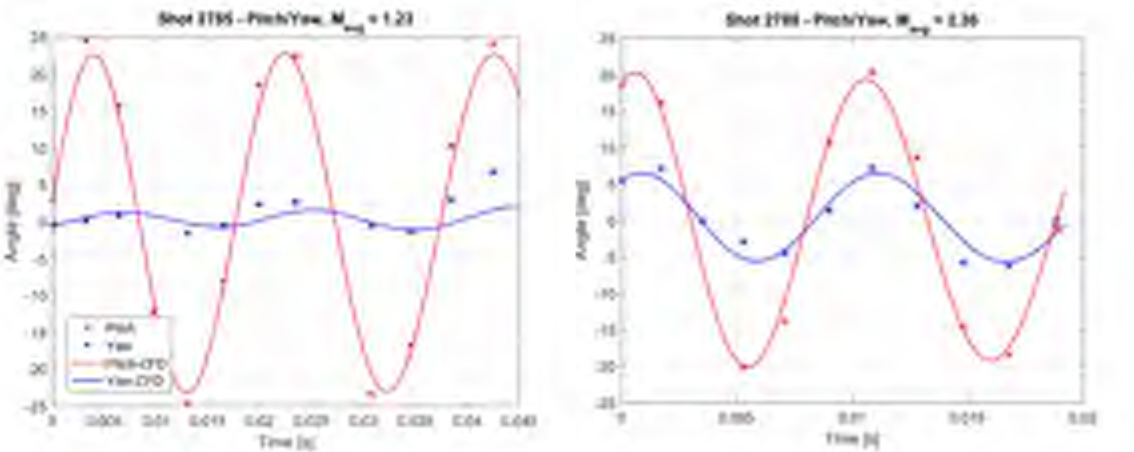
ESM Project: Free-flight CFD Code Validation from ADEPT SR-1 Data

- Data from the ADEPT ballistic range experiment is being utilized to assess the validity of the free-flight CFD solver at low supersonic Mach numbers
- Additionally, this experiment provides unique data for “flat-backed” aeroshell designs, which have highly separated flow fields at all supersonic Mach numbers
- Result from the analysis show good agreement with experiment at Mach 2.3
- Reasonable agreement with experiment for Mach numbers approaching 1.0



Schlieren from ballistic range experiment

Flow visualization from FF-CFD simulations of ballistic range experiment

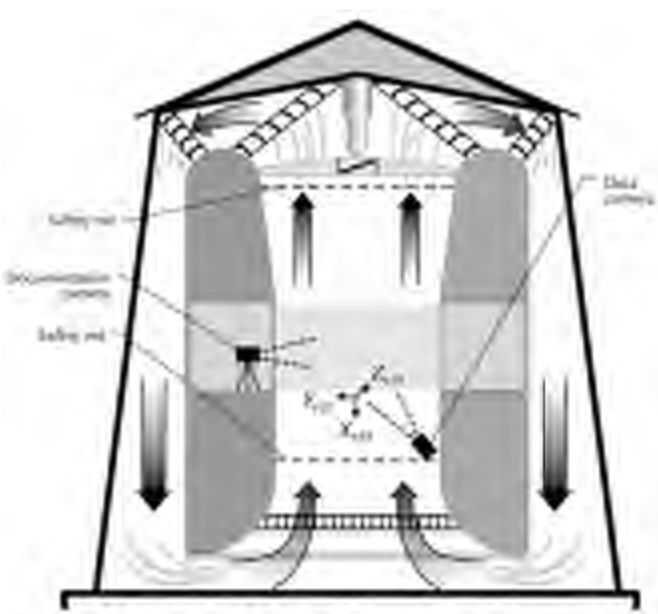


Comparison of predicted attitude (solid lines) to experimental data (symbols), for Mach 1.23 (left) and Mach 2.36 (right) trajectories

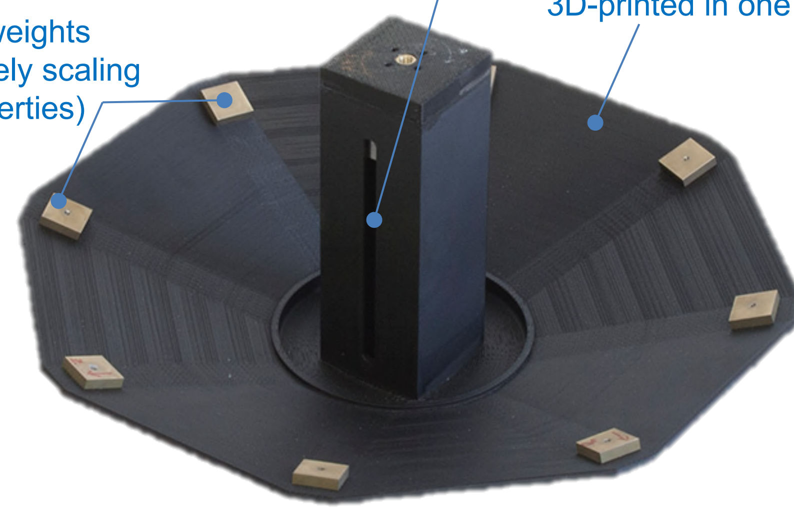
ADEPT SR-1 Vertical Spin Tunnel Test

Test Objectives:

1. Obtain the dynamic characteristics (i.e., attitude and rotation rates vs. time) at two full-scale altitudes (1.2 and 15 km MSL).
2. Determine the effects of large upsets on the dynamic characteristics.
3. Determine the effects of center of mass (CoM) location on the dynamic characteristics.
4. Determine the terminal descent velocity.
   - 50%-scale model designed for 1.2 km MSL (WSMR ground altitude)
   - 15%-scale model designed for 15 km MSL (high-altitude subsonic)



Vertical Spin Tunnel Schematic
NASA LaRC



50% scale test article, fabricated by ARC
(simulates flight dynamics at ground impact)

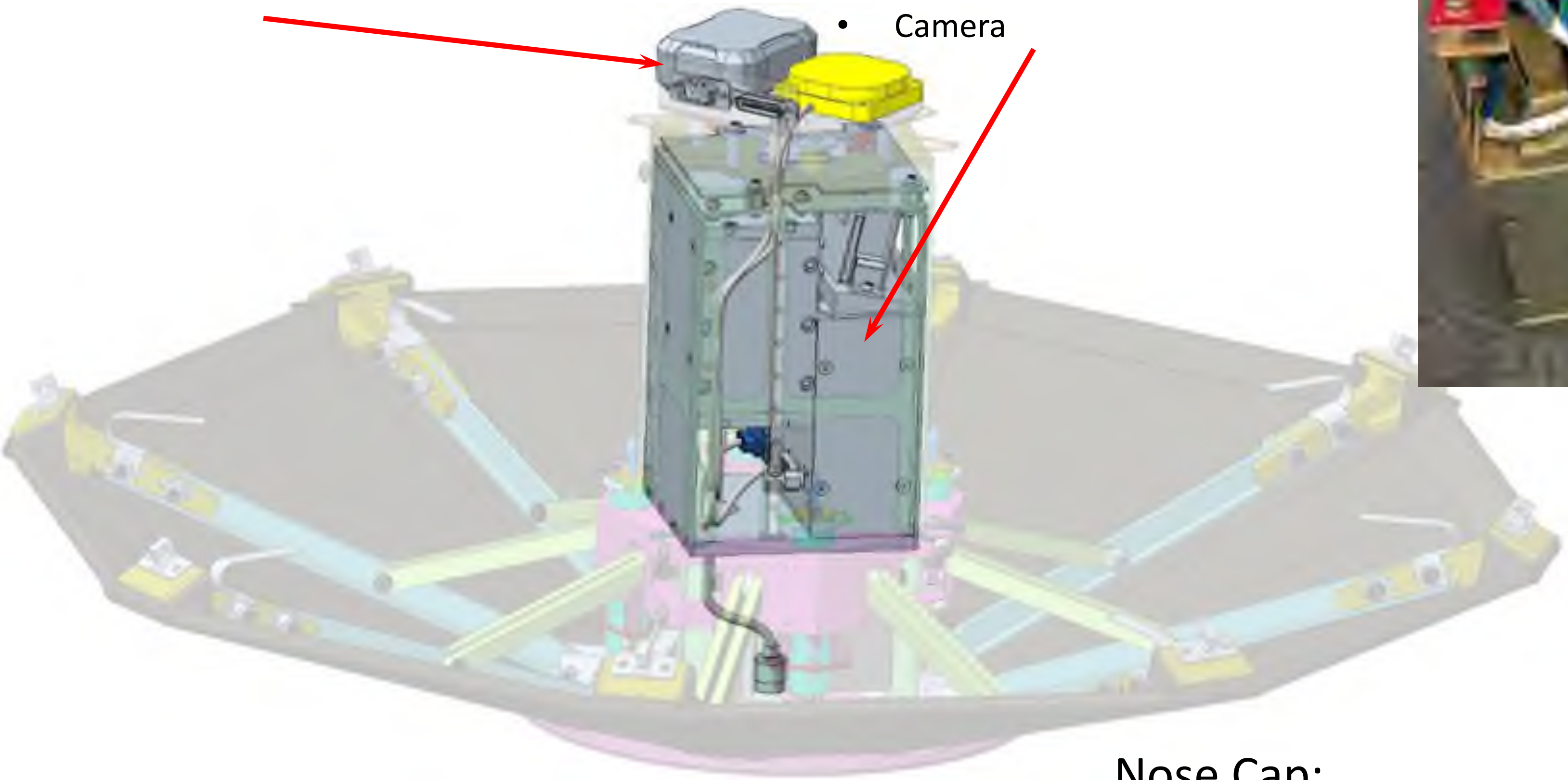
Preliminary VST Test Results

- The models flew near the expected airspeed.
- The 50% model was statically and dynamically stable at a wide range of CoM locations.
- Unperturbed pitch/yaw oscillations were relatively small in amplitude.
- Inverted, the model is statically stable and dynamically unstable: it eventually tumbles
- For the 15% model (high altitude), with the CoM in a near nominal location, the model was statically and dynamically stable *for the most part*.
- Once either model tumbles, they tend to glide (move laterally). The models give no indication that they will recover from a tumble if it occurs.

Bringing the Data Home
Avionics and Power Subsystems

Aft Deck:
- GPS Antenna
- Spot Trace
- Late Access Connectors

Electronics Carriage:
- Avionics
- C-Band Transponder
- Power System (EPS)
- Camera

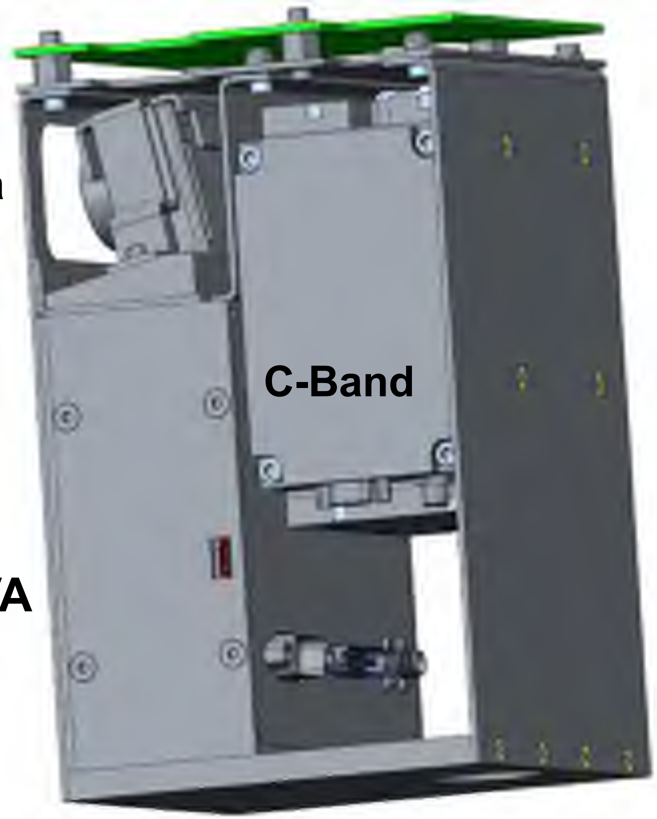


Nose Cap:
- C-Band Antenna
- Separation Sensors

How SR-1 Data Sources will be Used

EPS Board

GoPro Camera



AVA

GoPro® Camera on Launch Vehicle
Deployment Confirmation LED

USE: Confirm full and locked deployment

Primary IMU
Backup IMU
Magnetometer
GPS Receiver
GoPro® Camera on ADEPT
C-Band Transponder
Atmospheric Pressure and Temperature Measurement with Weather Balloon

USE: Trajectory reconstruction for dynamic stability assessment and FF-CFD simulation validation

WSMR Ground Tracking Stations

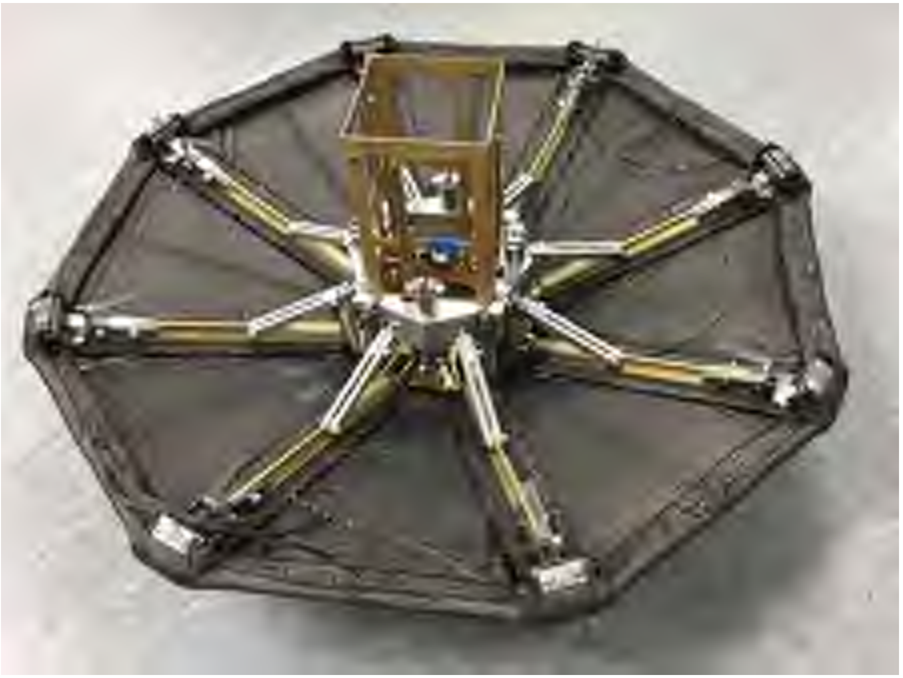
SPOT Trace®
C-Band Transponder
Ground Tracking Radar

USE: Locate SR-1 after ground impact

Electonics Carriage

- **SD cards must survive ~ 25 m/s (54 mph) impact velocity!**

ADEPT SR-1 Flight Hardware Integration Underway!

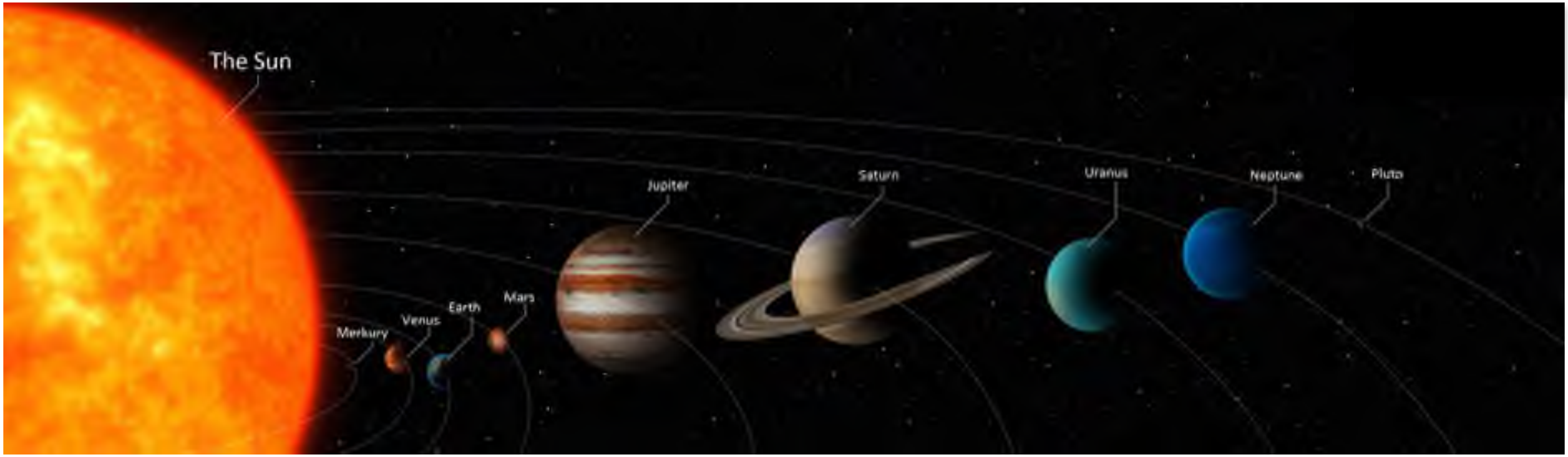


Carbon Fabric Skirt – Integration Fit Checks

Hardware Assembly, Integration and Test Progressing Well!
ADEPT SR-1 Flight Unit Ship Date is Aug 21, 2017
SL-12 Launch scheduled for Sept 18, 2017

After ADEPT SR-1…. Next Steps!

- **ADEPT SR-1 is a logical first step, but only a first step!**
- **Most mission applications will need…**
  - **Demonstrate larger scale**
  - **Demonstrate mission relevant entry heating**
  - **Demonstrate operational flight systems such as guided lift**



ADEPT Mission Capability Evolution

2017 2020 2023 2026

16m Scale

SR-1

- 0.7m 70deg Ballistic 15kg
- SR-125km apogee (Mach3)

Venus, Mars, Titan

Lifting/Non-lifting
Stowed Volume
Aeroheating

SR-2

- 2m L/D=0.25 80kg
- Unguided, hypersonic Lifting capable
- SR-450km apogee (Mach 7)

ORB-1

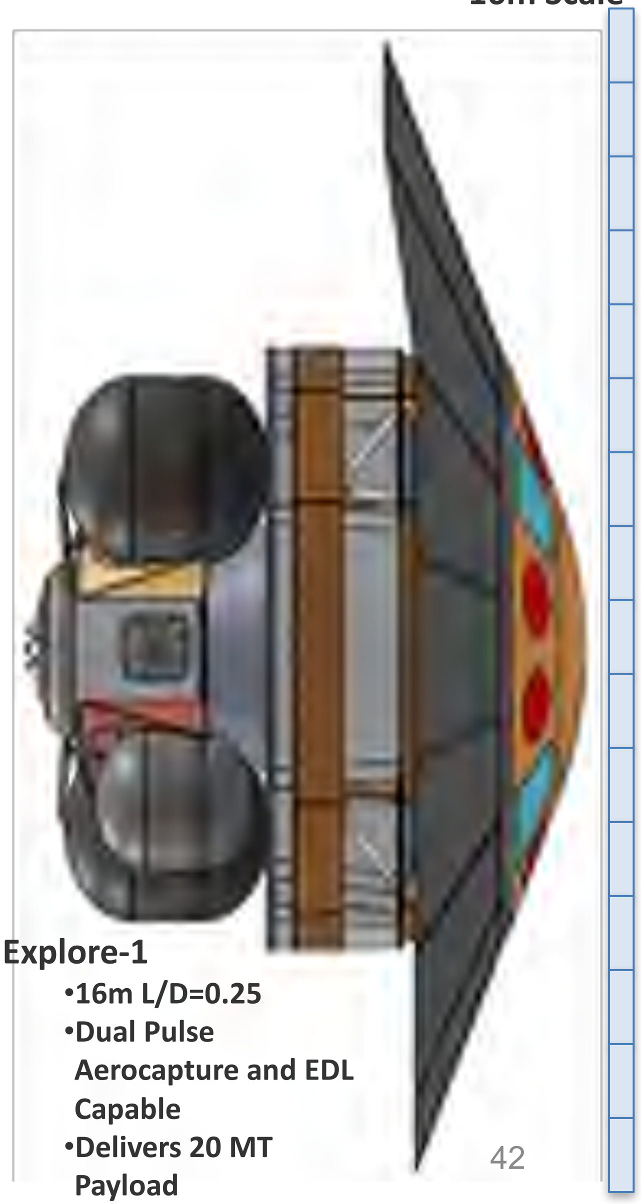
- 2m L/D=0.25 150kg
- LEO, Guided hypersonic flight

Large Mars Payloads

Lift Capability
Large Scale
Aeroheating

Mars Precursor-1

- 8m L/D=0.25
- Atlas LV compatible
- ~2mT landed payload
- Earth Demo Exploration-Class EDL Ops and Mars Entry Environments



Explore-1

- 16m L/D=0.25
- Dual Pulse Aerocapture and EDL Capable
- Delivers 20 MT Payload

ADEPT Mission Infusion Possibilities

2017 2020 2023 2026

SR-1

- 0.7m 70deg Ballistic 15kg
- SR-125km apogee (Mach3)

Mars Network Landers

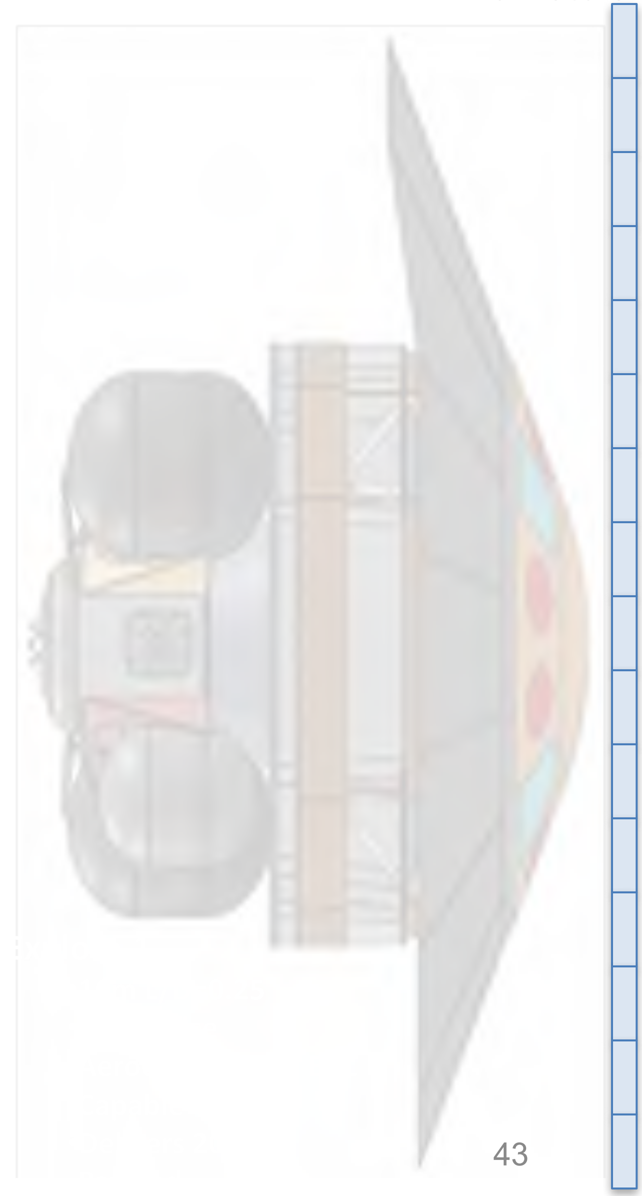
Venus, Mars, Titan

Lifting/Non-lifting
Stowed Volume
Aeroheating

Large Mars Payloads

Lift Capability
Large Scale
Aeroheating

16m Scale



ADEPT Mission Infusion Possibilities

2017 2020 2023 2026

Venus, Mars, Titan

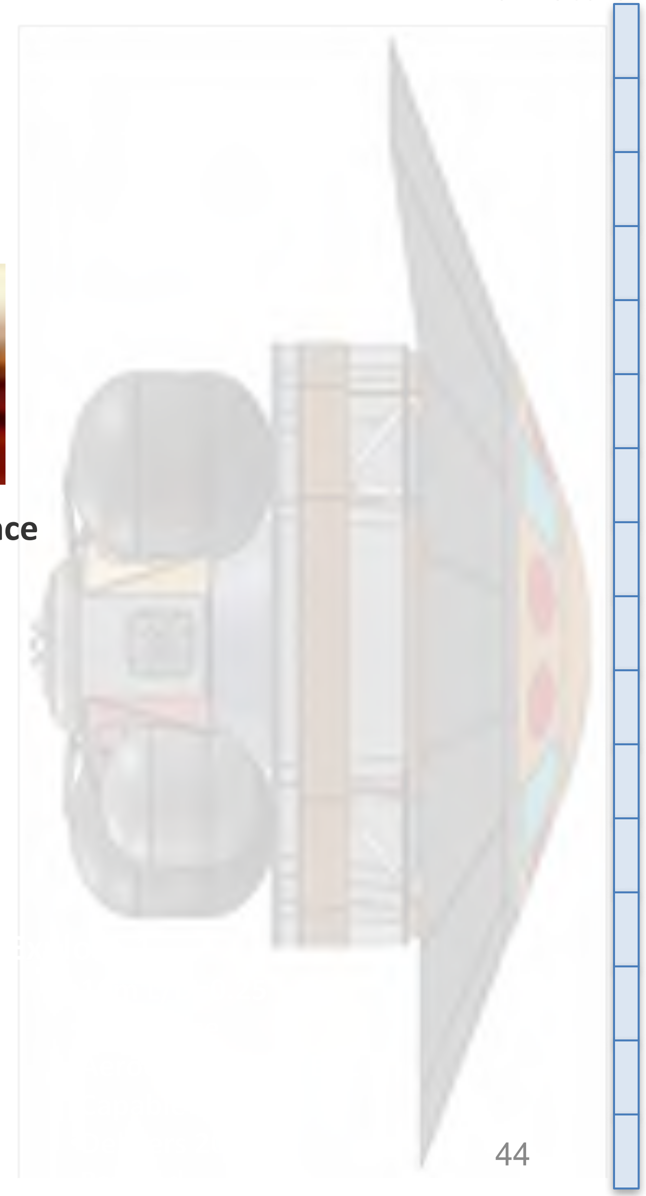
Lifting/Non-lifting
Stowed Volume
Aeroheating

Venus Atmosphere in-situ science

Large Mars Payloads

Lift Capability
Large Scale
Aeroheating

16m Scale



Lifting Nano ADEPT Flight Test Overview

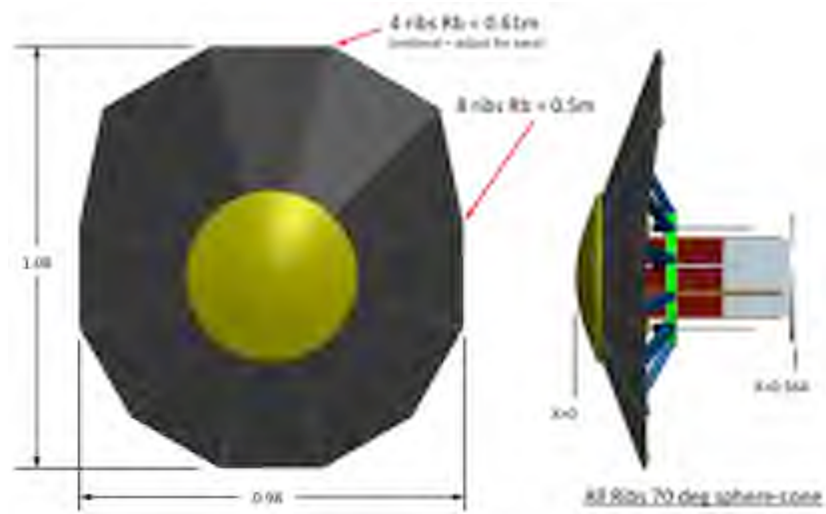
Problem / Current Solution:

- Large payload delivery to Mars Surface requires guided lift capability to support aerocapture and precision EDL concept of operations
- New capabilities for science missions to other planets (Venus, Titan, Mars) provided by Lifting ADEPT architecture
- Design of the mechanical deployable ADEPT for lifting configurations able to execute hypersonic guided flight
    - Demonstrate low L/D deployable capable of relevant heating environments

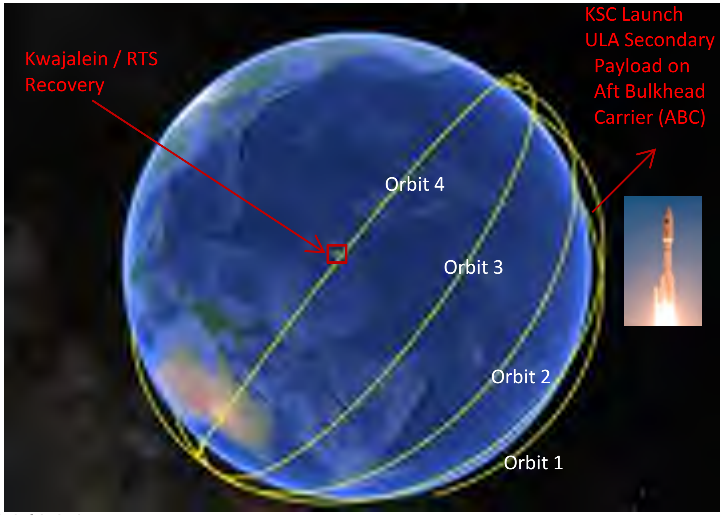
Proposed solution:

- Perform design studies of an Earth flight test (LEO) of an asymmetric shaped Nano (1m class)-ADEPT
- Leverages design experience from ADEPT SR-1 sounding rocket flight test

Lifting Nano ADEPT Vehicle Concept



Con-Ops Overview



Terminal Descent and Recovery

ADEPT Mission Infusion Possibilities

2017 2020 2023 2026

16m Scale

Venus, Mars, Titan

Lifting/Non-lifting
Stowed Volume
Aeroheating

Large Mars Payloads

Lift Capability
Large Scale
Aeroheating

Mars Precursor-1
- 8m L/D=0.25
- Atlas LV compatible
- ~2mT landed payload
- Earth Demo Exploration-Class EDL Ops and Mars Entry Environments

Medium Mars (Precursor Concept)

Concept Overview and Targeted Capability

- Atlas V 541 (4000 kg inject to Mars)
- 3500kg at Mars entry (500 kg cruise stage)
    - 2000+ kg payload to Mars surface
- Global access (deliver up to +2km MOLA)
- Subsonic parachute (Orion design), terminal descent prop
    - No supersonic chutes, No supersonic retro propulsion

Open Concerns:

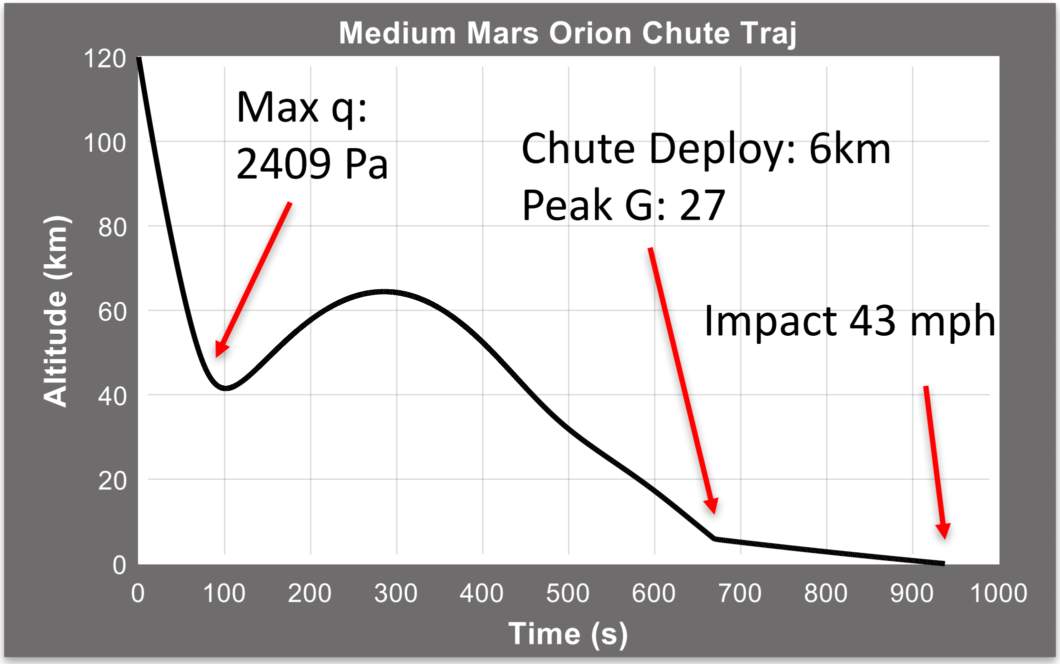
- Limited analysis to date, More trades and assessments needed
- Orion Chute opening process
    - Chute deploy Mach and q conditons
    - Drogue/Pilot deploy
    - Packaging volume
- Packaging and Entry trajectory design

Medium ADEPT Mars Characteristics

- 8.5m Diameter
- L/D=0.25
- m/CdA = 35 kg/m2
- Chute Term. Vel. = 19.2 m/s (43 mph)

Entry Conditions:

- Mass: 3500 kg
- V = 6 km/s
- H = 120 km
- Gam = -12°

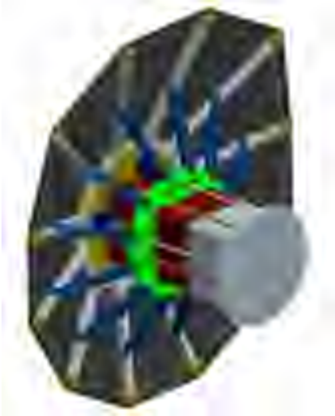


- Assumes shoot deployed at 8 km but does not open until 6 km
- Terminal descent prop burn not simulated

Summary

- **ADEPT SR-1**
  - "First step" flight experiment demonstrating ADEPT flight and operations
- **Looking beyond SR-1…**
  - Small spacecraft mission using an ADEPT EDL to overcome volume limits
  - Secondary payloads to Venus, Mars, and LEO entry are feasible near-term applications. Consider Discovery and New Frontiers pathways.
  - Nano-ADEPT provides technology development extensible to large ADEPT applications

1m ADEPT Mars Lander Malin SSS Concept (2014)



2m-3m Lifting ADEPT LEO Flight Test Concept NASA Ames & JHU-APL Study (2016)

8m Lifting ADEPT Mars Precursor Human Exploration