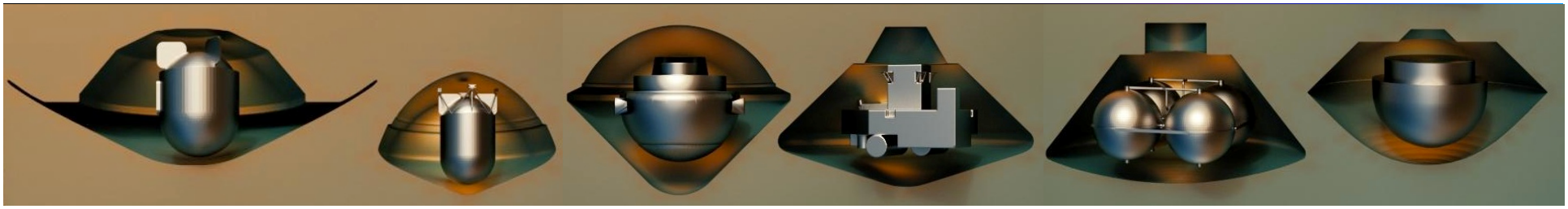

Entry, Descent, and Landing Systems Short Course

Subject: Hypersonic Inflatable Aerodynamic Decelerators (HIAD)

Author: Henry Wright
NASA – Langley Research Center

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Acknowledgements

- This module is a summary presentation of the elements to be considered when implementing a HIAD on a flight project.

- This work has been the subject of intense development over the last decade with multiple flight tests, numerous ground tests, and countless reviews, reports, and analyses

- There has been a focused team performing this development – where, without their diligence, this technology would remain just “another good idea”

Topics

- What is a HIAD?
- Aerocapture, Entry, Descent, and Landing (AEDL)
- Benefits of a HIAD
- Elements of a HIAD
- Environments of Interest
- Sizing a HIAD
  - Structure
  - Inflation Subsystem
  - Thermal Protection System (TPS)
- Other Considerations
- Summary
- Helpful Sources

What is a HIAD?

- ***HIAD: Hypersonic Inflatable Aerodynamic Decelerator***
- A HIAD is:
  - A deployable heatshield (forebody) for entry systems
  - A means of achieving a large entry drag area while remaining within the launch system constraints
  - An entry system comparable to existing blunt body entry systems
  - An entry system ***scalable*** across the spectrum of entry masses – from robotic through crewed-scale missions

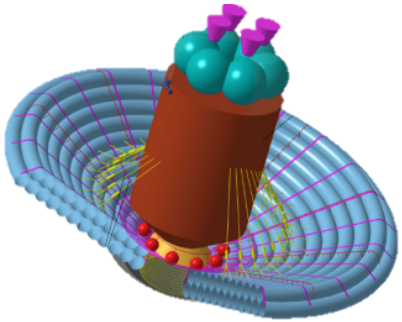
- HIADs include multiple different configurations

What is a HIAD?

Inflatable Re-Entry and Descent Technology (IRDT)

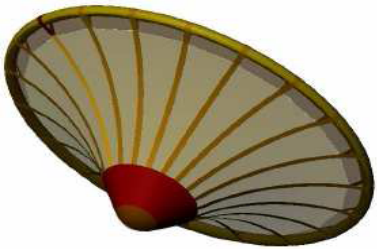
Inflatable Re-entry Vehicle Experiment (IRVE)

Mars Inflatable Aeroshell System (MIAS)

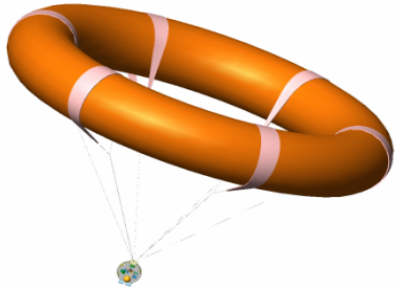


Flare

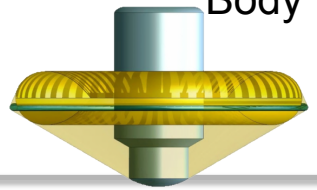
Hypercone



Trailing IAD

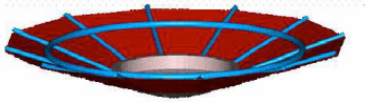


Ultra-High Performance Vessel (UHPV) – Dual Body

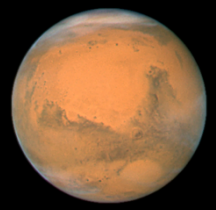


Spars & Rims

Spars & Rims

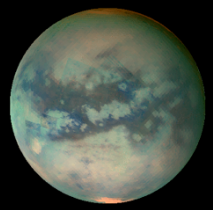


HIAD as Part of AEDL

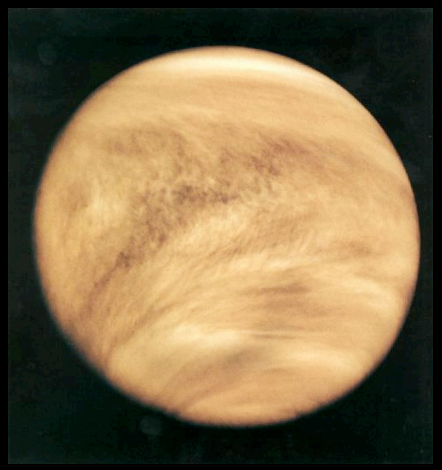


Mars

Earth



Titan

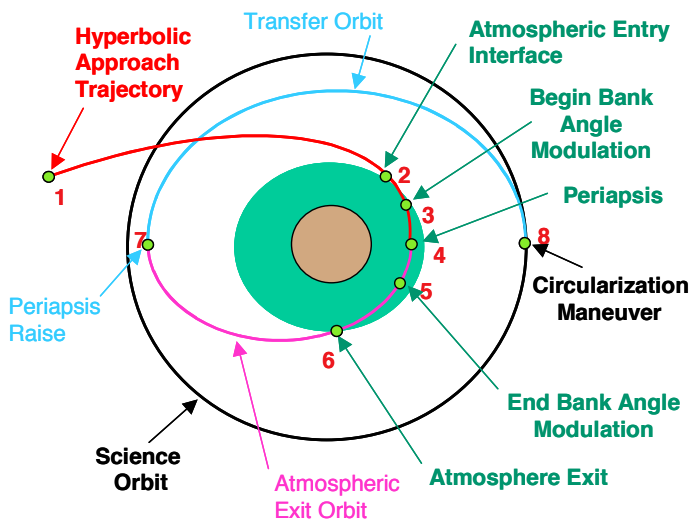


Venus

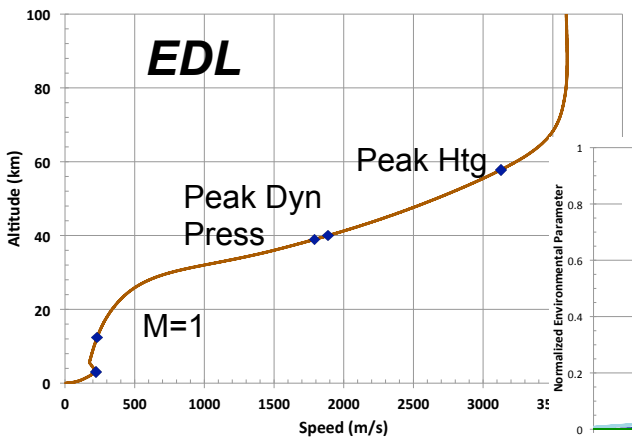
HIADs can be used wherever there is an atmosphere (except for the gas giants). HIADs can be used for Aerocapture or as part of an integrated EDL approach

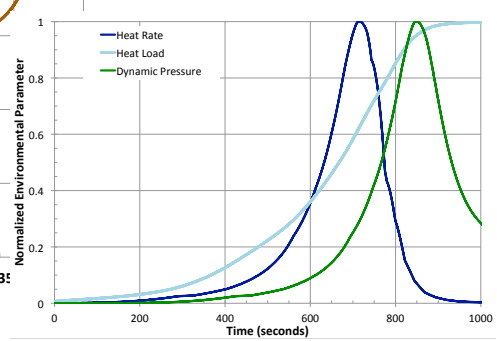
HIAD as Part of AEDL

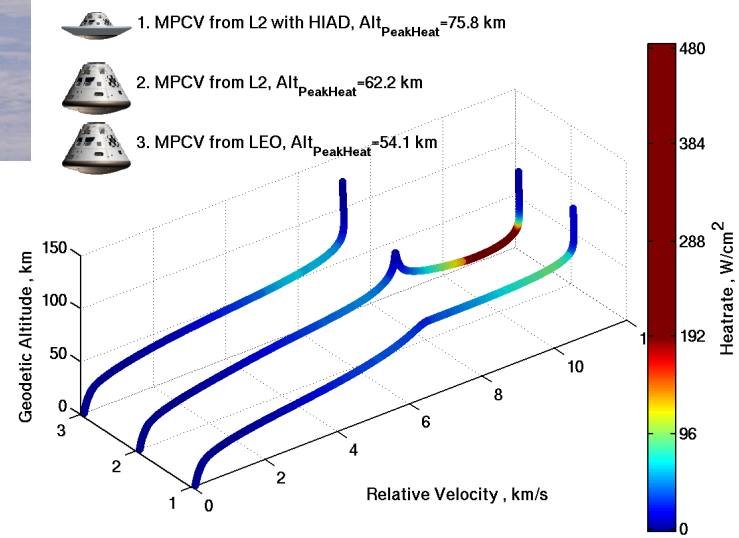
Aerocapture



HIADs can be used for Aerocapture; Traditional Entry, Descent, Landing; and as Augmentations to EDL systems







HIAD Augmentation to MPCV Lunar Return

Potential HIAD Benefits

Launch: reduced entry system mass leads to reduced launch mass – either use smaller (less cost) LV or increase C3 (launch flexibility)

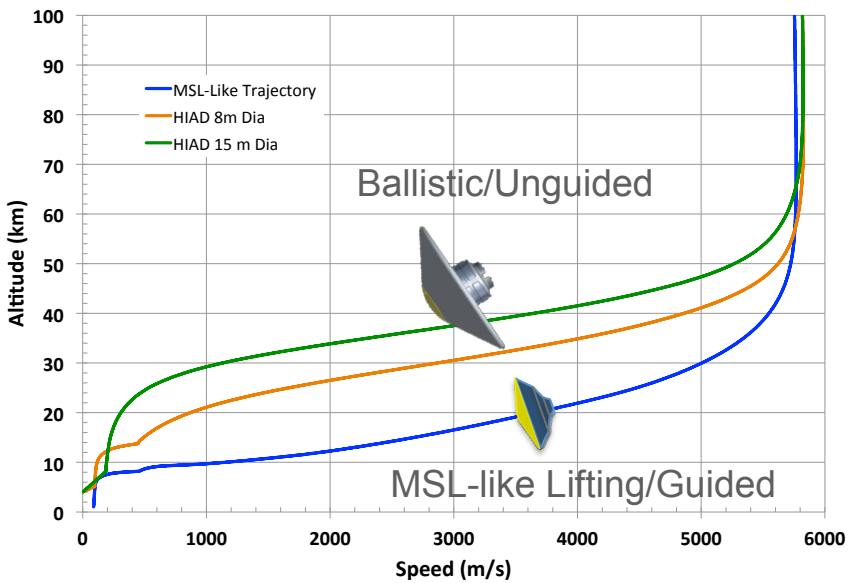
Spacecraft Flexibility: with HIAD being only a forebody, spacecraft is accessible longer in the mission integration flow; operational features visible during cruise reducing system complexity; not constrained by launch vehicle fairing size increasing spacecraft packaging flexibility

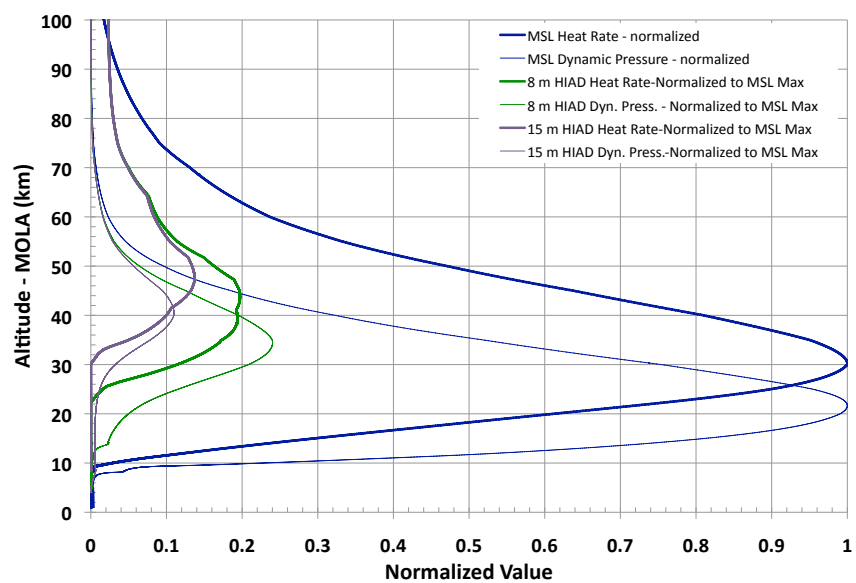
EDL Margins: deceleration higher in the atmosphere leads to - increased timeline margin between significant EDL events; access to higher surface elevation sites; option for steeper entry flight path angle resulting in a smaller landing footprint

Expanded mission potential and science return: HIADs allow larger payload masses to the surface

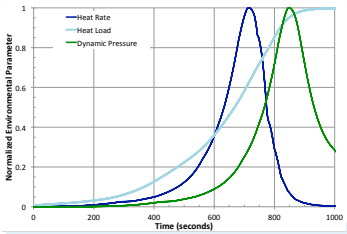
MSL-like Comparison

- Staging condition drives HIAD sizing
- 15-meter HIAD to subsonic retropropulsion allows MSL-class payload to +4 km MOLA with no supersonic or parachute events
- Staging at higher Mach numbers could allow significantly more payload mass
- Landed payload mass nearly constant over landing sites ranging from 0 to 4 km MOLA elevation





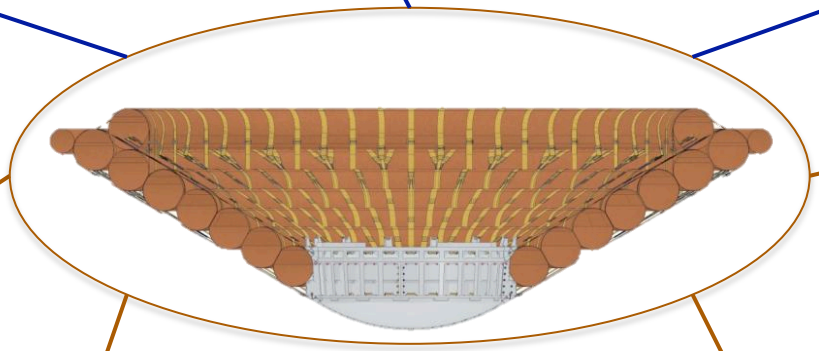
HIAD Implementation Considerations



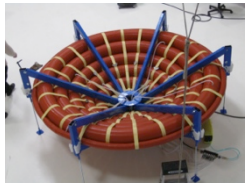
Environments
Heating, pressures, atmosphere

Size/Stability
Ballistic Coefficient, Cone Angle, Flow Impingement, Spacecraft Accommodation

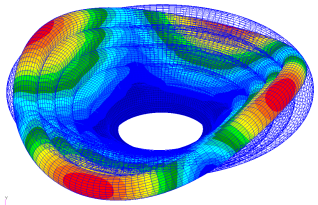
Intended Use
Entry vs Aerocapture
Lifting vs Ballistic



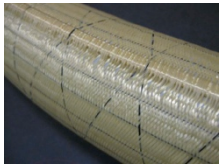
Fabrication

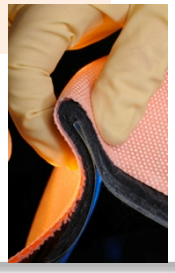


Analysis
Type, Margins, Factor of Safety

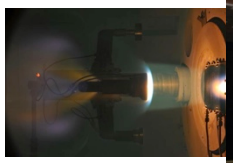


Materials
Mass, capabilities, availability

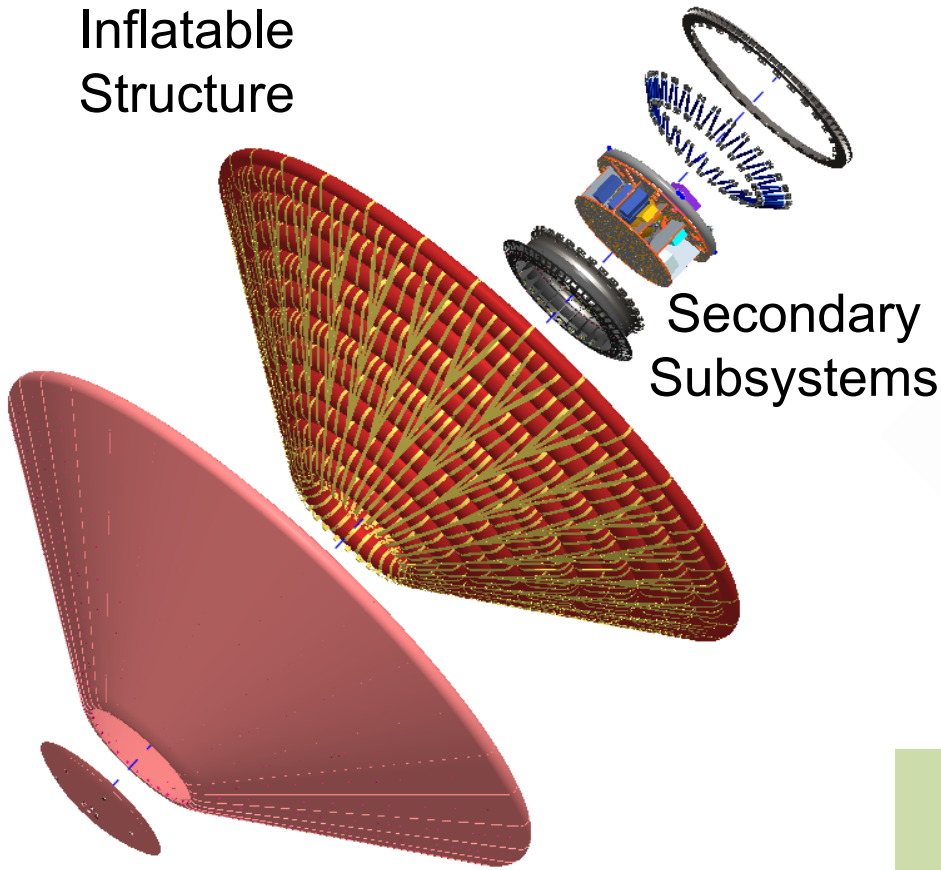




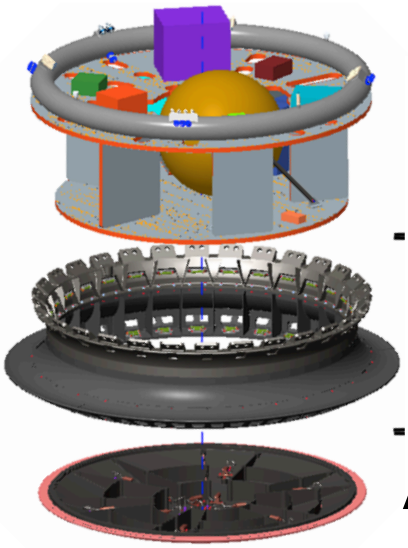
Testing



HIAD Elements



Secondary Subsystems



- Inflation, Data Acq., Control Avionics
- Rigid Structure for HIAD Attachment

HIAD Shapes may be different, but all have these elements

Arrival Environments

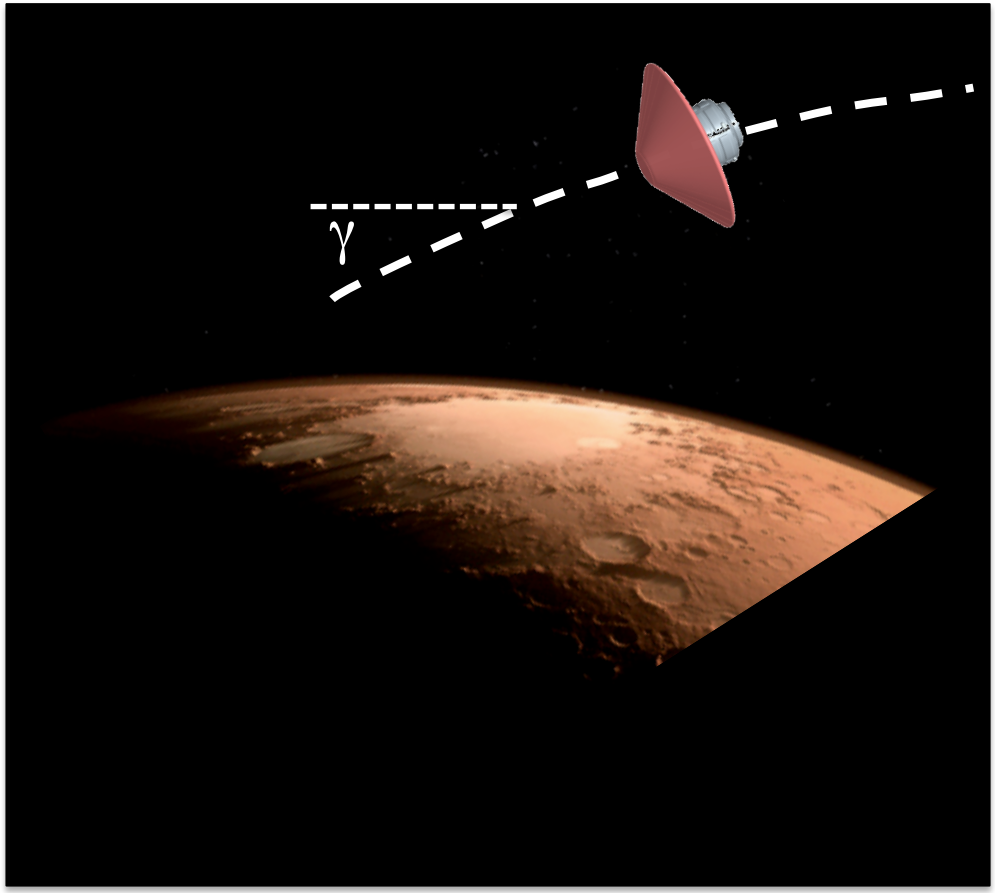


Image source: http://newsfeed.time.com/2012/02/21/picky-eaters-need-not-apply-nasa-seeks-taste-testers-for-mars-simulation/

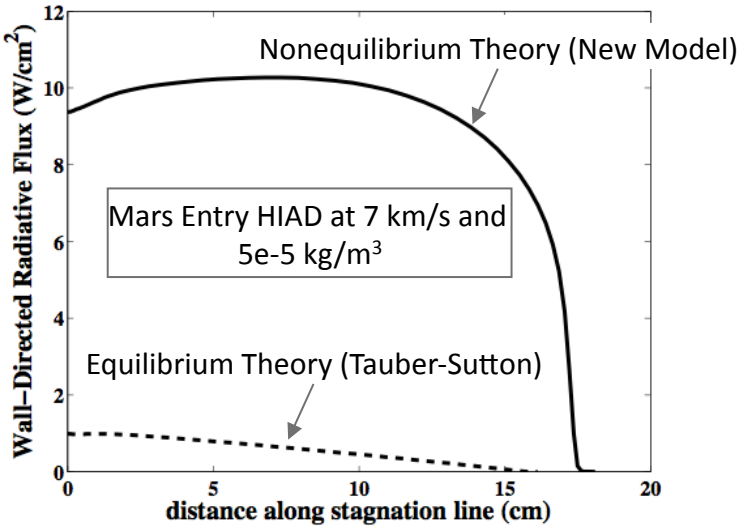
- Entry Speed
  - Defines energy level
  - Mars 5.5 to 7.4 km/s
  - Titan ~6 km/s
  - Venus 10 – 12 km/s
  - Earth 7.5 to 12 km/s
- Flight Path Angle (γ)
  - Key element of loads
  - Influences footprint size
- Atmosphere
  - Density
  - Speed of Sound
  - Scale Height

Environment Design Considerations

- HIADs – low ballistic coefficient, typically between 10 to 50 kg/m^2
- Not constrained by LV fairing – have greater flexibility to tailor to conditions – within LV mass constraints – and environmental limits
- Peak Heat Rates – with margins
  - Less than 45 W/cm^2 for demonstrated systems
  - Less than 75 W/cm^2 for systems in near term development
- Heat Loads – mass consideration versus material choice
- Peak Dynamic Pressure
  - Prefer less than 5000 Pa
  - Can accommodate higher with some additional design features
- Local features of interest
  - Local deformations between toruses leading to increased local heat rate
  - Radiative heating due to larger entry system (secondary effect)
  - Relative motion between HIAD and rigid part of system – leads to effective angle of attack

Aerothermal Modeling

- Update engineering models for convective and radiative heating using state-of-the-art prediction methods.
- Previous Models:
  - Sutton-Graves correlation for convective heating assumes thermochemical equilibrium stagnation point flow.
  - Tauber-Sutton correlation for radiative heating assumes thermochemical equilibrium stagnation point flow.
- These previous models are inadequate for the high-altitude nonequilibrium conditions of interest for HIADs.



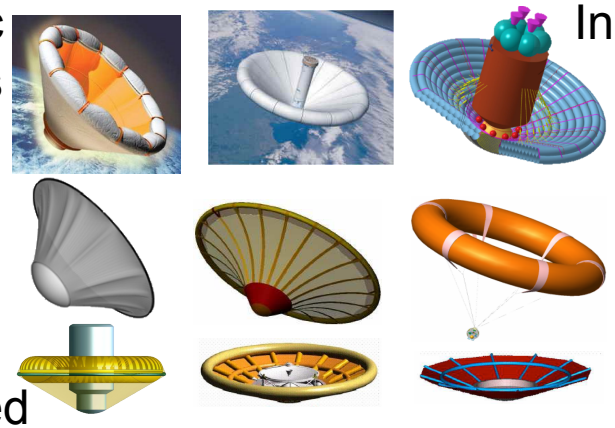
HIAD Structural Sizing

Geometry

- Basic Shape/Type
- Max Dia – Ballistic Coeff & Flow Impingement
- Ratio of Rigid to Inflatable
- Thickness – Torus Size, etc
- Cone Angle & Nose Radius
- Shoulder radius

Manufacturing

- Materials – Type, Ballistic Coeff
- Seams/Joining
- Reinforcing
- Handling
- Inspection



Other

- Accommodation
- Stowage
- Mass - limits
- TPS integration

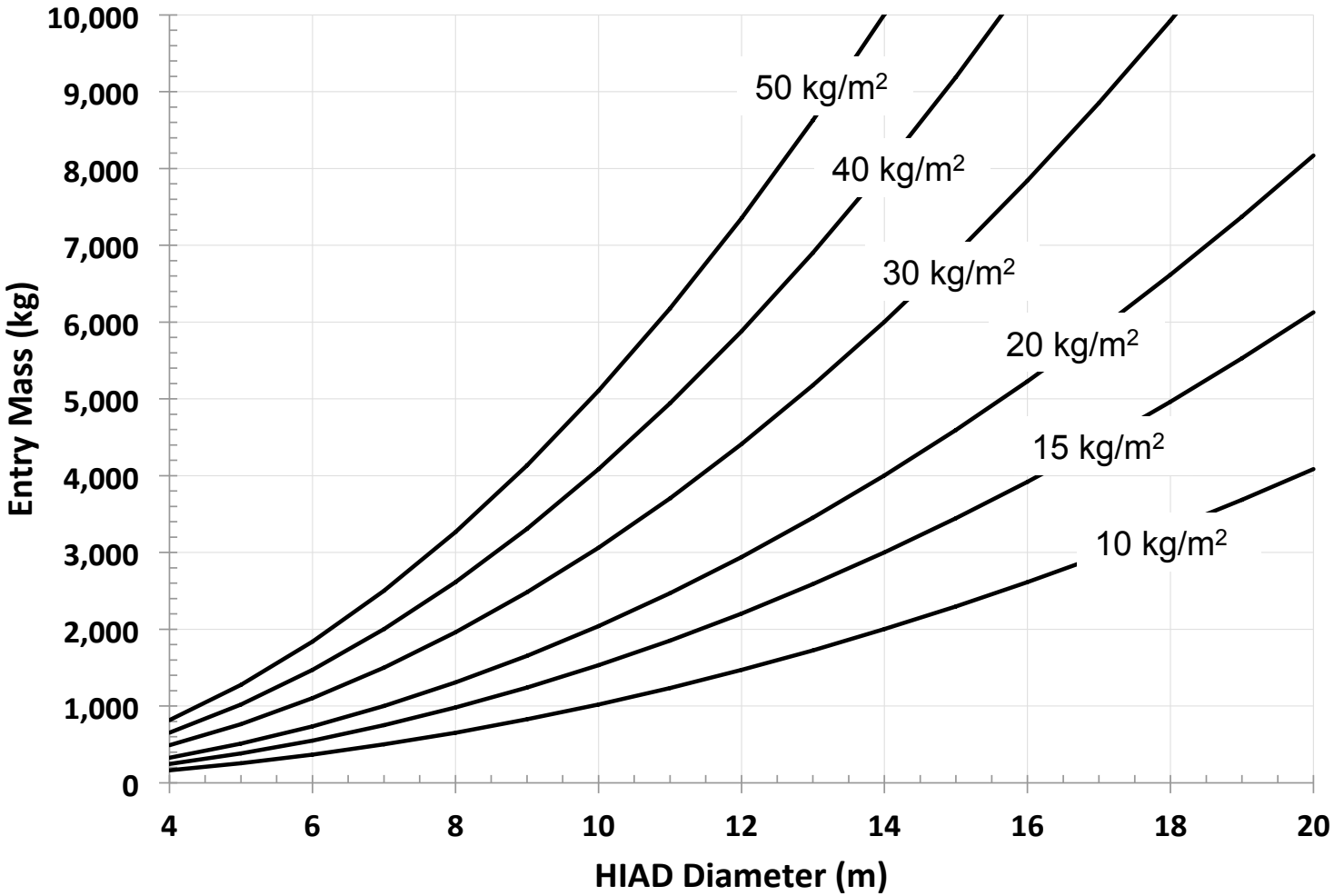
Design/Analysis

- Loads – Stowed and Inflated
- Loads – Static and Dynamic
- Load paths – straps, etc.
- Inflation - gas/pressure/leakage
- Factors of Safety
- Knockdown Factors
- Allowable deflections

Testing

- Structural Qual
- Allowable Deflections
- Buckling
- Model Correlation
- Development Units

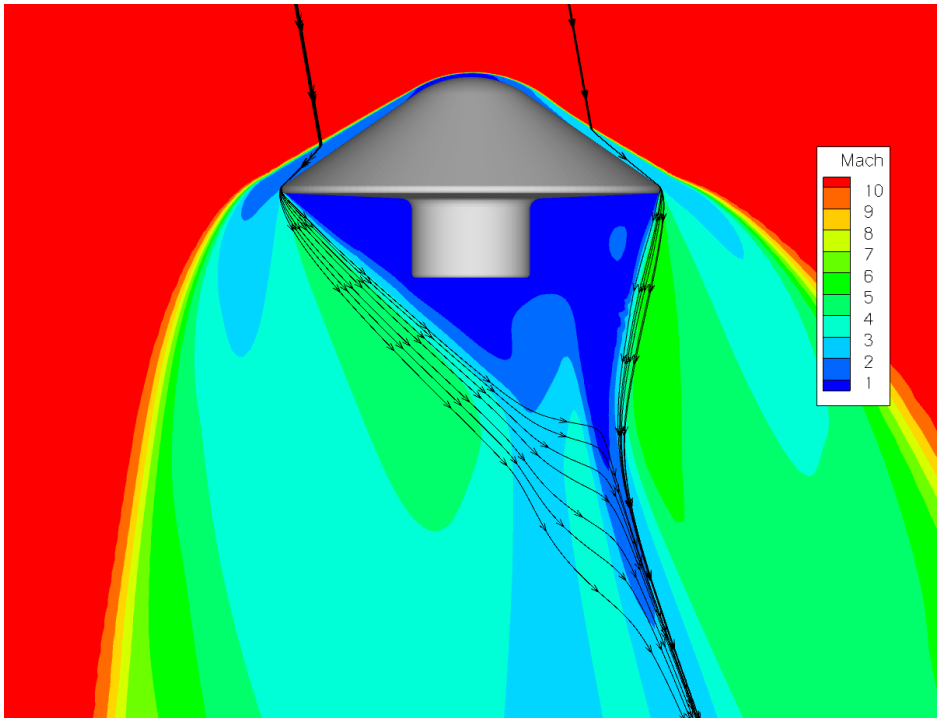
Size – Ballistic Coefficient



Note: Curves will shift based on blunt configuration – C_D – Typical range is 1.2 – 1.5

Size – Angle of Attack

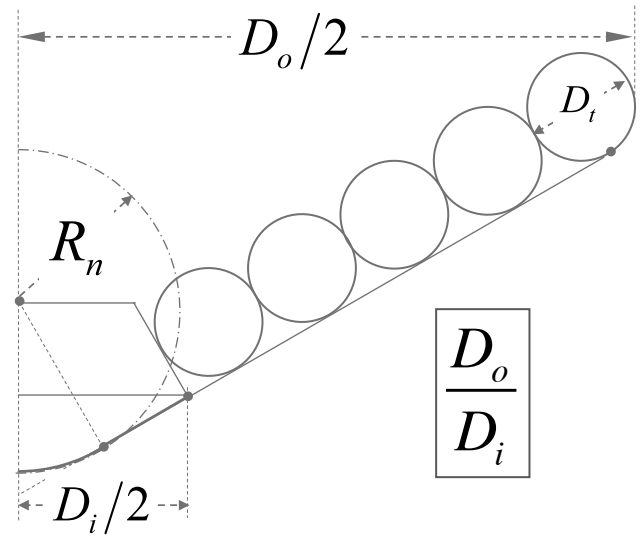
- HIADs can fly at an angle of attack and generate lift
- Flow impingement on payload can contribute to desired size of HIAD
- Impingement during hypersonic flight – ***payload heating***
- Impingement during supersonic or transonic flight – ***stability***



Stream lines for 10 degree angle of attack, Hypersonic Mach No.
(Courtesy John Van Norman)

Size – Inflatable to Rigid Ratio

- HIADs typically have a rigid central structure for load reaction and payload attachment
- Maximum Diameter to Rigid Diameter ratio:
  - Can influence cone angle (drag)
  - Can influence structural modes (dynamic coupling)
- Upper bound defined through testing
  - Increasing ratio can reduce ballistic coefficient - reduced environments
  - Increasing internal pressure can allow for larger ratio
  - Increasing depth of inflatable can allow for larger ratio
  - Inclusion of additional radial structures can allow for larger ratio
  - Demonstrated range of 3 to 5.5 without significant changes



Factor of Safety Considerations

Historical Values for Inflatable Design Factor of Safety

- 4 per NASA STD 5001, Table 6
- 4 for airship (FAA airworthiness requirement, 881)
- 5 for inflatable lunar habitation (Roberts 1992)
- 4-5 for inflatable lunar habitation (Ruess et al. 2006)
- 3 for STEM lunar habitat (Cadogan et al. 1999)
- 5 for airlock (Cadogan et al. 98)
- 3 for tanks and 4 for lines (Human-Robotic Hybrids for Deep-Space EVA)
- 1.6 for Venus balloons (Izutsu 2000)
- 1.5 – 1.7 for Parachutes per JSC 65828; Table 3.3.1.5-1

Structural Knockdown Factors

- Need to consider allowable strength when loads applied at elevated temperatures
  - Vendor data - long duration exposure
  - Flight exposure – short duration
- Vendor data useful – starting point
  - Sacrificing system mass when use vendor data
  - Can realize mass savings through focused material characterization testing

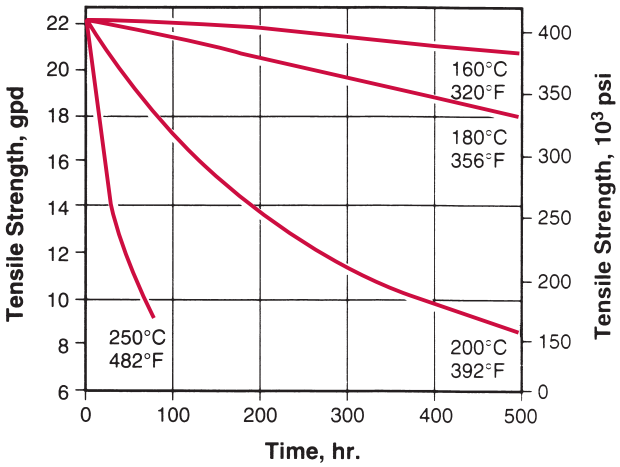


FIGURE 2.7. Effect of Elevated Temperatures on the Tensile Strength of KEVLAR® 29.

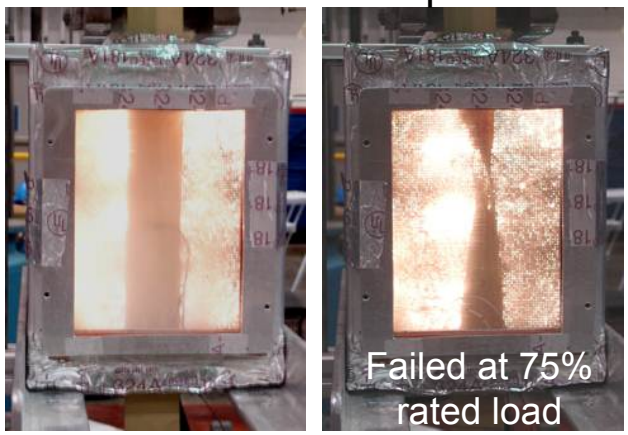
Kevlar Technical Guide (Dupont)

Examples of Material Testing

Inflatable Structure Material Property Testing from HIAD Project (LaRC)

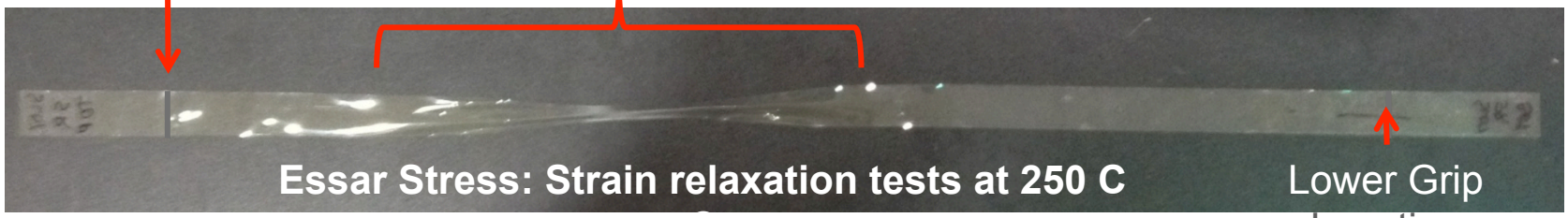
- Intent is to test materials to failure over range of temperatures - 20°C, 250°C, 350°C, 400°C
  - Technora Webbing tensile tests
  - Zylon Webbing tensile tests
  - Carbon fiber webbing tensile tests
  - Essar Stretch 225 Tests
  - High Temperature Silicone adhesives

Technora Load Application
Elevated Temp



Upper Grip Location

Specimen necking due to heating

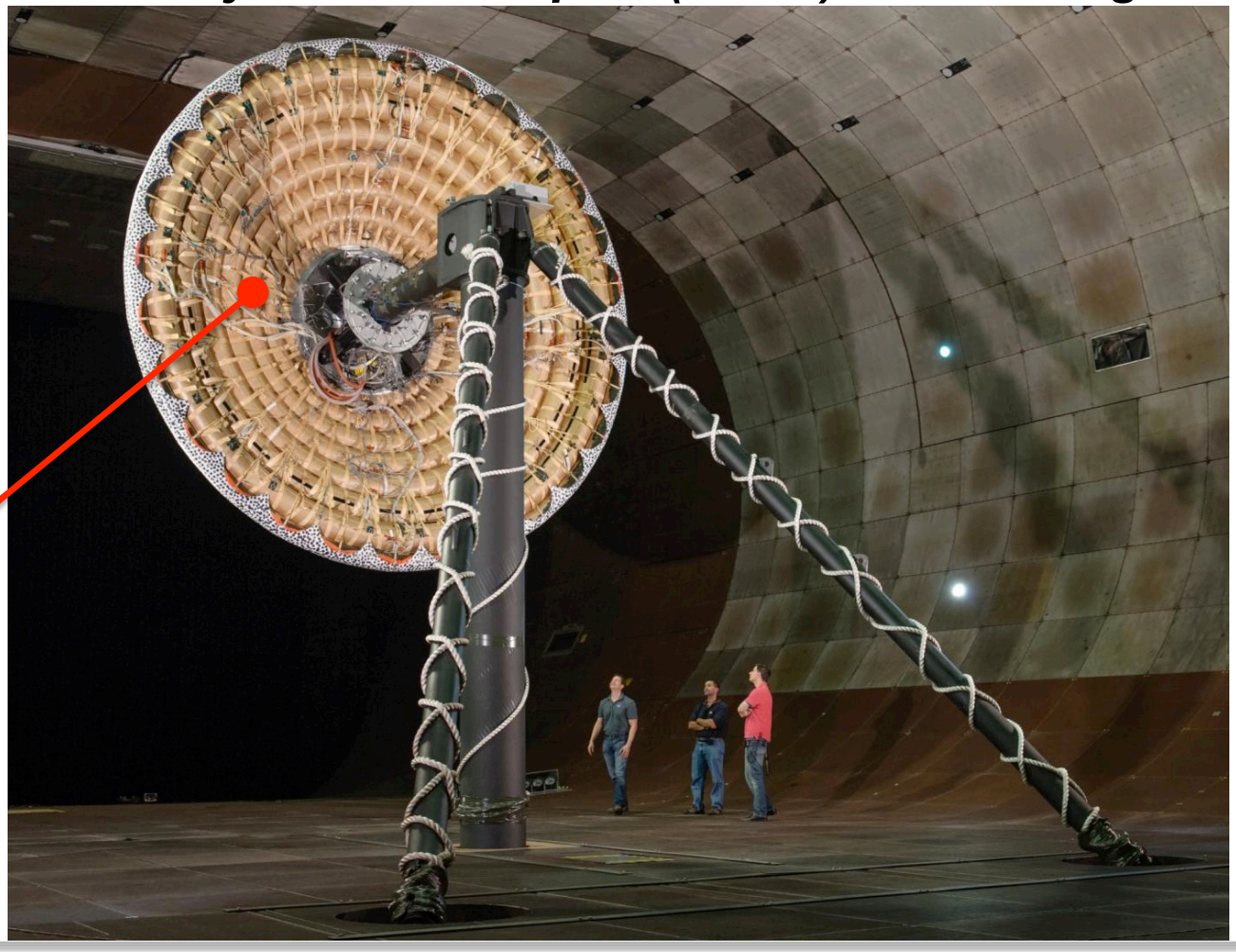


Lower Grip Location

Aero Load Testing

Aerodynamic load testing (model validation) at National Full-Scale Aerodynamics Complex (NFAC) – 40x80 Leg

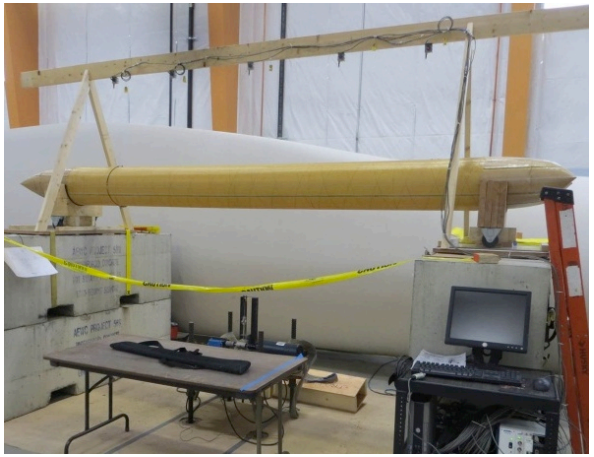
6m HIAD



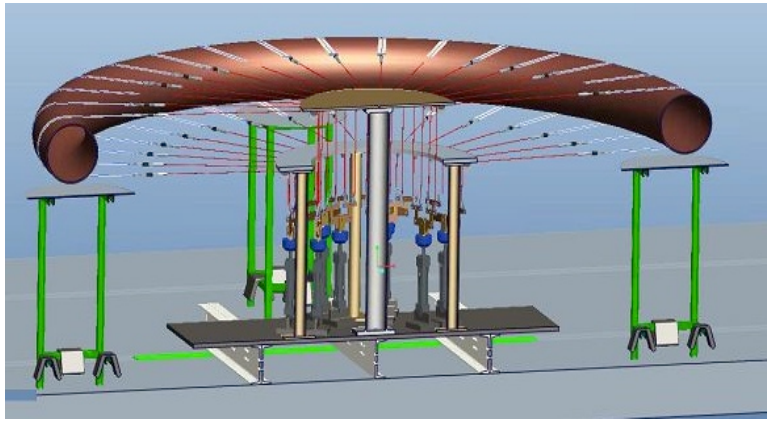
Structural Properties

- Base effort to improve modeling of fundamental elements *(HIAD Project – LaRC)*
- Establishes proven technique for modeling these types of elements

Tension/Torsion Test (Univ. of Maine)

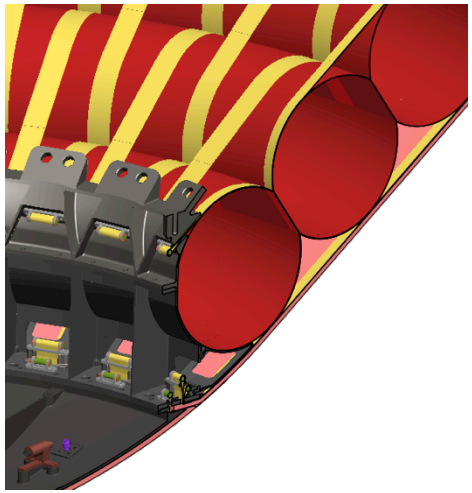


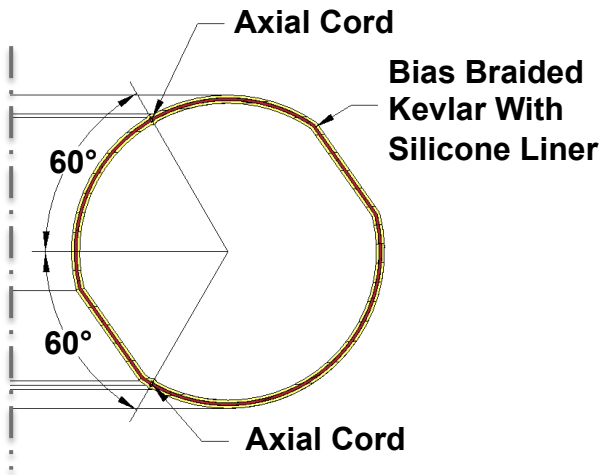
Beam Four Point Bending Test (Univ. of Maine)



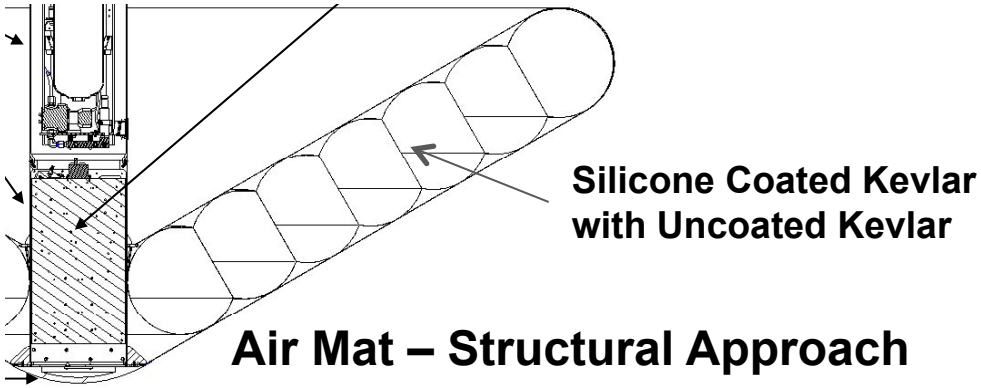
Torus Compression/Torsion Test Fixture (NASA Dryden)

Components

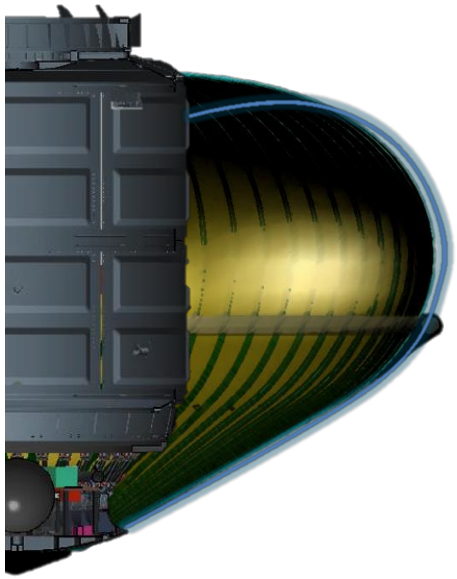




Stacked Torus – Structural Approach (IRVE-3)



Air Mat – Structural Approach (IRVE-II)



Ultra-High Performance Vessel – Membrane Structural Approach

Inflation Subsystem

- Exoatmospheric inflation requires use of on-board inflation subsystem
- Inflation pressure influenced by:
  - Aerodynamic load
  - Vehicle stiffness
  - Reducing local deflections

$$P_{\min} = F_{aero} \frac{4}{3\pi} \frac{\tan\theta \sin\theta}{Dd}$$

F_{aero} – applied drag force
θ – cone angle
D – maximum diameter
d – thickness of HIAD
From AIAA-2009-2970
Estimating Minimum Inflation Pressure for Inflatable Aerodynamic Decelerators (Glenn Brown)

- Compressed gas
  - Simple storage and pressure control
  - Thermal control – isentropic expansion from pressure vessel; adiabatic expansion through pressure control valve; isentropic compression during HIAD inflation
- Gas Generator
  - Reduce water and carbon dioxide content
  - Thermal management of gas generated

$$M_{gas} = VOL_{\inf} \frac{P_{\inf}}{RT_{\inf}} K_{\text{margin}}$$

M_{gas} – Mass of Inflation Gas
VOL_{inf} – inflated volume
P_{inf} – final inflation pressure
T_{inf} – final inflation temperature
R – Gas constant for inflation gas
K_{margin} – Margin to account for leakage, makeup, etc.

Requirements of Flexible TPS

Environments

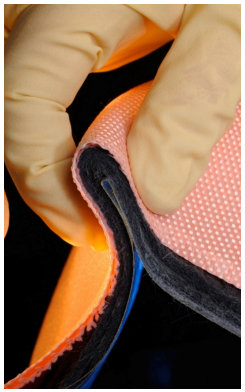
- Heat rate
- Heating augmentation
  - Turbulence, Local effects, Radiation, catalycity
- Integrated heat load
- Stagnation Pressure
- Shear
- Atmosphere

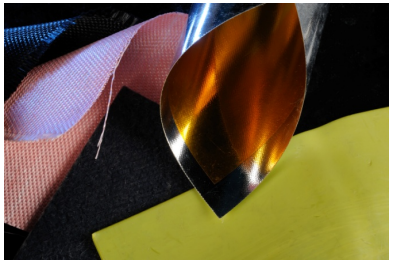
Materials

- Areal weight - low
- Permeability – low
- Temperature limits
- Thermal transport – low
- Material malleability
- Material uniformity after packing

Analysis

- Modeling of key physical processes
- Repeatable performance
- Testing – properties and certification
- Margins





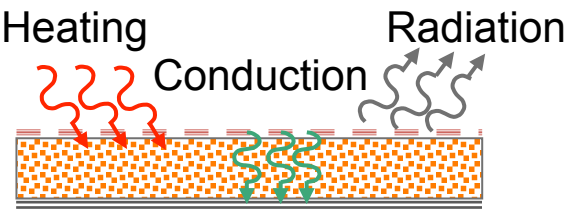
Stowage

- High density packing – ~400 kg/m^3 packed &~40 kg/m^3 deployed)
- Fold materials to a hard crease while retaining functionality
- Deploy after long duration storage at high packing densities without significantly changing thermophysical characteristics

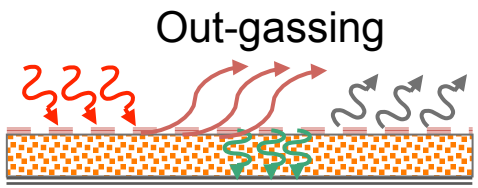
Manufacturing

- Assembly methods
- Handling
- Inspection
- Installation of sensors

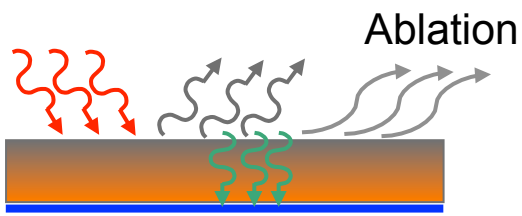
Flexible TPS Mechanisms



Fully-Insulative
20-50 W/cm^2



Transpiration-Insulative
30-100 W/cm^2



Ablative
75-150 W/cm^2

- **Fully Insulative**
  - Heating managed by conduction and re-radiation
  - Supports short duration (<200 seconds) mission profiles of 20 to 50 W/cm^2
- **Transpiration-Insulative**
  - Heating managed by conduction, re-radiation, and endothermic processes in active out-gassing
  - Supports a range of long duration (<500 seconds) and mid range entry profiles of 30 to 100 W/cm^2
- **Ablative**
  - Heating managed by pyrolysis and characterized by recession of material
  - Supports long duration (>500 seconds) and high heating entry mission profiles of 75 to 150 W/cm^2

Sizing the TPS

- Determine margin approach
- Determine backside temperature upper limit
- Select outer layer material
  - Extract peak heat rate from trajectory/aerothermal
  - Assess heat distribution – localized heating vs acreage heating
  - Consider heating augmentation – turbulent augmentation (transition vs tripping); radiative
- Select insulating layer material layup
  - Determine integrated heat load
  - Determine TPS mass
- Iterate results to optimize mass

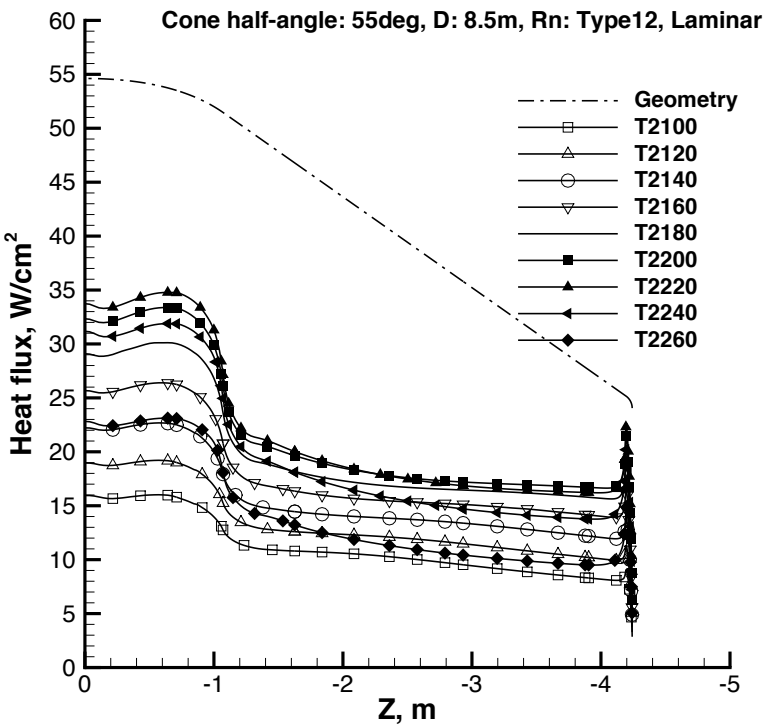
Flexible Thermal Protection Function

Heat Rate	**Refractory Cloth**
Heat Load	**Insulator**
Permeability	**Gas Barrier**

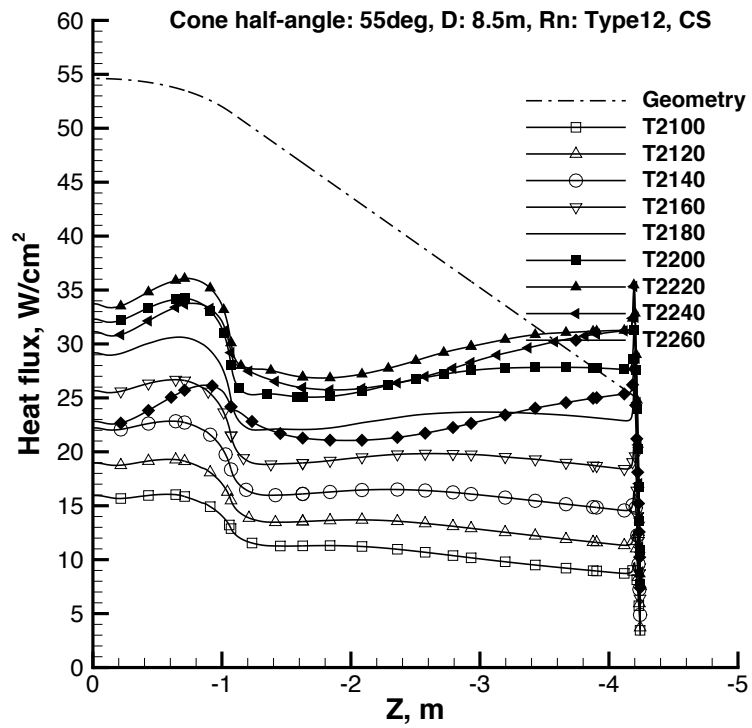
Modular design using functional layers

Heating Augmentation - Turbulent

Laminar



Turbulent

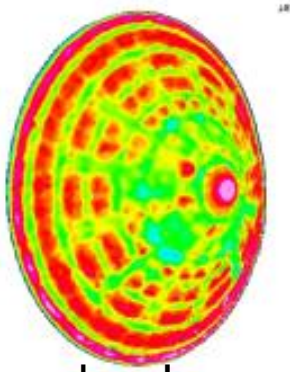


Comparison of Laminar vs Turbulent heating on a generic HIAD – natural transition
Shows with long running length, turbulent heating can exist on acreage.
Transition using Re_θ criteria - presence of transition can depend on cone angle

Heating Augmentation - Local

- "Flexible" nature of HIADs result in some local deformations
- Local deformations can lead to localized heating – eddies, etc.
- Assess heating augmentation via testing and analysis
- Typical results indicate modest increase in heat rate – less than turbulent effects
- But need to be assessed in conjunction with turbulence – additive, etc.

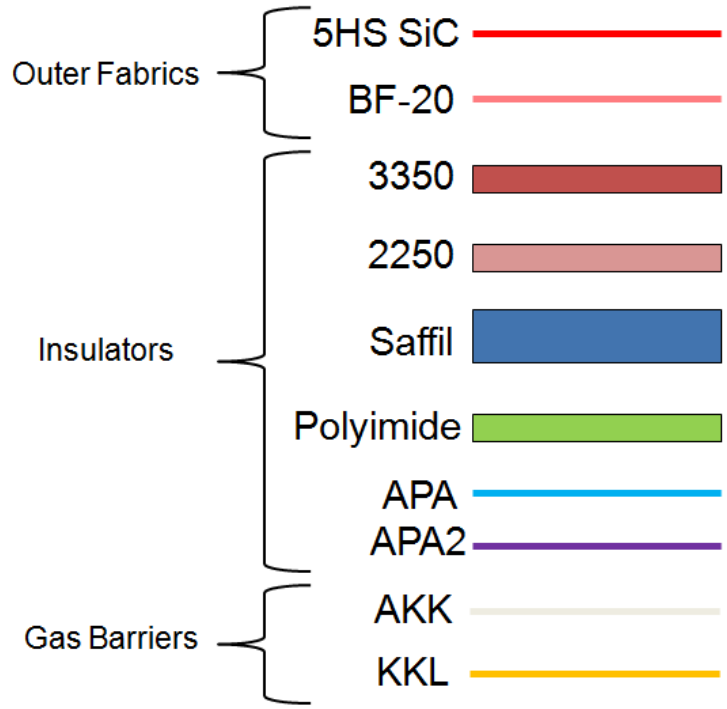
Model of deflected HIAD Shape



Phosphor Image of Local Heating

Material Considerations

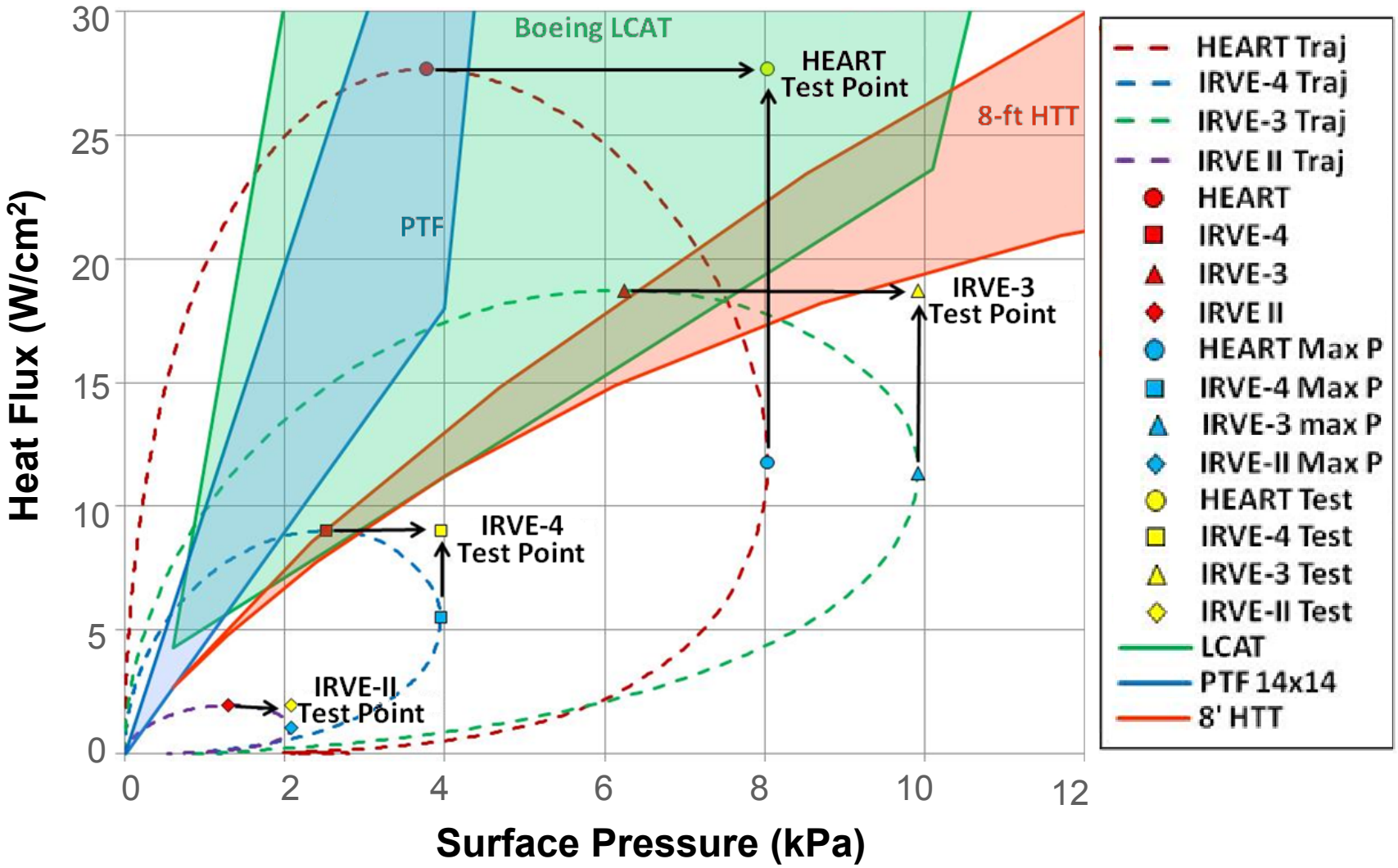
- Outer Fabrics
  - Nextel – BF-20 – 505 g/m^2
  - Nicalon – Silicon Carbide – 425 g/m^2
- Insulators
  - Pyrogel – 3350 – 510 g/m^2
  - Pyrogel – 2250 – 340 g/m^2
  - Saffil – 1220 g/m^2
  - GFA-5
  - OFI-2
- Gas Barrier
  - Sheldahl – Kapton covered Kevlar – 130 g/m^2
  - Sheldahl – Aluminized Kapton covered Kevlar – 130 g/m^2



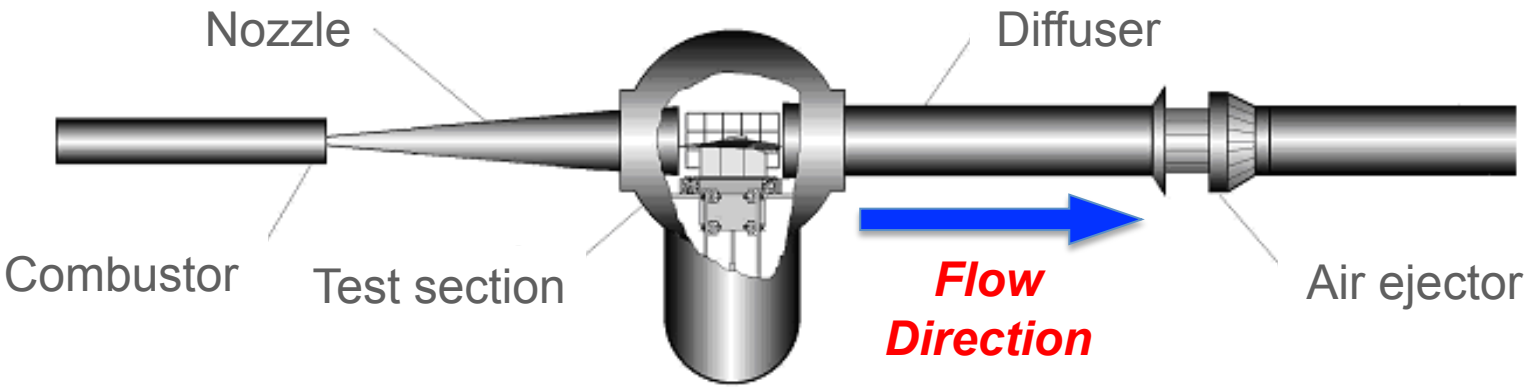
Verification

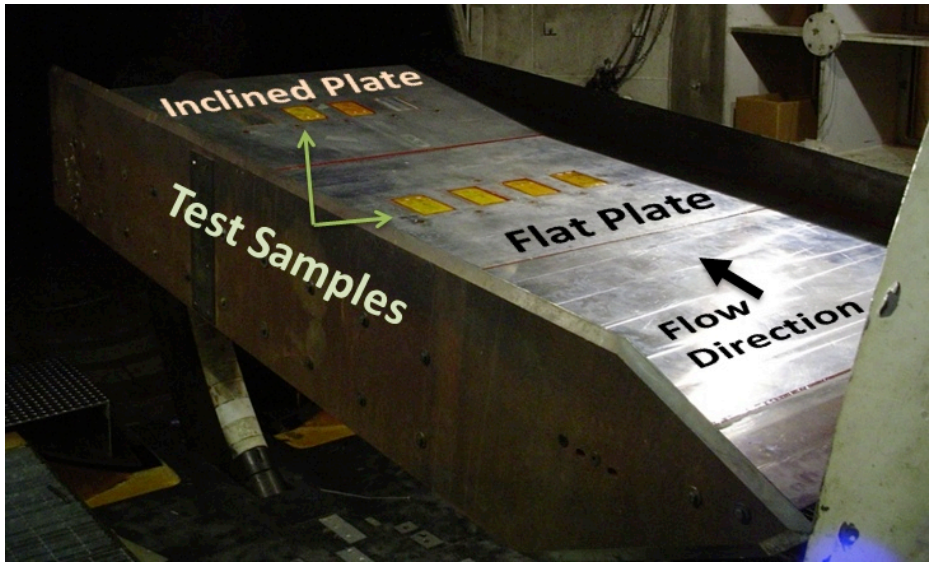
- As with traditional ablative TPS – Flexible TPS needs to have Flight Lot Certification as part of the final implementation
- Testing early in a program is a good idea to establish the design performance for the specified layup
- Need to establish flight to ground correlations
  - Need to convert the “hot-wall” heat rate from the trajectory and CFD to an Arc-Jet “cold-wall” heat rate
  - Need to determine test approach – square pulse vs profile
  - Need to consider other conditions – stagnation, shear, etc.

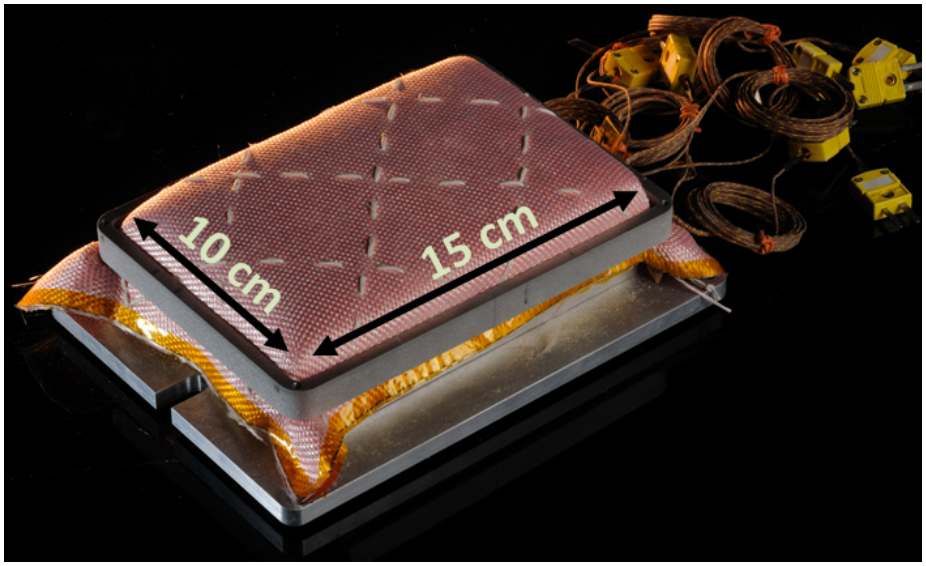
Mission Profiles/Facility Envelopes



8-ft High Temperature Tunnel (8'HTT)



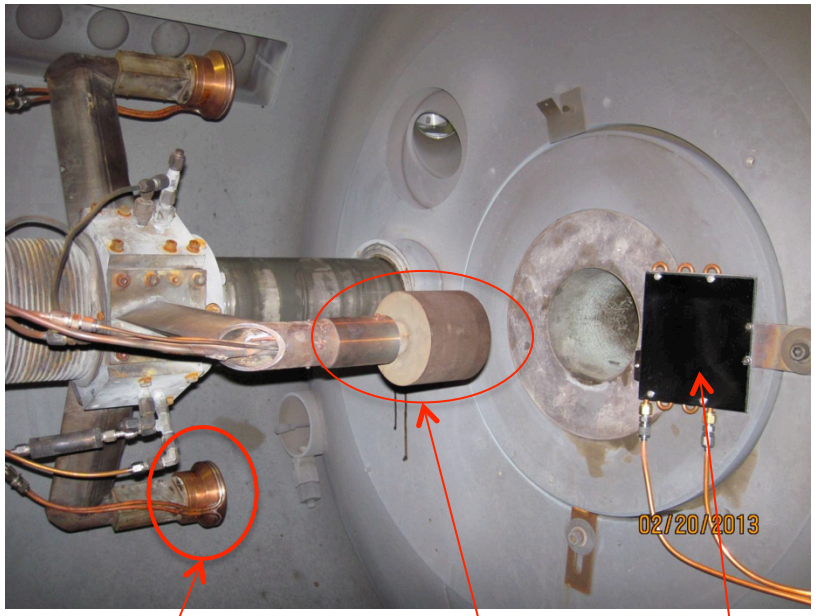




- **Located at NASA Langley Research Center**

Boeing LCAT

Boeing – Large Core Arc Tunnel (LCAT) – St. Louis, MO

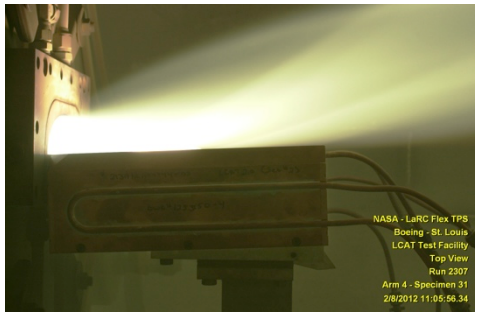


Test Article (Stagnation)

Calibration Gauge

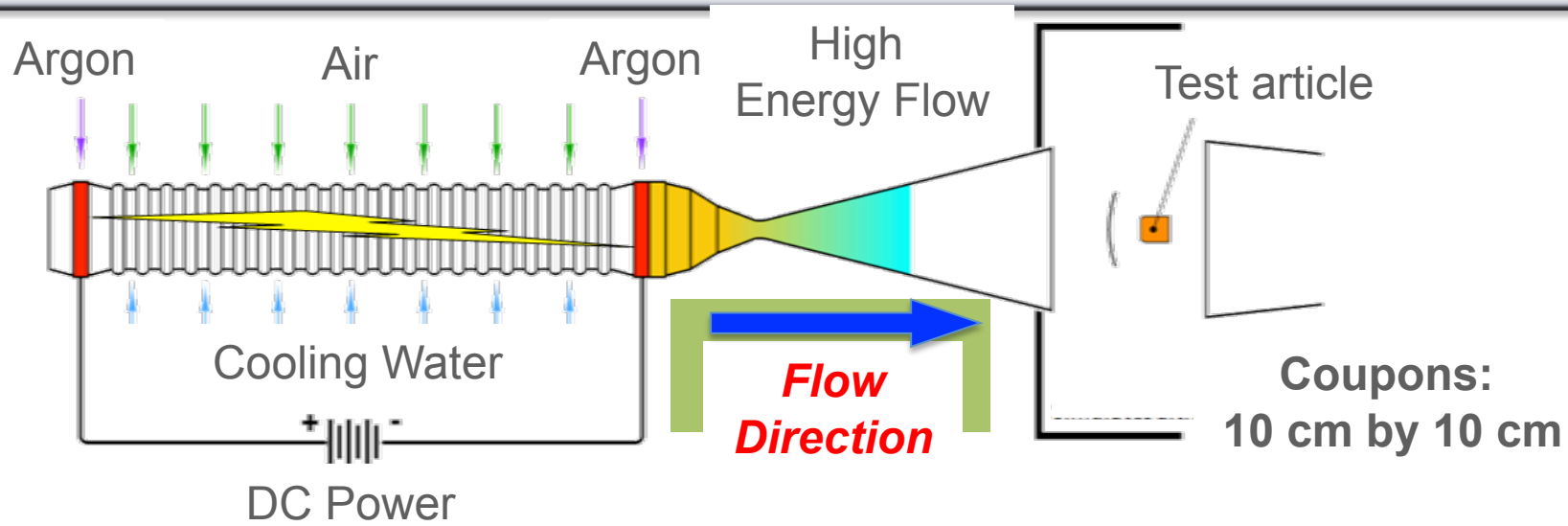
"Mirror"

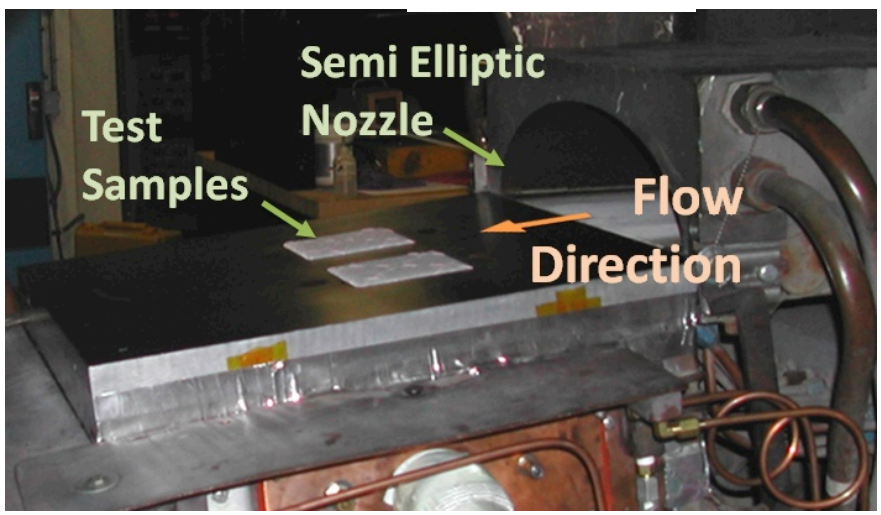
Stagnation Testing

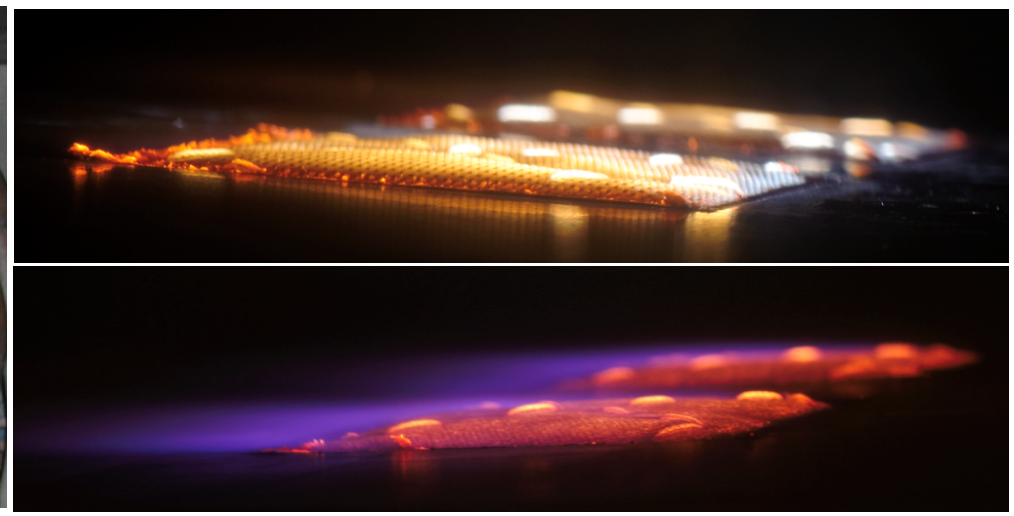


Shear Testing

Panel Test Facility (PTF)





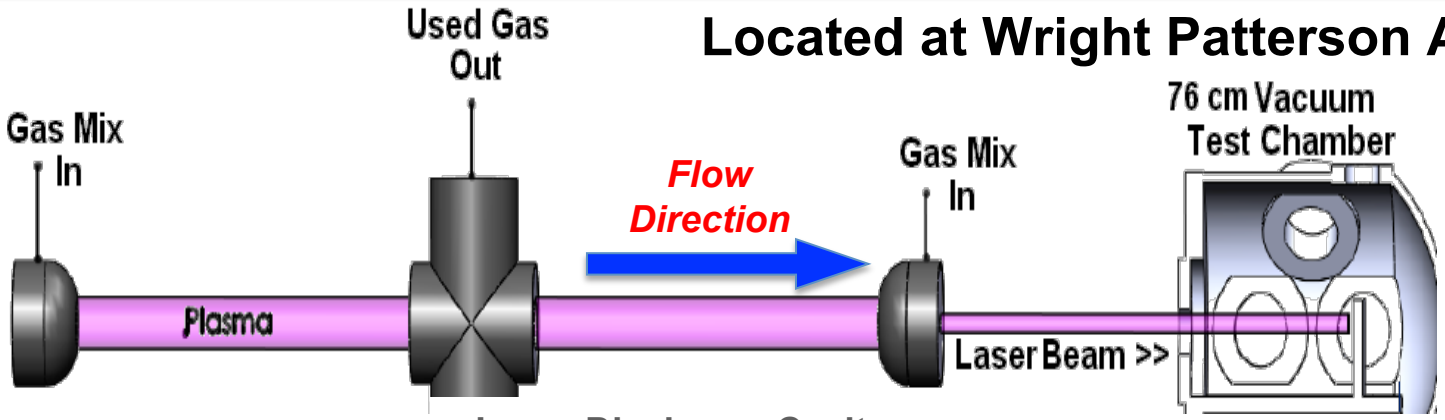


Located at NASA Ames Research Center

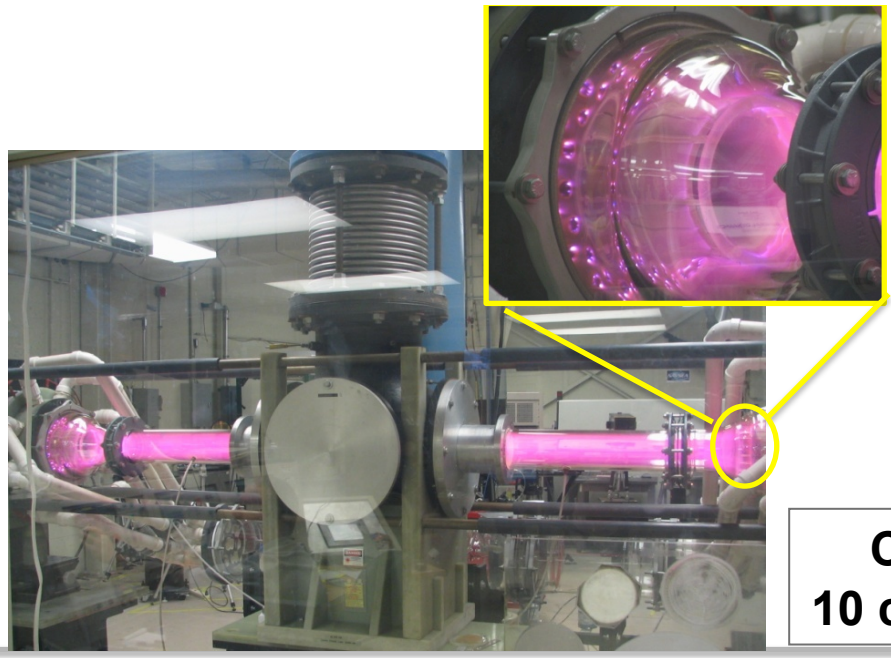
Langley Research Center

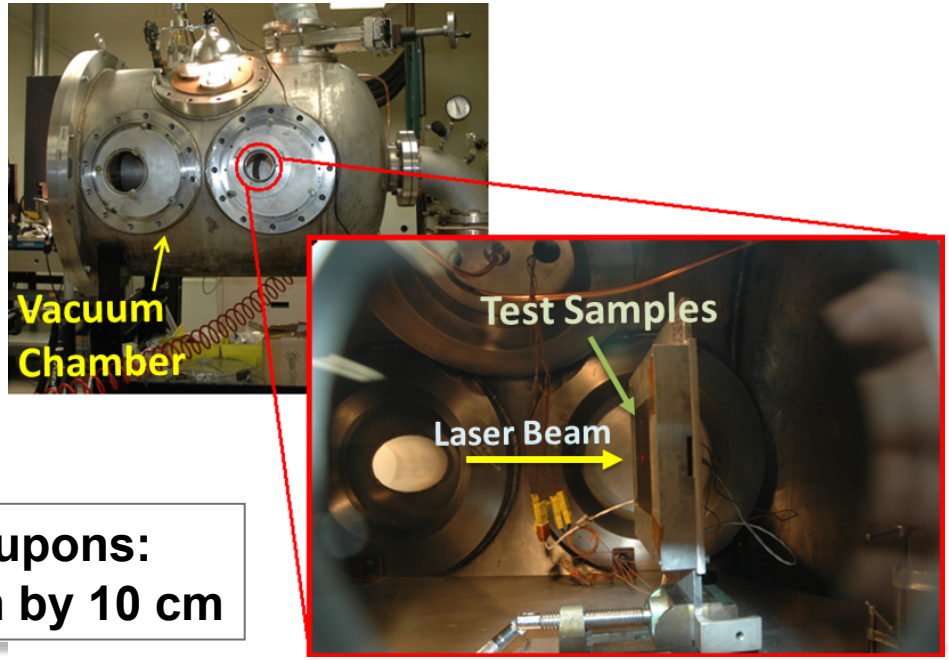
Laser-Hardened Materials Evaluation Laboratory (LHMEL)

Located at Wright Patterson Air Force Base



Laser Discharge Cavity

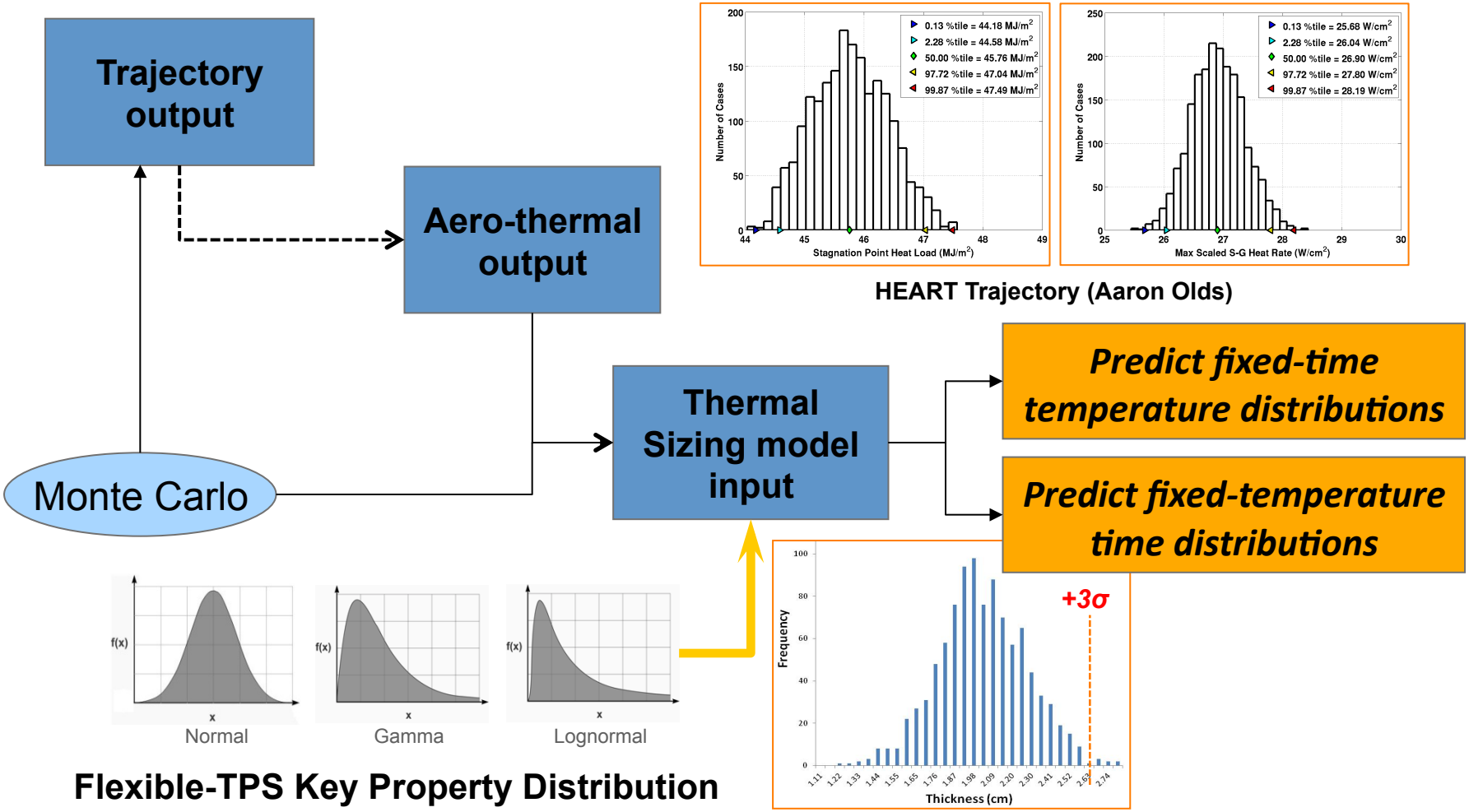




Coupons:
10 cm by 10 cm

Flexible-TPS Margins Policy Approach

Flexible-TPS sizing pipelined within trajectory and aerothermal dispersion analysis

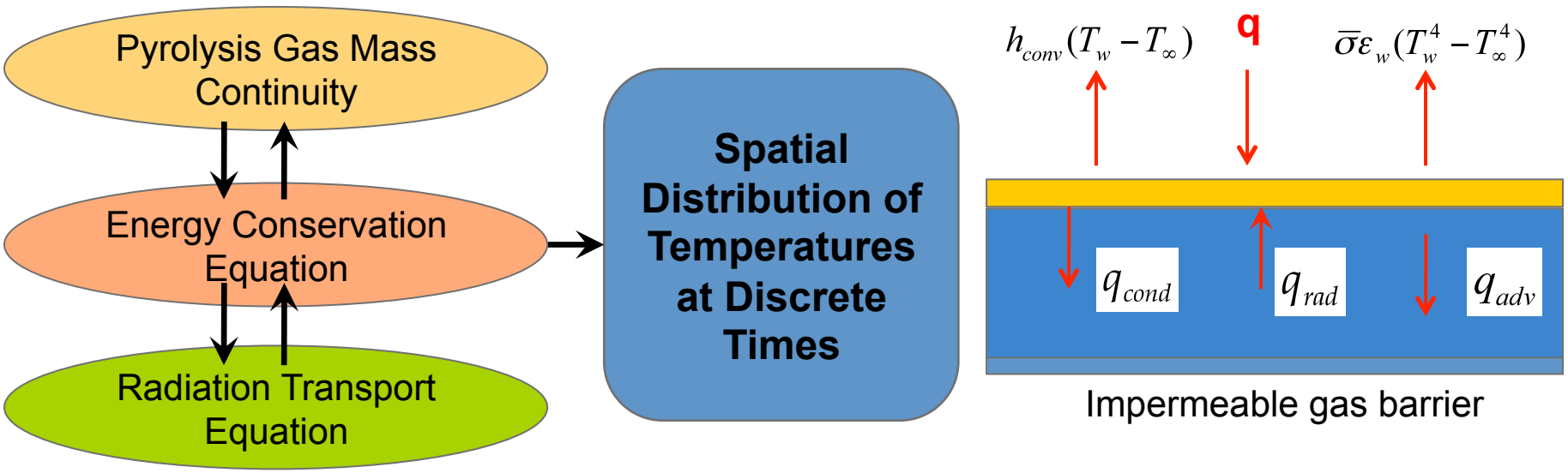


HEART Trajectory (Aaron Olds)

Flexible-TPS Key Property Distribution

Flexible TPS Thermal Model

High fidelity thermal model of flexible f-TPS materials under development using COMSOL



$$\underbrace{\left((1-\phi)\rho_s C_{p_s} + \phi\rho_g C_{p_g}\right)\frac{\partial T}{\partial t}}_{\text{Capacitance}} - \underbrace{\frac{\partial}{\partial x}\left(\left((1-\phi)K_s + \phi K_g\right)\frac{\partial T}{\partial x}\right)}_{\text{Conduction}} + \underbrace{\frac{\partial}{\partial x}\left(\rho_g h_g v_g\right)}_{\text{Advection}} + \underbrace{h_R\frac{d\rho_s}{dt}}_{\text{Pyrolysis}} - \underbrace{\frac{\partial q_{rad}}{\partial x}}_{\text{Radiation}} = 0$$

Thermal model requires the simultaneous, time-accurate solution of three coupled differential equations:

Other Considerations

- Planetary Protection
  - Ability to be exposed to Dry Heat Microbial Reduction
  - Or Accept additional Bio-Burden based on estimated sterilization during entry
  - Being assessed as part of overall TPS thermal model development
- Vehicle cleanliness
  - Some of the TPS materials shed particulates
  - Current approach is to encapsulate HIAD with a cover released at inflation
  - Additional assessments need to be done

Summary

- We know how to build HIADs
- We know how to test HIADs
- We know (reasonably well) how to analyze HIADs
- HIADs have flown – TRL 5/6
- Current development plans will extend capability

Helpful Sources

- AIAA-2013-1389 – The Hypersonic Inflatable Aerodynamic Decelerator Mission Applications Study (Bose, et al.)
- AIAA-2013-1304 – Design and Execution of the Hypersonic Inflatable Aerodynamic Decelerator Large-Article Wind Tunnel Experiment (Cassell, et al.)
- AIAA-2013-1390 – IRVE-3 Post-Flight Reconstruction (Olds, et al.)
- JSR, vol 50, No. 2, pp 270-281 – High Energy Atmospheric Reentry Test Aerothermodynamic Analysis (Mazaheri)
- AIAA-2012-2866 – Shock Layer Radiation Modeling and Uncertainty for Mars Entry (Johnston, et al)
- AIAA-2012-1515 – Design and Testing of the Inflatable Aeroshell for the IRVE-3 Flight Experiment (Lichodziejewski, et al)
- AIAA-2011-2511 – Overview of Initial Development of Flexible Ablators for Hypersonic Inflatable Aerodynamic Decelerators (Beck, et al)
- AIAA-2010-7515 – IRVE-II Post-Flight Trajectory Reconstruction (O'Keefe and Bose)
- AIAA-2009-2970 - Estimating Minimum Inflation Pressure for Inflatable Aerodynamic Decelerators (Glenn Brown)
- AIAA-2008-3894 – Post-Flight Analysis of IRDT Blackout During Earth Reentry