National Aeronautics and Space Administration

Hypersonics Project
Fundamental Aeronautics Program

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FAP Annual Meeting
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Cleveland, OH

Hypersonic Fundamental Research Mission Areas

The NASA Hypersonics Project is focused on 2 very different mission areas:

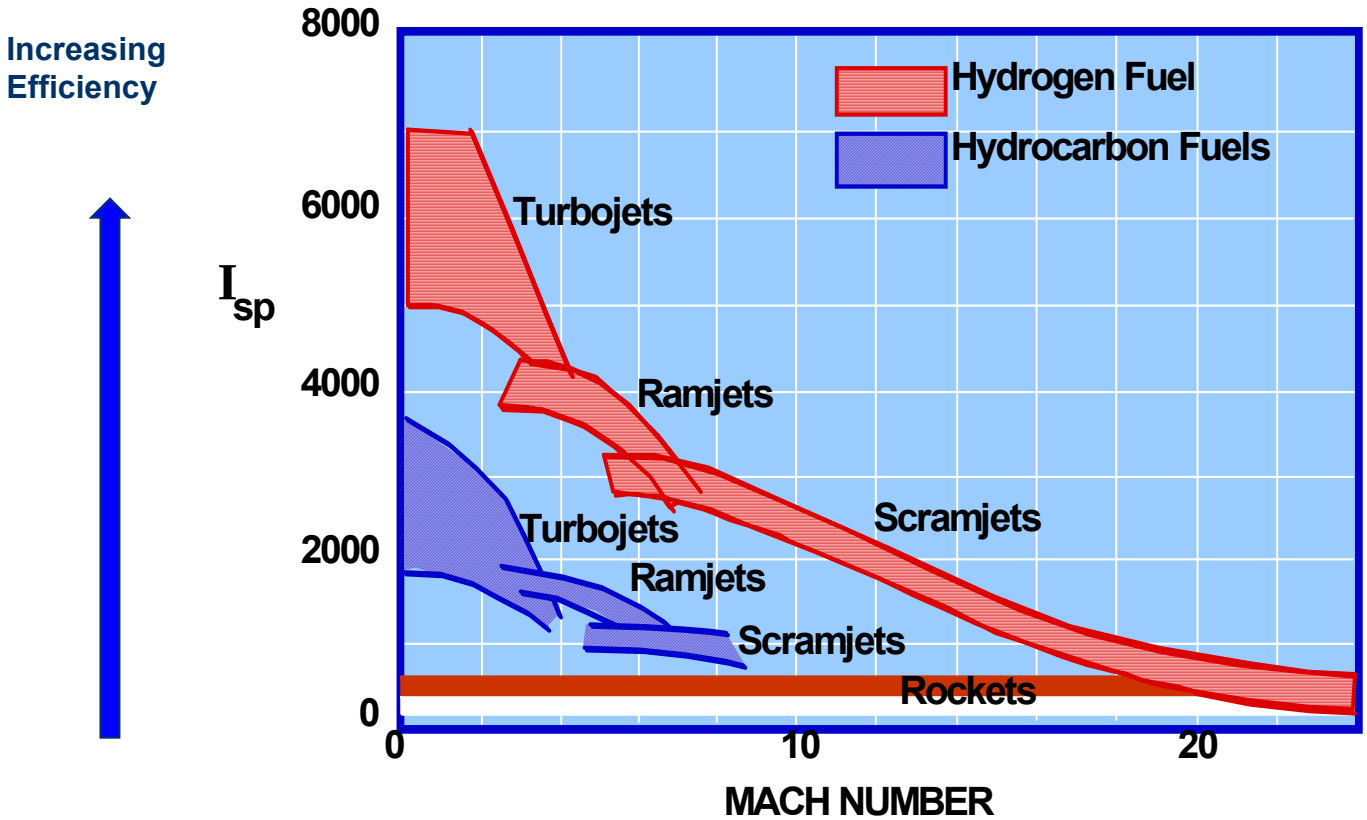
- Hypersonic airbreathing vehicle technologies, tools, and basic physics.
- Entry vehicle technologies, tools, and basic physics.

Each mission area has different challenges and technology solutions:

- Reusable, winged vehicles, highly integrated airbreathing propulsion, complex geometry, low earth orbit
- Single-use blunt bodies, high Earth entry velocities, high mass Martian entry.

Project Goal: Develop tools, technologies and knowledge to *enable* hypersonic airbreathing vehicles and large-mass entry into planetary atmospheres

Why Airbreathing?



Airbreathing propulsion enables lower vehicle gross weights by eliminating internal oxygen storage

But, airbreathing propulsion increases vehicle dry mass, complexity, R&D costs

Hypersonic Airbreathing Technology Roadmap

Vehicle Scale	1X Addressed in National Aeronautics Plan	10X Addressed in National Aeronautics Plan	100X
User	DoD	DoD Commercial	NASA DoD Commercial
Application	Weapon - Expendable	DoD-ISR/Strike Commercial Cruise – Reusable	Access to Space – Reusable
Est. Technology Availability Date (TRL 6)	2020	2030	2040

1X=10#/sec mass flow

Achieving airbreathing access to space vehicles must step from current state of the art, 1X, to 10X to 100X.

Airbreathing Technical Challenges

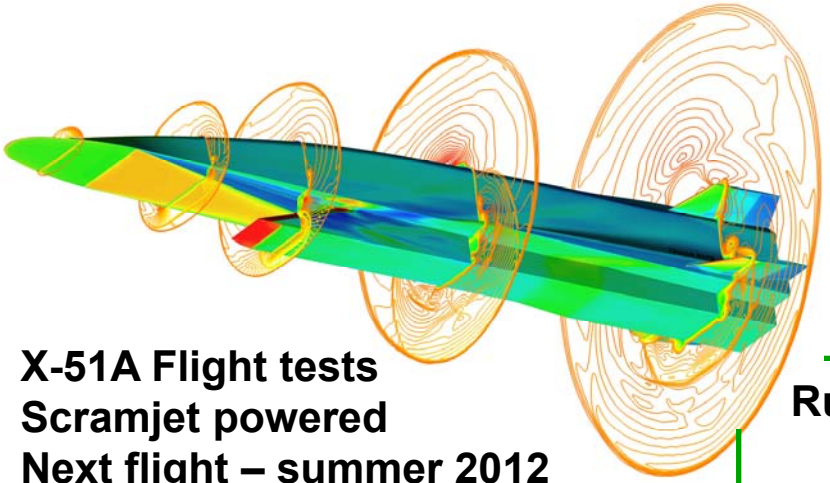
- Develop airbreathing propulsion technology for Two-Stage-to-Orbit Vehicles
  - 1X and 10X scramjet propulsion
  - Turbine Based Combined Cycle (TBCC) propulsion

- Develop integrated light-weight, reusable airframe and propulsion structures
  - Ceramic Matrix Composites (CMC)
  - Structurally integrated thermal protection systems (SITPS)
  - CMC scramjet heat exchangers

- Develop physics-based integrated multi-disciplinary design tools
  - Integrated multi-disciplinary, multi-fidelity tool suite
  - Vehicle concept studies

Ground to Flight "Scaling" Process

Inform future scramjet designs, ground test techniques, and flight demos



X-51A Flight tests
Scramjet powered
Next flight – summer 2012

Collect ground test data

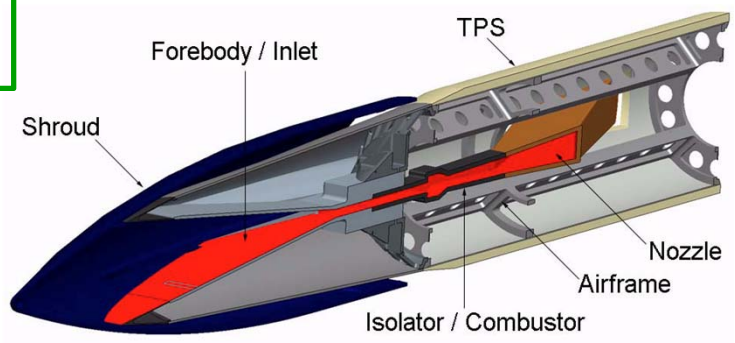
Validate CFD tools

Run pre-flight analysis predictions with quantified uncertainties

Collect flight data

Run post-flight CFD

X-51A ground test in Langley 8' HTT



HIFiRE Flight 2 Scramjet Launch May 2012

10X Scramjet Partnership with Air Force

Objective

- Develop the physics knowledge, design approaches, tools and test techniques to design and test scramjets 10X > the state of the art (1X = X-51A scramjet)

Approach

- Investigate scale effects on fundamental combustion processes
- Develop new test techniques utilizing existing infrastructure
- Validate 10X scramjet design approach (test techniques, combustion CFD codes)

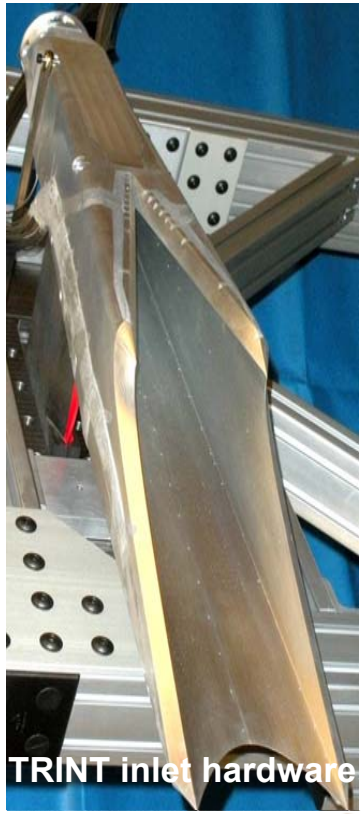
Status

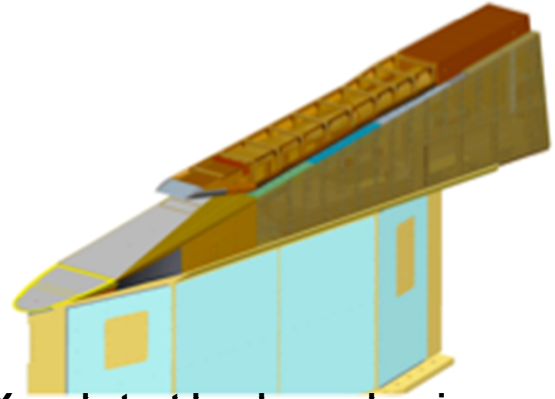
- Joint 10X scramjet test technique partnership established
- Truncated inlet (TRINT) test in GRC 1' X 1' Supersonic Wind Tunnel completed Dec 2011
- 10X scale test in LaRC 8' High Temperature Tunnel April 2012

Significance

- New NASA/Air Force partnership required to develop 10X scramjet scaling technology
- Enabling technology leading to new vehicle classes for long range cruise or access to space missions

Partners: OSD Advanced Propulsion Test Technology Program
AFRL Robust Scramjet Program

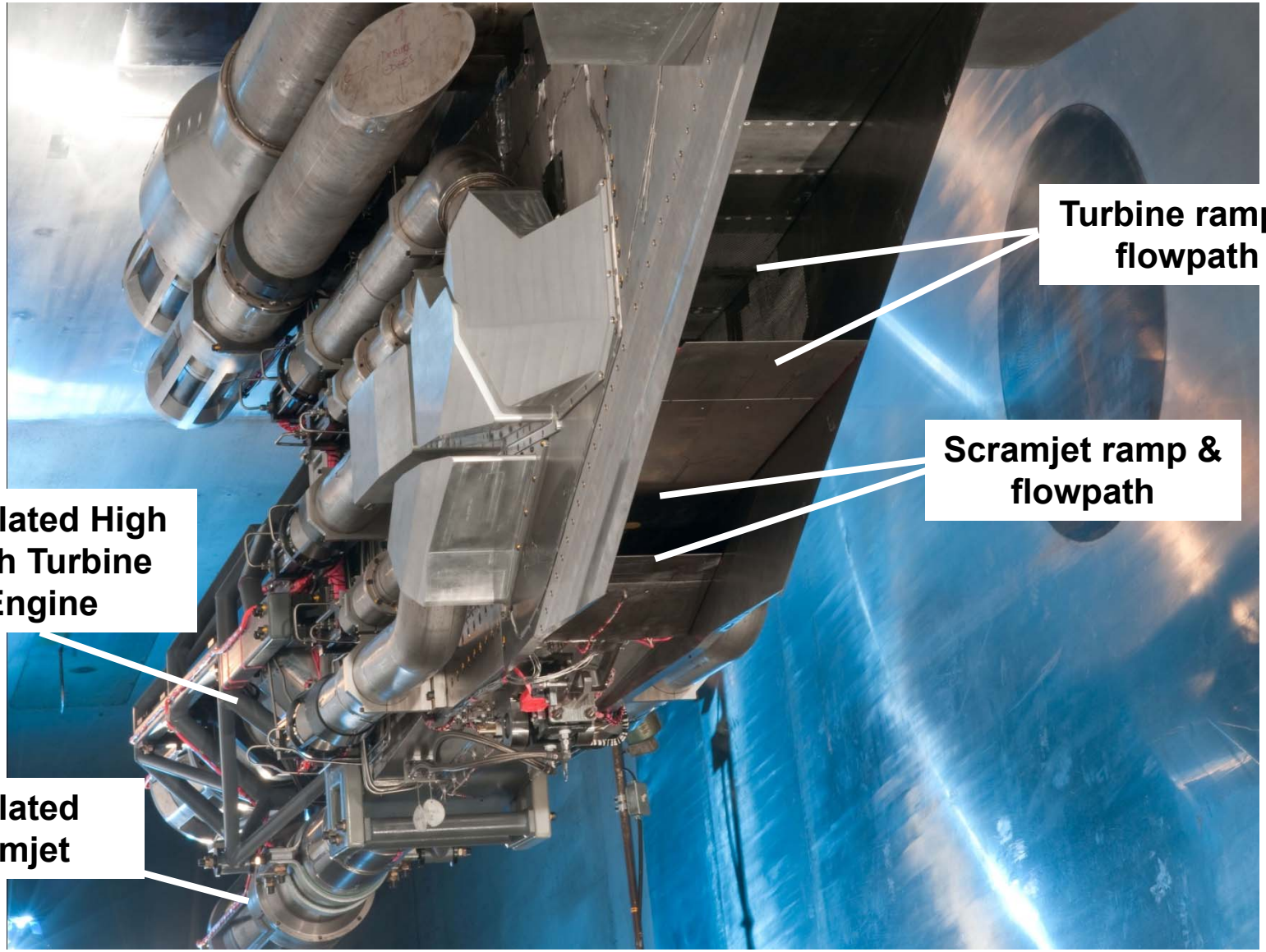




6X scale test hardware drawing

Turbine Based Combined Cycle Technology Inlet Wind Tunnel Model

Installed in GRC 10' x 10' Supersonic Wind Tunnel



TBCC Propulsion System Mode Transition

Focus on Mach 4 Design Point

Phase I testing March 7 – June 17, 2011

- A series of “cane curves” were generated which serve to outline operating limits and define performance at Mach 4, Mach 3 (abbreviated), and Mach 2 (limited)
- (Open Loop) Mode transition sequences were demonstrated at Mach 4 and 3.
- ***Overall achieved phase 1 critical objectives.***

Phase II testing August 29 – October 19, 2011

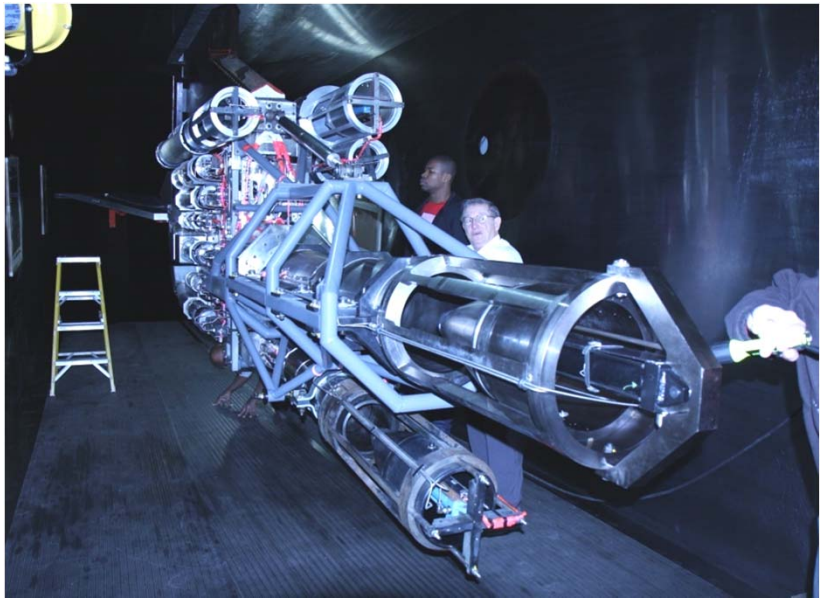
- Systems Identification (Dynamics) Study
- 378 Experiments completed in 38.25 hours (11 test nights)
- ***Overall achieved phase 2 critical objectives.***

Testing resumed March 2012

- Expanding database for both steady state and dynamic studies.
- Explore model parametrics over expanded operating range

Phases III & IV are planned but currently unfunded

- Controlled Mode transition demonstration FY14
- Controlled Mode transition demonstration with high Mach turbine installed FY15



Hybrid LES/RANS CFD Capability

Objective

- Develop numerical propulsion tools to more accurately simulate large scale (10X, 100X) and hypervelocity flowpaths where data is difficult / expensive to acquire

Approach

- Develop Large Eddy Simulation (LES) capability
- Integrate with existing SOA Reynolds Averaged Navier Stokes (RANS) code

Status

- Hybrid LES/RANS capability integrated into SOA Vulcan code
- Beta testing underway to validate new capability

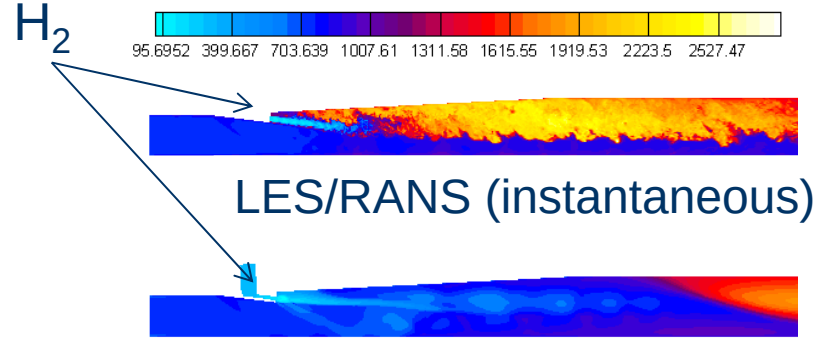
Significance

- The LES approach is more accurate than state of the art RANS codes, but has ~ 100x solution times of RANS
- Use LES solutions to calibrate the less expensive RANS model for the flows of interest

NRA: North Carolina State Univ.

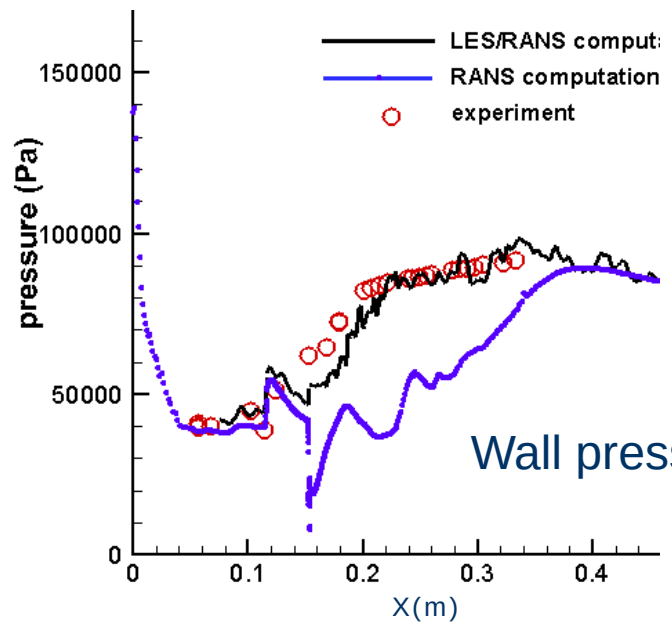
UVA Combustor

Temperature (K)



LES/RANS (instantaneous)

RANS



Wall pressures

Temperature/H2O Tomography Measurements

Objective

- To rapidly & simultaneously measure the temperature and water distribution in a plane in a scramjet flowpath.

Approach

- Use non-intrusive tunable diode lasers and tomographic techniques.

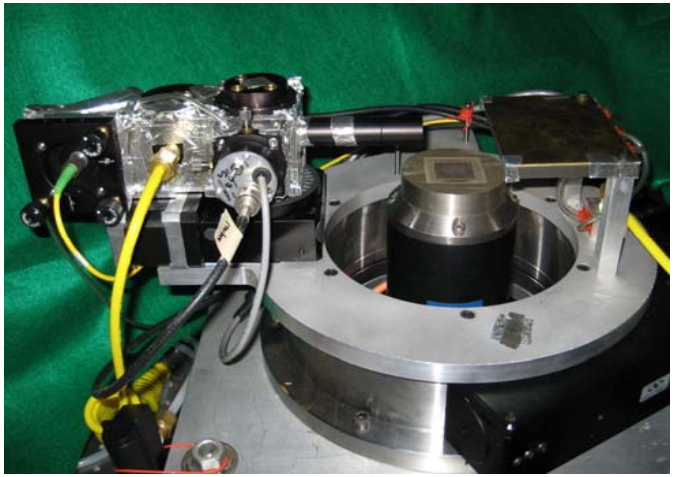
Status

- Developed a tomographic system via an NRA with UVA
- Demonstrated the system in a flat flame burner under controlled conditions
- Demonstrated the system in the UVA combustor
- Demonstrate the technique in the Langley Scramjet Complex 3rd quarter FY12.

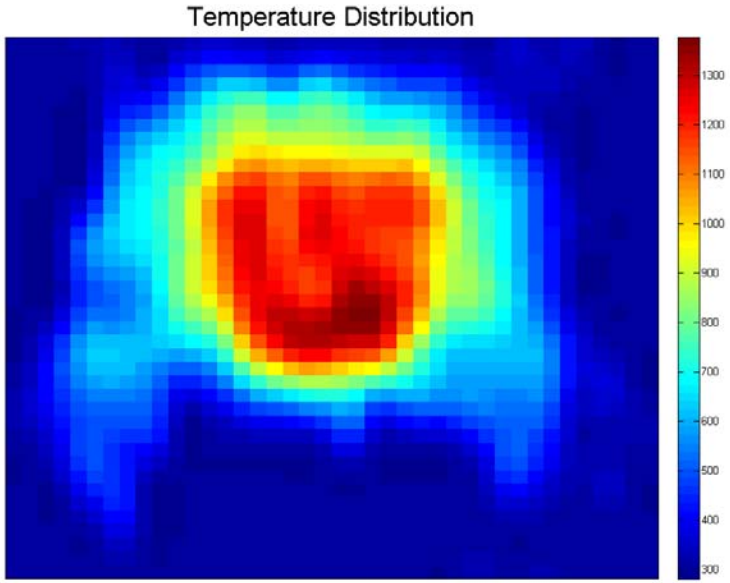
Significance

- The ability to rapidly and accurately obtain T and H2O data in the entire plane downstream of the scramjet combustor is a major leap forward in scramjet diagnostic capability
- New, detailed insight into scramjet combustors (e.g where is the fuel burning?) will ultimately yield more efficient, higher performance scramjets
- Will also provide data for CFD validation

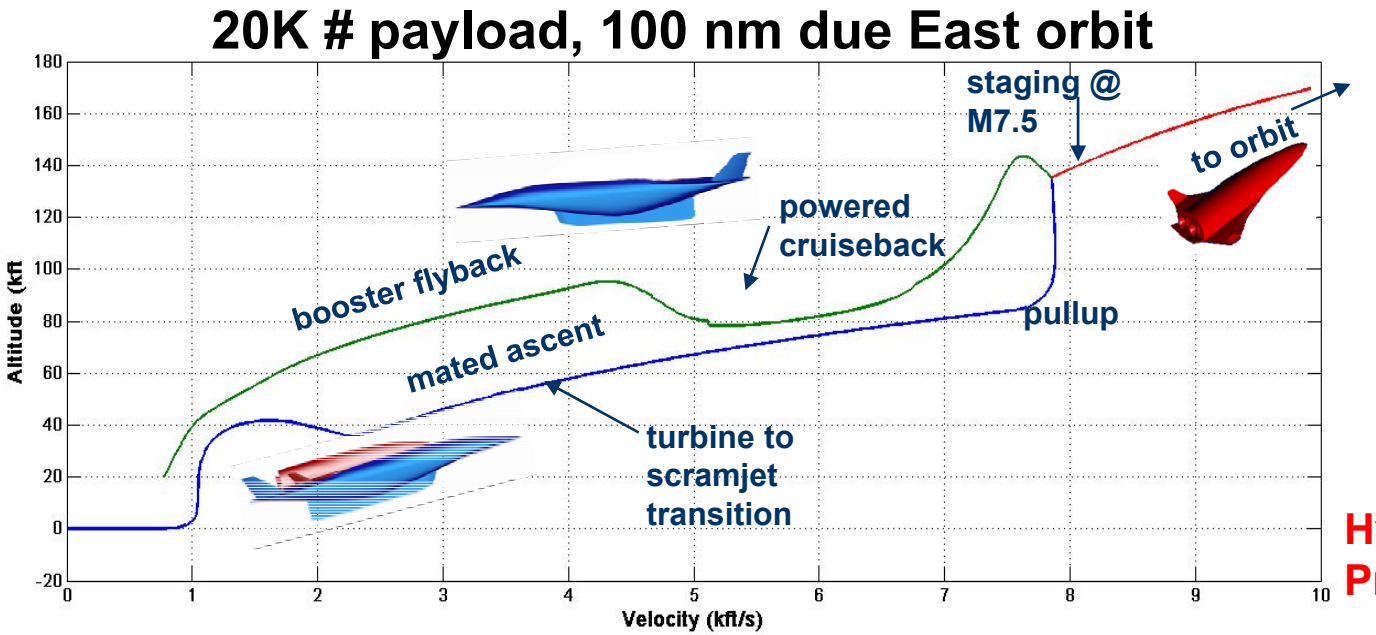
NRA: Univ. of Virginia



Flat flame burner laboratory calibration



Airbreathing Space Access Vehicle Temperatures



Hypersonics Project Focus

- **Leading Edges**
  - Blunt or sharp
  - 3000°F – 3800°F
- **Control Surfaces**
  - Hot structure or Insulated structure
  - 2400°F – 2800°F
- **Acreage Surfaces**
  - **Windward: 2200°F – 2500°F**
  - Leeward: 700°F – 1500°F
- **Vehicle Internal Environment**
  - 300°F – 600°F
- **Scramjet CMC HEX panels**
  - <2400 °F

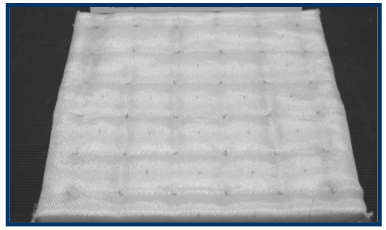
Trajectory and vehicle location determine TPS requirements

Options for Vehicle Reusable Acreage Thermal Protection System (TPS)

Improved Shuttle tile or blanket insulators

- Insulator bonded or mechanically attached to vehicle mechanical load carrying substructure

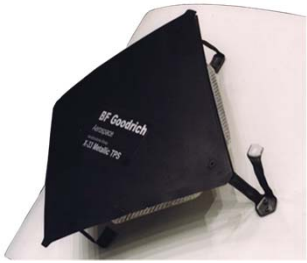
Rigid Tiles



Flexible Blankets

Metallic or CMC standoff TPS

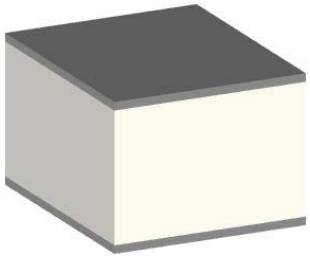
- TPS system isolated from the airframe to prevent thermal loads from reaching the vehicle mechanical load carrying substructure



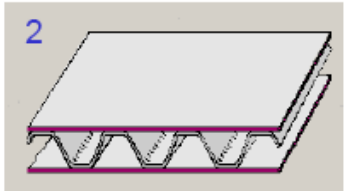
Standoff Tile TPS

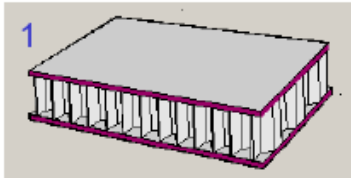
Structurally integrated TPS (SITPS)

- TPS system with integrated thermal / mechanical load carrying capability <u>and</u> the ability to share mechanical loads with the airframe
- Outer CMC layer is the vehicle outer moldline



Rigid Insulator Core Concept





Discrete Element Core Concepts

SITPS fabricated with CMC materials has the potential of light weight, high volumetric efficiency, and increased durability

Structurally Integrated Thermal Protection System (SITPS) Panel Development

Objective

- Develop design methods and materials & processing (M&P) technology to fabricate SITPS panels

Approach

- Demonstrate M&P technology by fabricating sub-scale (~12-in x ~12-in) panels
  - Current focus: rigid insulator (RI) concept
  - Future: discrete element core concepts (e.g. honeycomb panels)
- Validate by thermal / mechanical testing of sub-scale panels

Status

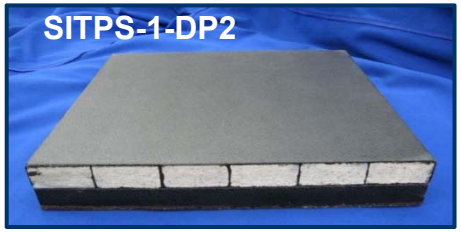
- Fabrication and evaluation of 4 RI demo panels completed
- Fabrication of scale-up RI panel (20-in x 36-in) completed

Significance

- Studies have indicated weight savings of ~9% in structural weight compared to state of the art parasitic TPS

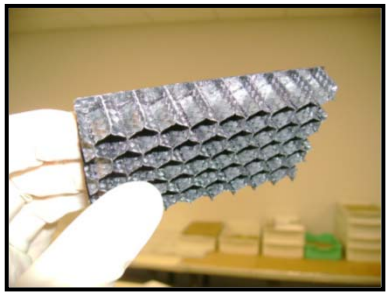
NRA and/or partners:

- NRA: ATK-COIC, RI panel M&P
- NRA: MR&D Inc., SITPS design analysis support
- NRA: SMARF, Oxide / Oxide honeycomb panel development
- Phase 2 SBIR: Ultracor Inc., CMC honeycomb development



Rigid Insulator Concept

Alumina / Nextel Honeycomb (SMARF NRA)



C/SiC Honeycomb (Ultracor Phase 2 SBIR)

CMC-HEX Panel Development

Objective

- Develop actively-cooled CMC heat exchanger (HEX) panel concepts

Approach

- Design, manufacture, and test CMC heat exchanger concepts with progressively advanced features

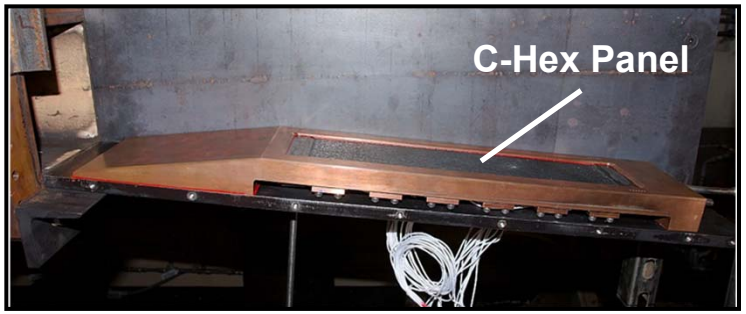
Status

- Design, fabrication, and NDE of CMC-HEX panel completed
  - Metallic tube and manifold fabricated
  - SiC/SiC CMC processing completed
- Final preparations for testing in the LaRC Scramjet Complex
  - Panel instrumented and integrated into the test facility
- Fabrication of an alternate CMC-HEX panel (manifold design with no metallic tubes) completed

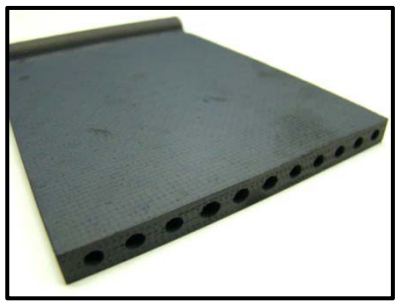
Significance

- Development of lighter weight and higher temperature capable structure for airbreathing hypersonic scramjet propulsion

NRA and/or partners: Hyper-Therm HTC



CMC-HEX Panel integrated into LaRC Scramjet Test Complex



Alternate CMC-HEX Panel (No Metallic Tubes)

Probabilistic CMC Modeling

Objective

- Develop more accurate life and durability models for Ceramic Matrix Composites (CMC)

Approach

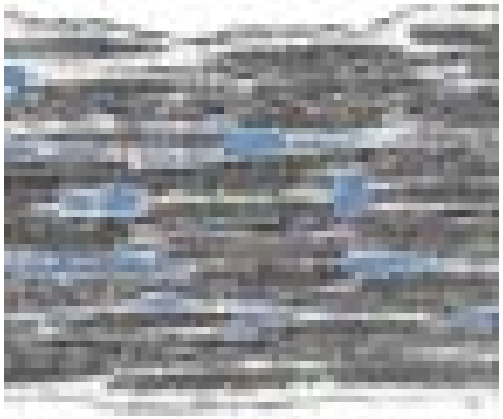
- Digitally capture actual composite material microstructures and generate geometric population distributions
- Identify key geometric features that influence solid failure and damage progression
- Establish progressive damage models that incorporate as manufactured statistical variations in architecture

Status

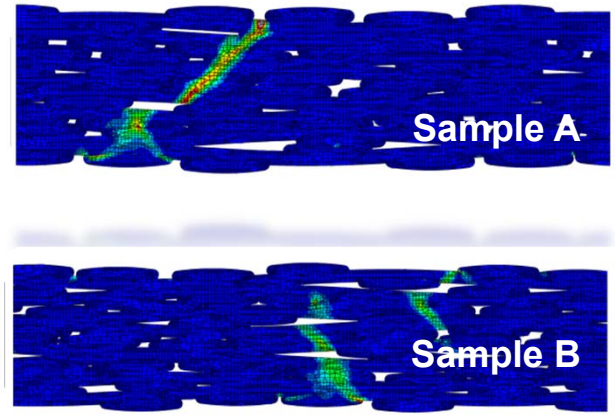
- Quantitative image analysis software developed to support progressive damage analysis of composite
- Monte-Carlo algorithm developed for statistical analysis.
- Statistics of the stress distributions within real structures compared to idealized analysis methods

Significance

- Improve knowledge of progressive CMC material degradation
- Guide development of new materials with improved properties



Actual CMC material showing material voids,in blue



Progressive Damage Analysis
Computed after 1 limit load cycle
Red is major damage

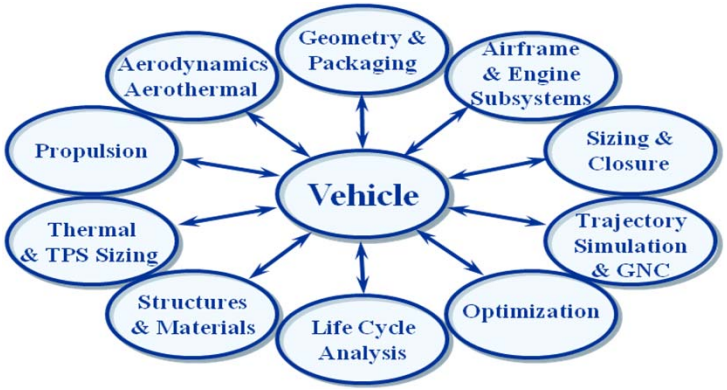
Integrated Design and Engineering Analysis (IDEA) Environment Development

Objective

- Develop an integrated multidisciplinary tool set with multiple levels of fidelity (representation of physics) for the analysis, design and optimization of air-breathing launch and high-speed atmospheric flight vehicles

Approach

- IDEA will ultimately feature a mid-level fidelity analysis capability with the ability to directly support higher fidelity analyses and perform rapid design exploration and optimization at lower levels
- IDEA will contain parametric geometry and design knowledge for multiple vehicle classes of different shapes and propulsion (airbreathing and rocket)
- IDEA will include the ability to estimate vehicle performance as well as vehicle "ilities" and be able to optimize (or at least inform design decisions) based on a variety of figures of merit



Status

- Proof of concept version (Gen 0) completed in 2009
- Initial operational capability (Gen 1) due in FY12 (APG)

Significance

- Order of magnitude reduction in design cycle time
  - From months to weeks, perhaps days
- Reduced uncertainty through increased fidelity, software automation

Joint NASA/AFRL Two-Stage-To-Orbit (TSTO) Vehicle Study

Mission: 20K# payload, 100 nm orbit due East

Objective

- Rigorously compare 2 different airbreathing TSTO concepts to understand vehicle trade space and to determine the state of the art for conceptual design tools

Approach

- Define single mission, common ground rules and assumptions, and methods fidelity for both study teams
- Each organization independently develop a TSTO vehicle
- Each organization conduct blind assessment of the other organization's TSTO vehicle concept

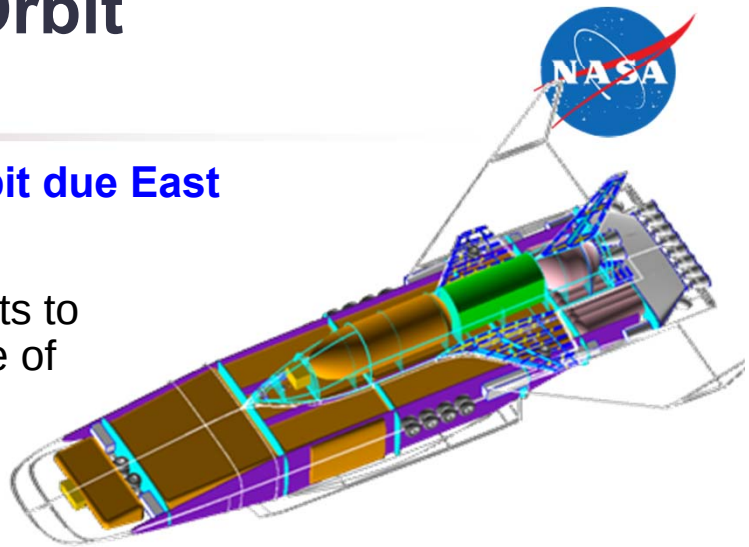
Status

- Concept definition and blind studies complete
- Briefed NASA/Air Force Executive Research Council Meeting, Aug 2011

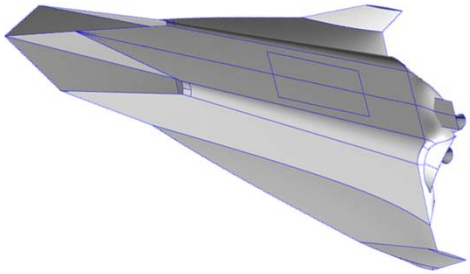
Significance

- Created community-wide benchmark for design process, minimum methods fidelity requirements
- Increased vehicle design knowledge, identified capability gaps

Partner: AFRL



NASA TBCC (turbine-based combined cycle) booster (1st stage) with rocket-powered orbiter



Air Force (RBCC) rocket-based combined cycle orbiter (2nd stage) concept

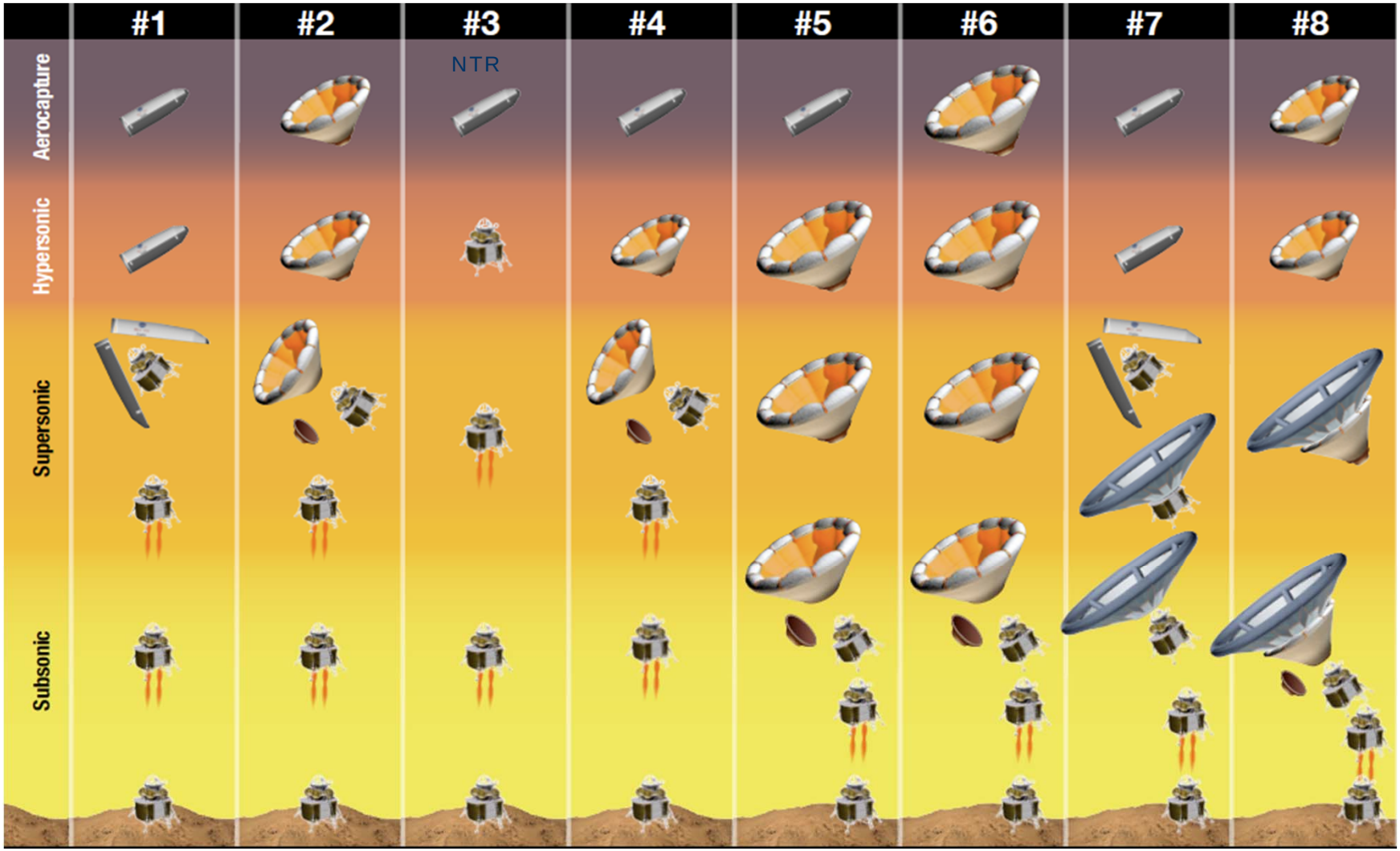
Why Invest in EDL Technologies?

- Many NASA missions enter an atmosphere.
  - Entry, Descent & Landing (EDL) technologies are required for these missions
  - Mars is a prime candidate for beyond LEO human missions from 2011 NASA Strategic Plan
  - Advancements in EDL technologies required to enable some new missions, ie, humans or heavy robotic missions to Mars
    - Current Viking era technology limited to ~1 MT of landed mass
  - Novel EDL technologies & more capable ablators may benefit the more routine missions performed today with lower cost, higher safety, etc
  - May also foster commercial space activities if lower cost EDL options are developed
- EDL is recognized as a NASA Grand Challenge
- Advancements in EDL tools, technologies & knowledge require a sustained stable investment over many years

EDL-Systems Analysis Exploration Architectures

40 metric ton usable landed mass

Arrival Mass:	110 mt	84 mt	265 mt	109 mt	134 mt	141 mt	107 mt	81 mt



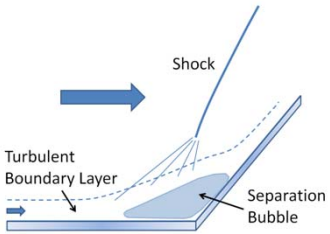
EDL Technical Challenges

- Decrease uncertainty in aeroheating prediction by 50%
  - Next generation computational tools and models
  - Boundary layer transition
  - Characterization of Martian atmosphere

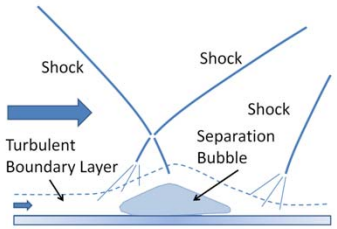
- Develop tools and technologies to enable large-mass planetary entry
  - Hypersonic Inflatable Atmospheric Decelerators
  - Supersonic Inflatable Atmospheric Decelerators
  - Flexible and conformal thermal protection systems

Mission Relevant Problems (MRP) for Uncertainty Assessment

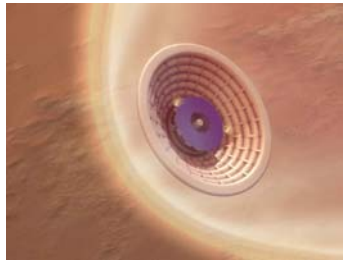
- Methodology needed to document the state of the art in aeroheating environment definition
- Select Mission Relevant Problems from trajectory maps of both airbreathing vehicles & re-entry vehicles
- Perform uncertainty assessment in the region of peak heating conditions in flight
  - Assumes fully turbulent boundary layer
- A Subject Matter Expert Panel considered model uncertainties and ground and flight data to quantify prediction uncertainties



MRP 1. Compression Corner



MRP 2. Impinging Shock



MRP 3. Mars Aerocapture & Entry

MRP 4. High Speed Earth Return

±55%	±50%	± 60%	±81%
•Turbulence modeling • Numerical techniques	• Turbulence modeling • Numerical techniques	• Nonequilibrium kinetics • Gas surface interactions	• Radiation • Ablation coupling

Radiative Heating Models and Measurements

Objective

- Develop and validate shock layer radiative heating models for Mars and high-speed Earth entries

Approach

- Measure spectrally resolved radiation intensities behind flight-relevant shock waves
- Upgrade and validate radiation models in vacuum ultraviolet and mid-wave infrared

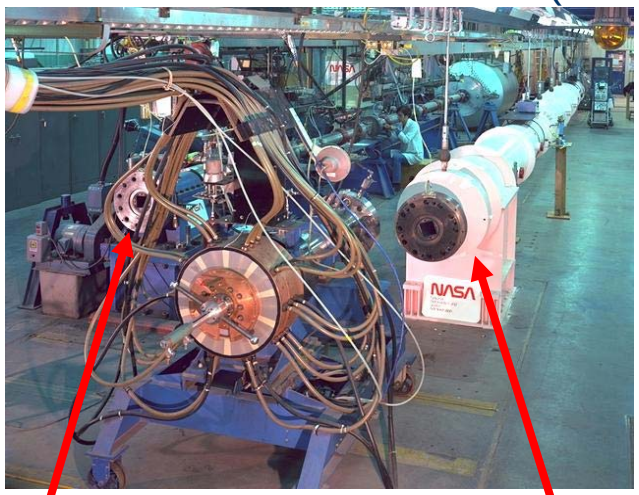
Status

- Quantitative assessment of uncertainty reduction underway
- Newly developed spectroscopic database shows good agreement with data

Significance

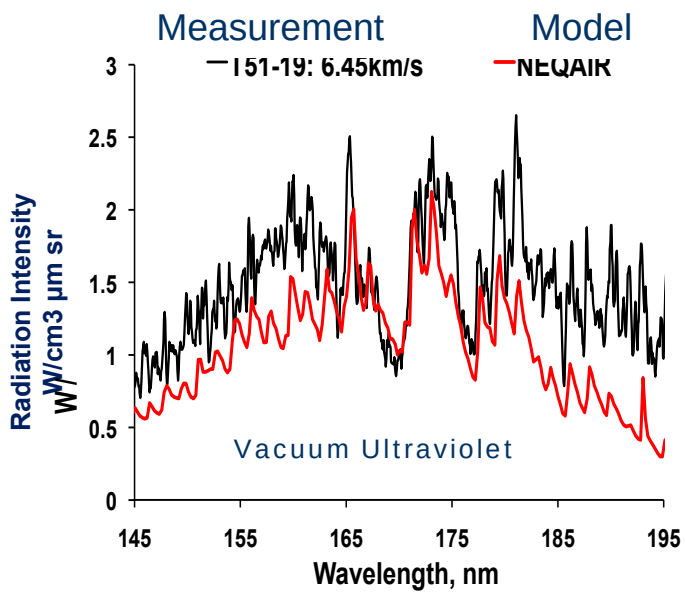
- Identified significant Martian radiation source in mid-wave IR for the first time.
- Data will enable a new validated model that will be critical for design of Mars entry systems, particularly HIADs.
- Validation will greatly reduce uncertainty and margin in predicted radiative heating in Mission Relevant Problems 3 & 4 (currently 53% estimated for lunar return Orion entry)

NASA Ames Electric Arc Shock (EAST)



4” tube

24” tube



Multi-Disciplinary Coupled Codes

Objective

- Develop coupled multi-disciplinary tools for hypersonic systems

Approach

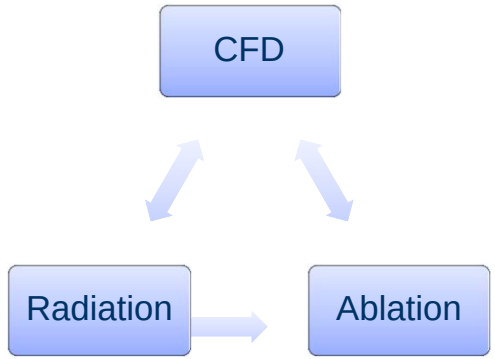
- Integrate CFD, radiation, and ablation codes to create a coupled system
- Implement shape change algorithms between air and the vehicle surface

Status

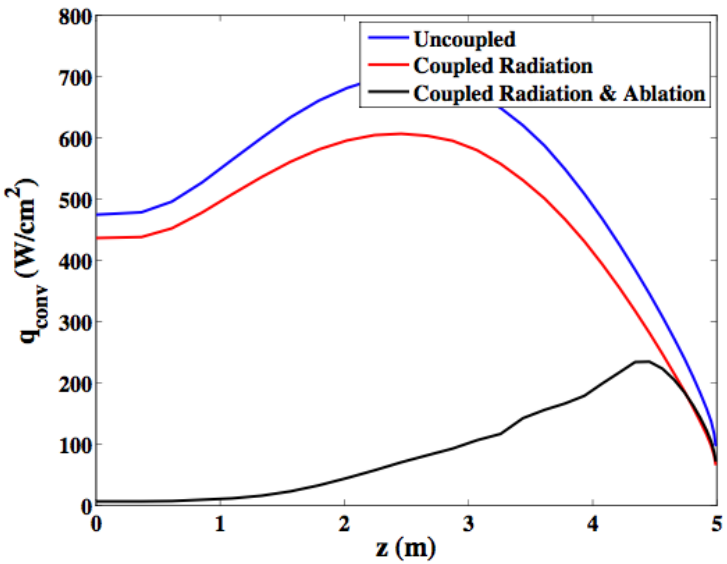
- LAURA-HARA released as a coupled code at NASA Langley, is coupled to Chaleur (Sandia's ablation code)
- DPLR-TITAN (2D ablation) codes are being coupled at NASA Ames
- Shape change algorithm demonstrated

Significance

- Accurately compute heating reductions due to ablation product blowing and absorption of radiation in boundary layer
- Improved accuracy for coupled problems leads to reduced uncertainty



Multi-disciplinary Iterative Solver



Coupled Flow and Ablation Simulation

Inflatable Reentry Vehicle Flight Experiment (IRVE)

Objective

Demonstrate test technique, stability and survivability of an inflatable reentry aeroshell (HIAD).

Approach

- Design and flight test sub-scale hardware via sounding rockets.

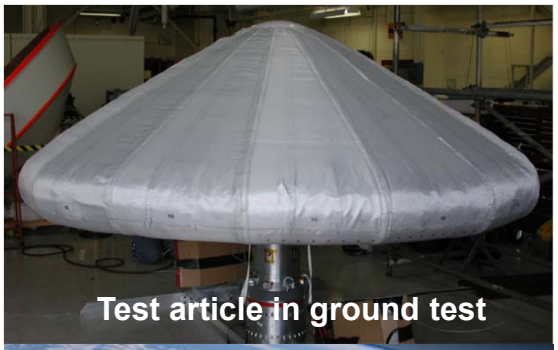
Status

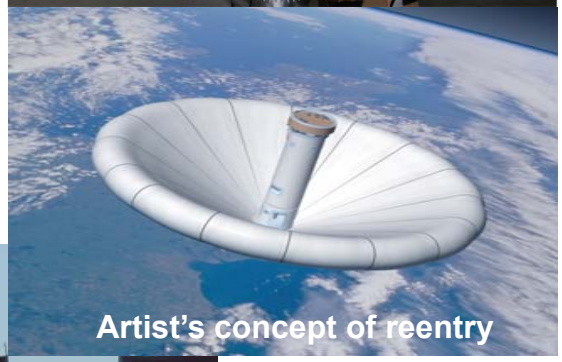
- Developed and flight tested Inflatable Reentry Vehicle Experiment (IRVE-2) with Mach 6 entry (2 W/cm^2) August 2009.
- IRVE flight tests transferred to NASA OCT in FY11, with IRVE-3 (20 W/cm^2) scheduled for 2012 launch.
- Hypersonics Project continues development of next generation 50 W/cm^2 flexible insulative thermal protection system.

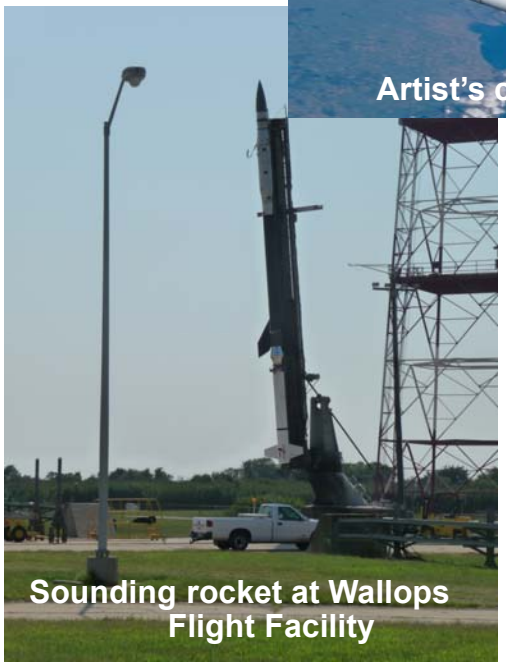
Significance

- First fully successful HIAD demonstration
- Enabling flight demos for HIAD mission infusion.
- Creates path to potential ISS downmass mission (HEART) and eventual missions to Mars.

Partners: ILC Dover, NASA OCT


Test article in ground test


Artist's concept of reentry


Sounding rocket at Wallops Flight Facility

Stacked Toroid Mockup

Flexible Thermal Protection Systems

Objective

Develop flexible thermal protection systems capable of safely sustaining Hypersonic Inflatable Aerodynamic Decelerator (HIAD) entry heating and pressure loads.

Approach

- Identify refractory fiber weaves capable of sustaining peak heat rates of >50 W/cm^2.
- Develop advanced high temperature flexible insulators to sustain maximum heating and integrated heat loads. Able to survive packing, stowage, and deployment.
- Characterize thermophysical and mechanical properties, establish thermal models, and verify thermal performance through flight relevant ground-based testing.

Status

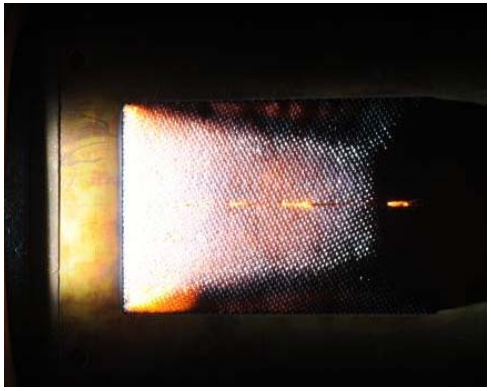
- Established >20W/cm^2 baseline shield for IRVE-3 flight demonstration project.
- Developed thin-film inorganic and organic insulators with reduced thermal conductivity and gas permeability.
- Demonstrated viability of extending capability to >50W/cm^2.

Significance

- Enabling technology for HIAD mission infusion

NRA: U of Akron

IRVE-3 baseline >20W/cm^2 thermal shield



Thermal testing of IRVE-3 baseline thermal shield in PTF arc-jet at Ames

High Fidelity Ablation Modeling

Objective

Develop computational tool set for the design, characterization, and optimization of ablation thermal protection materials.

Approach

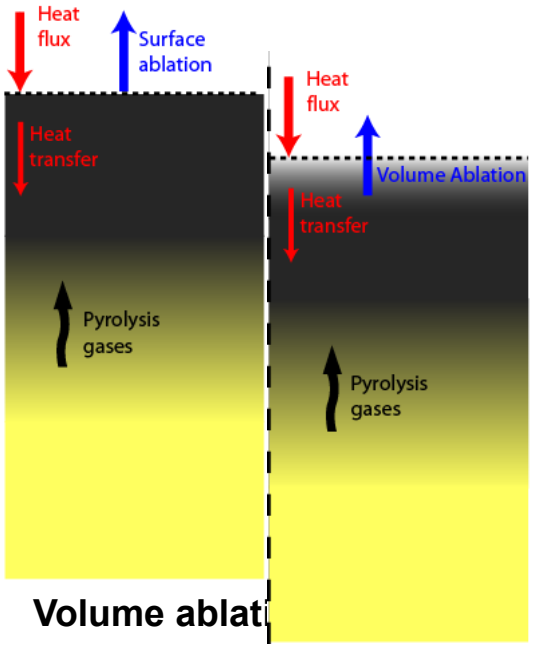
- Pursue in-depth (subsurface) analysis capability.
- Model ingress/egress of reactants and reaction products.
- Address finite-rate chemical reactions with polymer gases.
- Establish three dimensional analysis code that couples with CFD analysis code at thermal protection surface.

Status

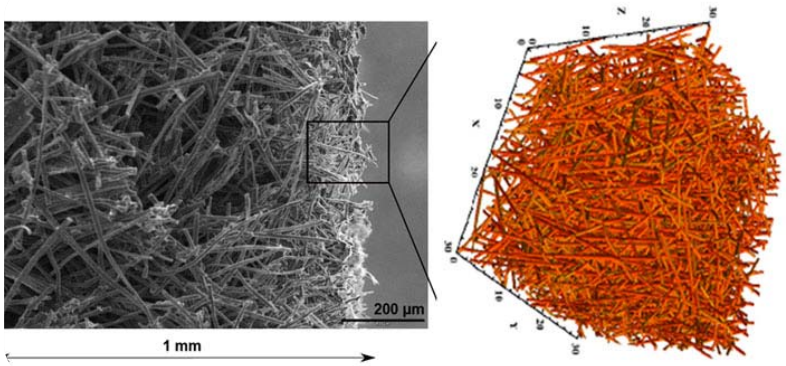
- Developed a phenomenological model for oxidation of carbon fibers showing agreement with experimental observations
- Software developed to extend state-of-the-art capability to include pyrolysis and gas blowing.
- Assessment of required predictive accuracy to existing codes validated

Significance

- Improved fidelity leads to better quantified design margins, increased system reliability
- Physical understanding of ablation process supports improved material properties.



Volume ablati



Carbon fiber oxidation modeling

NASA/AFOSR National Hypersonic Science Centers

- National Center for Hypersonic Combined Cycle Propulsion at the University of Virginia: 28 grad students in 1st 3 years

- Hypersonic Boundary Layer Transition Center at Texas A&M University: 47 grad students in 1st 3 years

- National Center for Hypersonic Materials and Structures at Teledyne Scientific Company: 28 grad students in 1st 3 years

18 Universities participate in the 3 Hypersonic Science Centers

Concluding Remarks

- Project has developed and delivered enabling tools and technologies and advanced physical understanding of critically important hypersonic phenomena

- Significant downsizing of the Hypersonics Project in FY12 and FY13
  - EDL research transitioned to Chief Technologist's Space Technology Program from FY11 to FY13

- Airbreathing hypersonic research descoped to primarily supporting DoD partnerships in FY13

NASA