# A Review of Hypersonic Experimental Capabilities

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***Associate Principal Investigator, Hypersonic Project Experimental Capabilities***

# Outline

- Mission Classes for Hypersonic Project Development
- Diagnostic Technologies
- Sensor Technologies
- Testbed for Flight Qualification/Validation
- Investments in New and Emerging Concepts
- Acknowledgements

# Mission Classes for Hypersonic Project Development

## Highly Reliable Reusable Launch Systems (HRRLS)

**Materials & Structures**
- Thermal Protection Systems
- Hot Structures
- High Temperature Seals
- Reusable Cryogenic Tanks

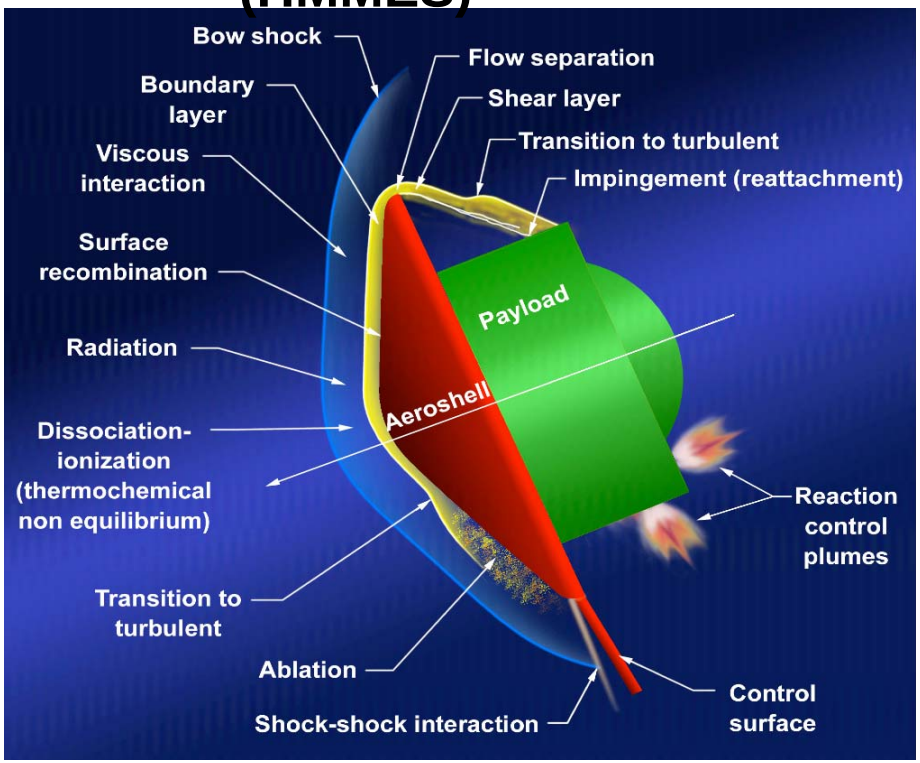
**Integrated Systems**
- Staging
- Thermal Management
- Power and Actuators
- Intelligent Controls

**Airframe-Propulsion Integration**
- Integrated Vehicle Performance
- Inlet Boundary Layer Ingestion
- Nozzle Performance

**Propulsion**
- High-Mach Turbojets
- Dual-Mode Scramjets
- Combined Cycle Engines

**Key technology requirements for TSTO TBCC systems with a staging Mach number of Mach 12 or less**

## High Mass Mars Entry System (HMMES)




**Entry vehicle technology and modeling improvement needs**

**These two mission classes address the technology and methods needs in the hypersonic project**

# Motivation, Goals and Objectives

## Motivation

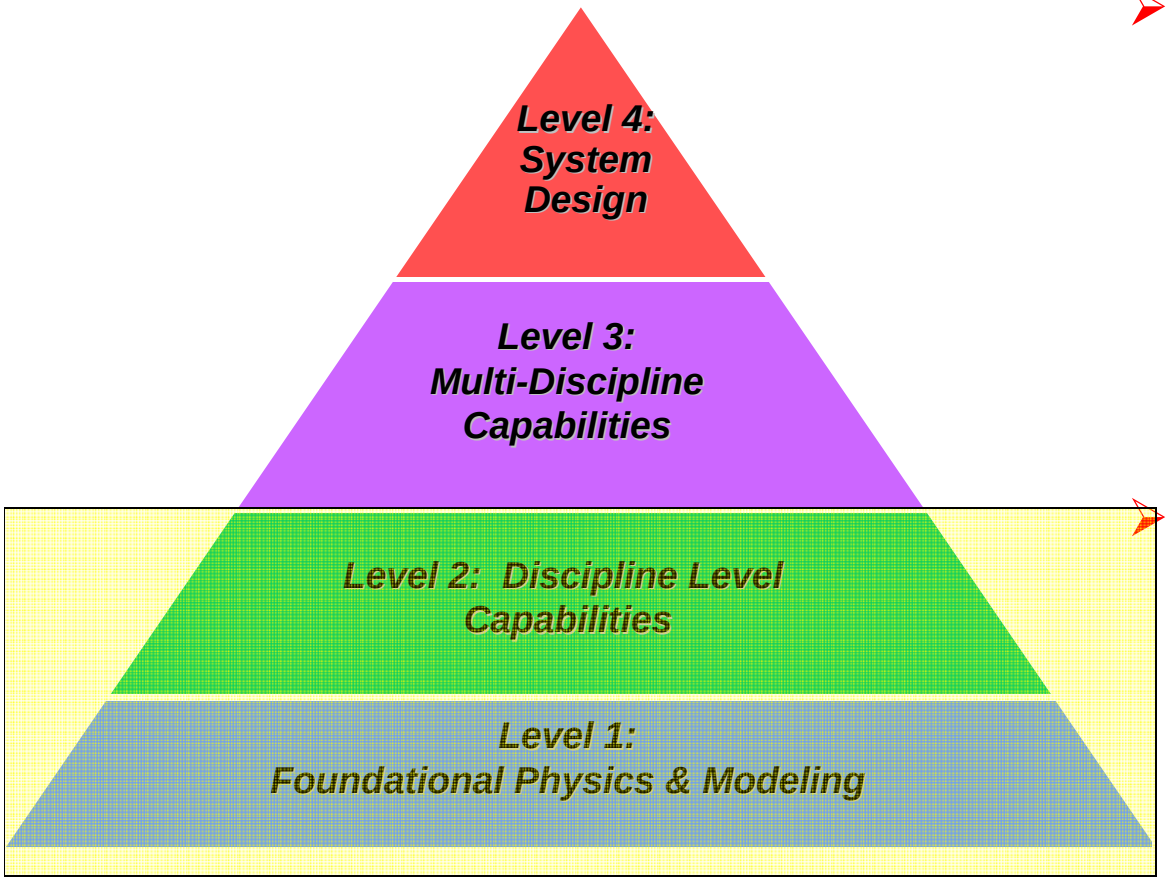
**Conventional measurement techniques not adequate for validating CFD codes developed for hypersonics environment. The extreme temperatures, specie ionization, non-equilibrium chemistry, and shocks encountered in hypersonic flows present fundamental challenges for many of these techniques.**

**These modeling codes are critical to development of predictive capabilities for design of HRRLS and HMMES, due to the high uncertainty in these flight regimes.**

## Goal

**Enhance existing capabilities, Develop new techniques, and Invest in fundamentally new concepts leading to improve accurate measurements thereby validating the CFD and other modeling codes being developed for hypersonics.**

# ARMD Research Philosophy and Experimental Capabilities Development @ Levels 1 and 2

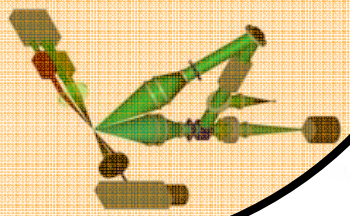



- **Diagnostic Technologies**
  - Fundamental Flow Meas. using CARS/Rayleigh
  - NO PLIF imaging for Hypersonic Flows
  - UV-Iodine PLIF Meas. in Hypersonic Flows
  - Thomson/Raman Scattering Measurements
  - Background-Based Shock Visualization
- **Sensor Technologies**
  - Plasma Sensing System
  - High-Sensitivity Heat Flux Gage For Calibrated Heat Transfer Measurements;
  - Temperature and Pressure Sensitive Paints;
  - Optical shock position sensors
  - Mass Flux Sensors
- **Testbed for Flight Instrumentation Qualification/Validation**
  - Phoenix Hypersonic Missile Tested

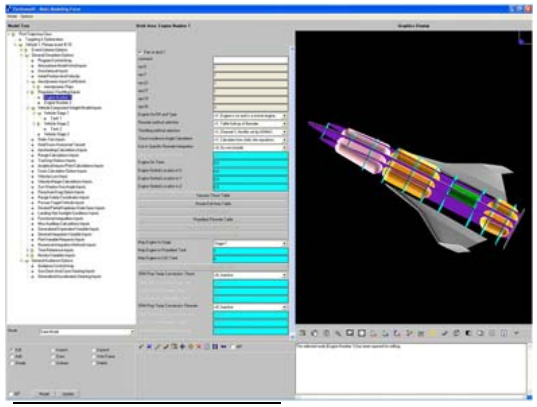
# Hypersonics Discipline Technical Focus

**Materials & Structures**
- Computation models and tools
- Improved materials
- Structural concepts

**Experimental Capabilities**
- Non-intrusive diagnostics
- High temperature structures instrumentation
- Low cost flight testbeds

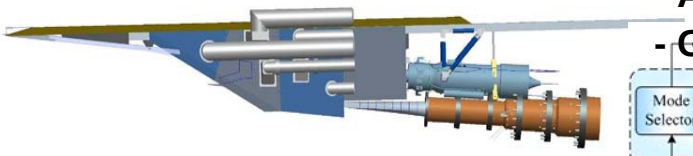


**Physics-based MDAO**
- Higher fidelity tools
- Vehicle concepts

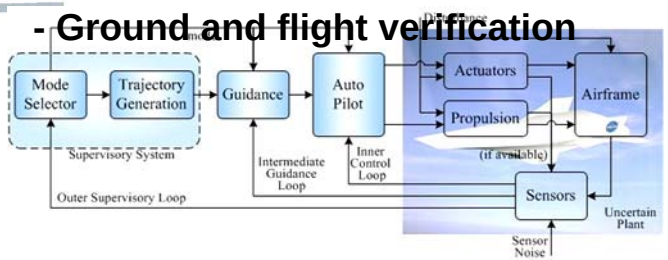


**Aerothermodynamics & Plasmadynamics**
- Physics-based models
- Computational methods
- Ground and flight tests

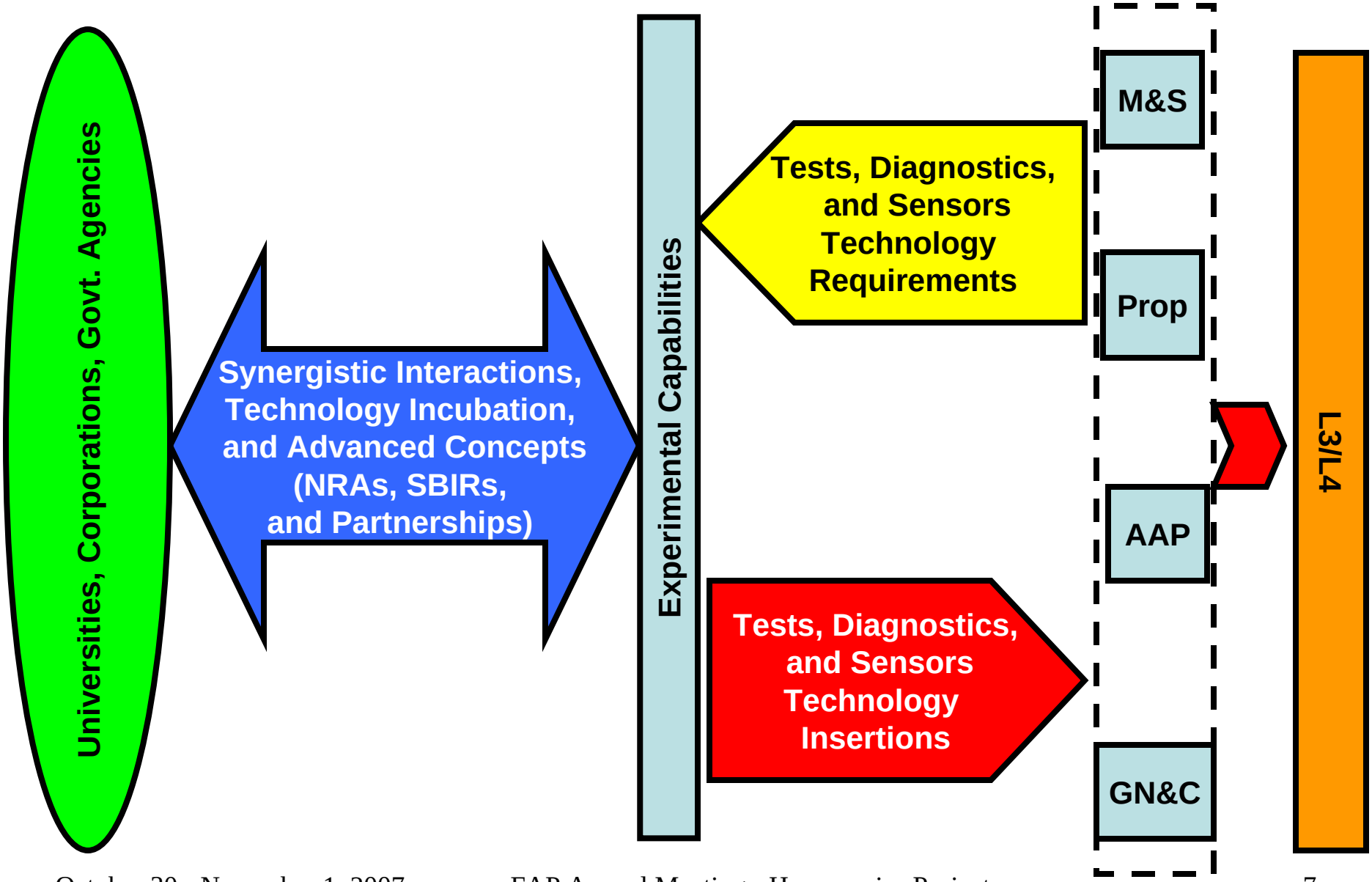
**Propulsion**
- Combustion Physics
- Propulsion Cycle Technology



**Guidance, Navigation & Control**
- Algorithms
- Ground and flight verification



# ExCap: The Technology "Salad Bar"



- **Diagnostic Technologies**
- Sensor Technologies
- Testbed for Flight Instrumentation Qualification/Validation
- Investments in New and Emerging Concepts

# Fundamental Flow Meas. using CARS/Rayleigh

*(POC: Paul Danehy, LaRC)*

**Description:**

**Multiple laser beams are crossed in a flow; dual-pump CARS (coherent anti-Stokes Raman Scattering) measures T, $N_2$, $O_2$, $H_2$ mole fraction while Interferometric Rayleigh Scattering (IRS) measures u, v velocities. All measurements at same time (in 10 ns) and place (0.1x0.1x1 mm3)**

**Application:**

**Generate accurate benchmark data sets to both develop and test new turbulence, chemistry, computational models.**

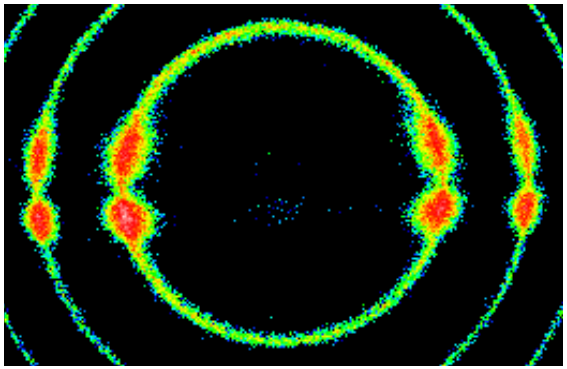
**Benefits:**

**CARS/Rayleigh measures all parameters simultaneously in a supersonic reacting flow.**

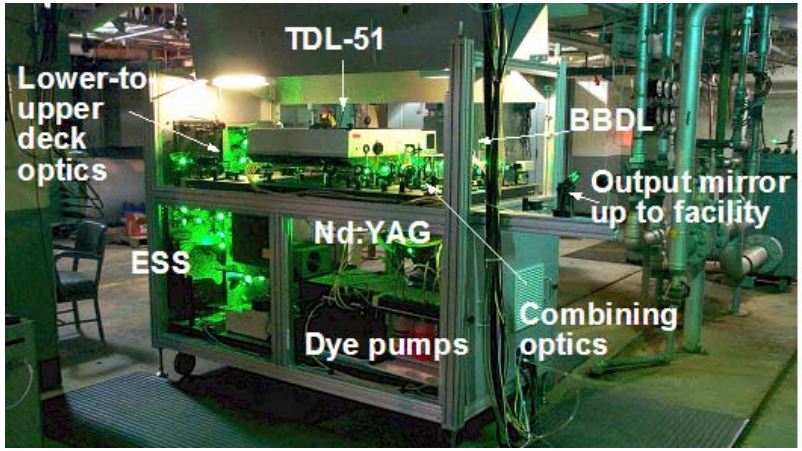
**Impact:**

**Data used to test CFD codes used to design scramjet engine flowpaths.**

**Recent Results**



***Rayleigh scattering spectrum obtained in reacting supersonic flow: 2 velocity components; multi-point***




***Construction/Installation of Mobile CARS/Rayleigh Instrument (ICIASF 2007)***

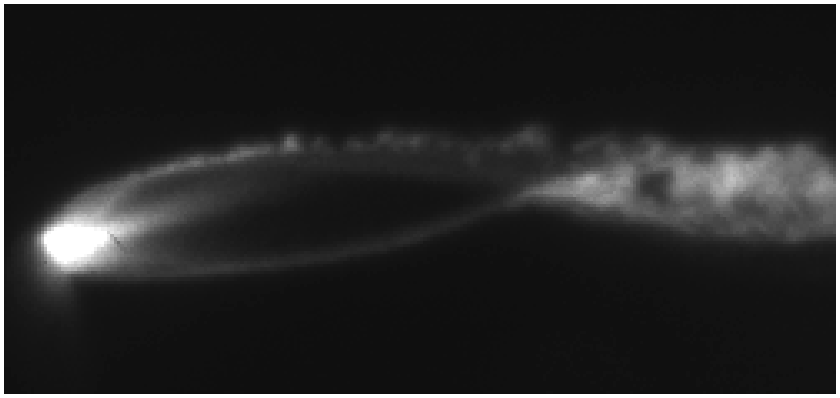
**Complemented by NRA**

# NO PLIF imaging for Hypersonic Flows

*(POC: Paul Danehy, LaRC)*

**Technology Description**

**NO (nitric oxide) PLIF (planar laser-induced fluorescence) uses a laser sheet and CCD camera to provide off-body flow visualization and quantitative measurement in hypersonic flows.**

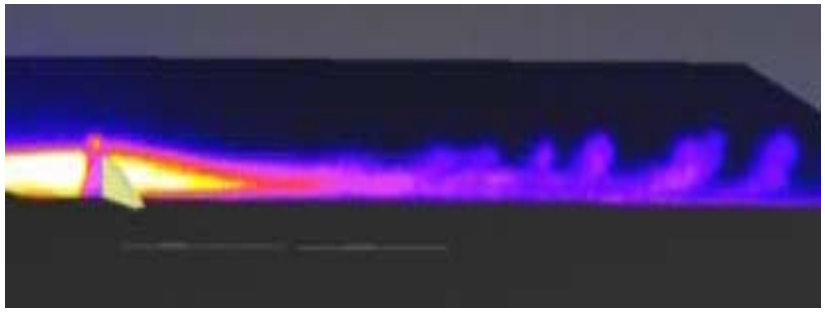


***Visualization of an RCS Jet Thruster (Reno AIAA Paper 2008-1231)***

**Applications:**

**•Transition detection, visualization of shocks, shock interactions, expansions, separated flows, RCS jets / interaction, wakes, shear layers, ablation for propulsion, aero and aeroheating.**

**•Quantitative measurements (vel, and temp.) can be obtained for CFD validation.**



***Transitional Flow over a Triangular Trip at Mach 10 (Reno AIAA Paper 2007-0536)***

**Impact:**

**Used to help test/design/understand Orion CEV RCS Jets; active and passive trips for scramjet engines and to study transition on Space Shuttle and CEV.**

# UV-Iodine PLIF Meas. in Hypersonic Flows

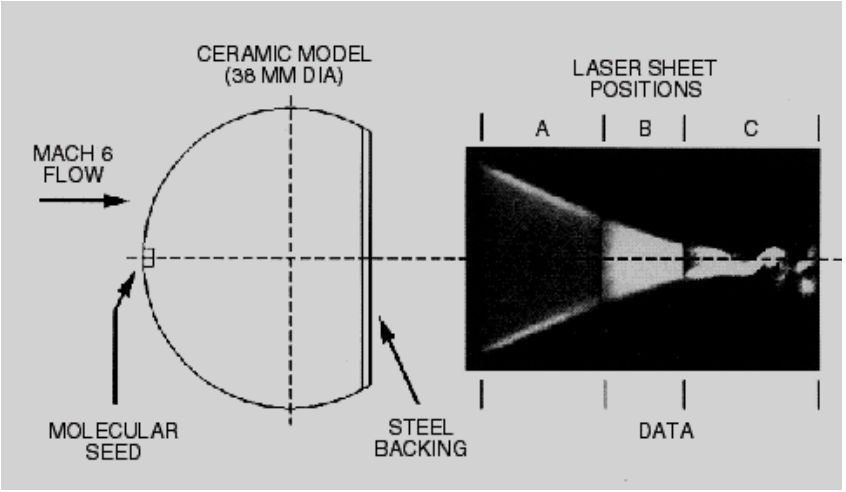
*(POC: R. Jeff Balla, LaRC)*

**Technology Description:**

**Iodine is excited with an Argon Fluoride excimer laser at 193 nm. Diagnostic takes advantage of ion-pair state spectroscopy for development of unique instrumentation.**

**Benefits:**

- **Provides fundamentally new instrumentation for previously unobtainable quantitative (temperature, density) and qualitative (flow visualization) measurements in hypersonic flows.**
- **Applicable to a wide variety of problems including shock/boundary layer measurements, RCS jets, trips, thermal protection systems, and wakes/separated flows.**
- **Data will increase confidence in CFD tools and fundamental aerothermodynamics for vehicle design.**




***Iodine visualization in hypersonic wake***

# Virtual Diagnostics Interface and LiveView3D

*(POC: Gary Fleming, LaRC)*

**Technology Description:**

- **3D Virtual Environment for interactive visualization of experimental data and comparison with CFD;**

**Applications:**

- **Post-test interactive data visualization & analysis and Real-time visualization of experimental data.**

**Benefits:**

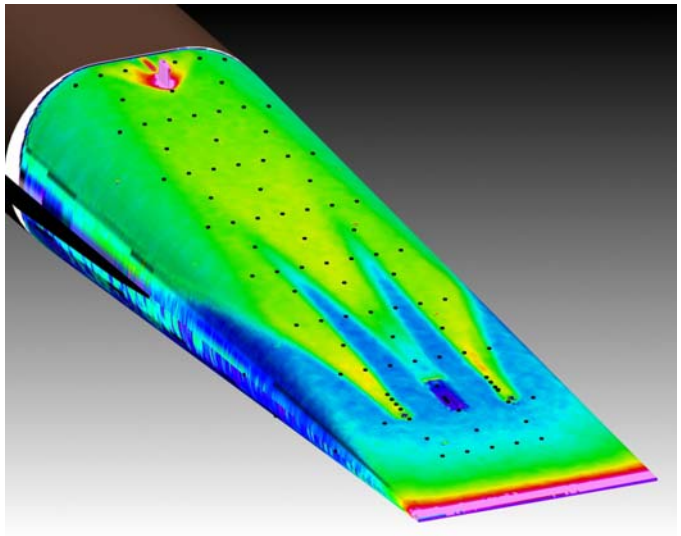
- **Advanced visualization provides researchers with significantly better understanding of flow physics; Risk and cost reduction.**

**Impact:**

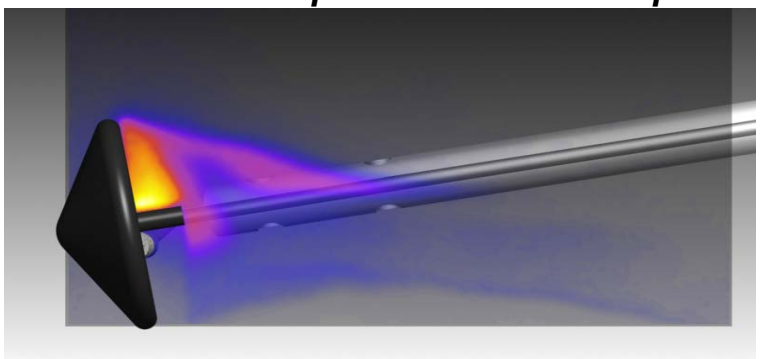
- **Used by every FA thrust area, CEV, CLV,**

**MSL, Shuttle, many reimbursables.**

**Recent Results:**



***3D Visualization of phosphor thermography measurements of HyBoLT model surface temperature with BL trips***



***Visualization of PLIF Imagery in wake region of hypersonic aeroshell***

- Diagnostic Technologies
- **Sensor Technologies**
- Testbed for Flight Instrumentation Qualification/Validation
- Investments in New and Emerging Concepts

# Plasma Sensing System

*(POC: Greg Adamovsky, GRC)*

**Objectives**

**Develop sensing and diagnostic techniques for plasmas generated during hypersonic flight**

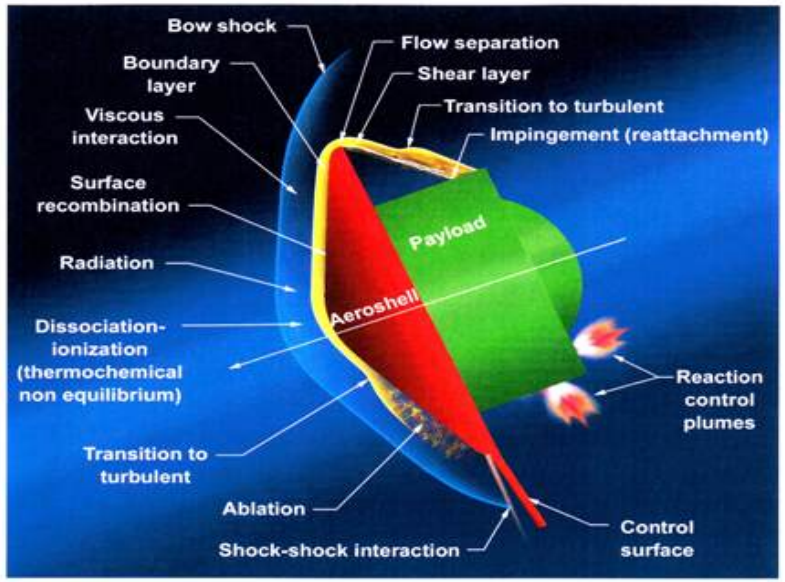
**Benefits**

- **Provide information on properties of plasmas generated under different conditions (flight regimes);**
- **Experimental data will help to validate theoretical models and provides understanding of processes associated with Mach transitions;**

**Impact**

**Data on plasma properties will help to mitigate communication blackout problem during entry.**

Mars Entry Vehicle



# Temperature Sensitive Paint

*(Tim Bencic, GRC)*

## Objective

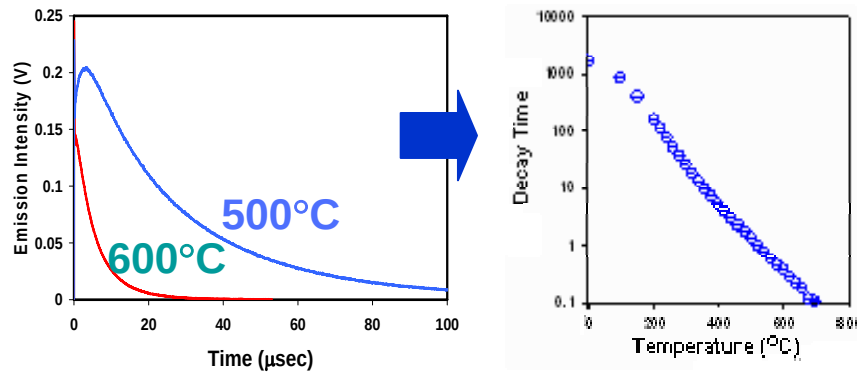
**Increase TSP accuracy by 2X over the current measurements for the range of 0-650 °C.**

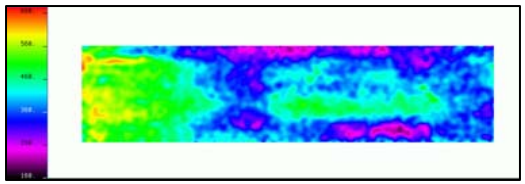
## Benefits

- **Surface temperature measurements where infrared techniques are not viable due to flames, contaminants, windows, etc**
- **Time response of photoluminescence in proportional to temperature**

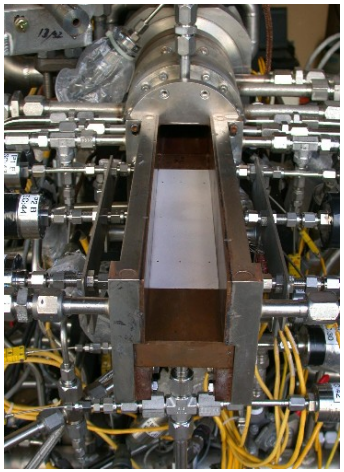
## Impact

**Develop better coatings to use in high speed flows and propulsion systems: TSP detected thermal gradients but was intrusive because of drastic thermal conductivity difference, good correlation with CFD**



**Flow** →



***Glenn Cell 21 Rocket Nozzle Calorimeter Test***

**Complemented by NRA**

# High Temp. PSP and TSP for Hypersonic Flows

*(A. Neal Watkins, LaRC)*

**Technology Description:**

**PSP utilizes oxygen quenching of luminescence from suspended molecules to indirectly measure global surface pressure;**

**Applications:**

**Measures surface pressure due to RCS interactions, transitions, and general aerodynamic effects (PSP);**
**Measures aerodynamic heating and heat flux due to surface interactions and aerodynamic effects;**

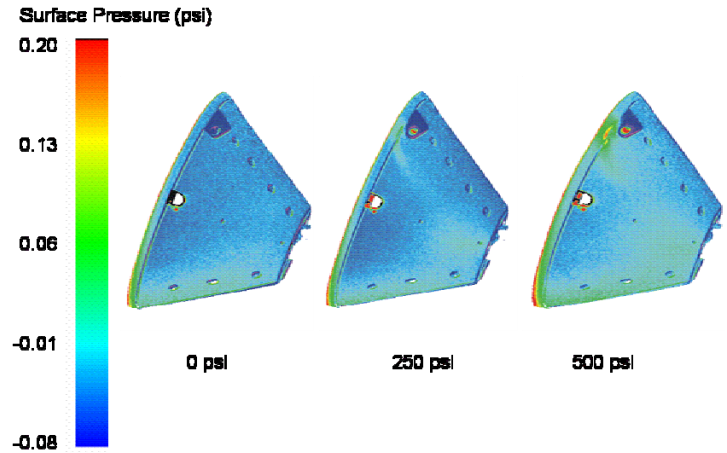
**Benefits:**

**Global surface pressure and temp. measurements. Can reduce model fabrication cost and time.**

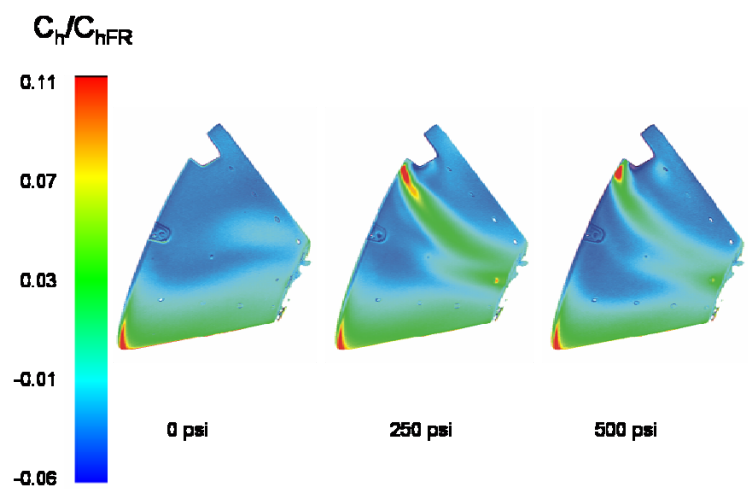
**Impact:**

**Measurements help to understand RCS jet interaction, re-entry aerodynamics.**

**Recent Results:**




*PSP results showing RCS interaction on the aft body of a re-entry vehicle. Re = 1.8M/ft and roll jet is blown at the listed pressure.*




*Aerodynamic heating measured using TSP. Conditions are the same as above.*

# Optical Shock Sensing System

*(Greg Adamovsky and Mark Wernet, GRC)*

**Objective:**

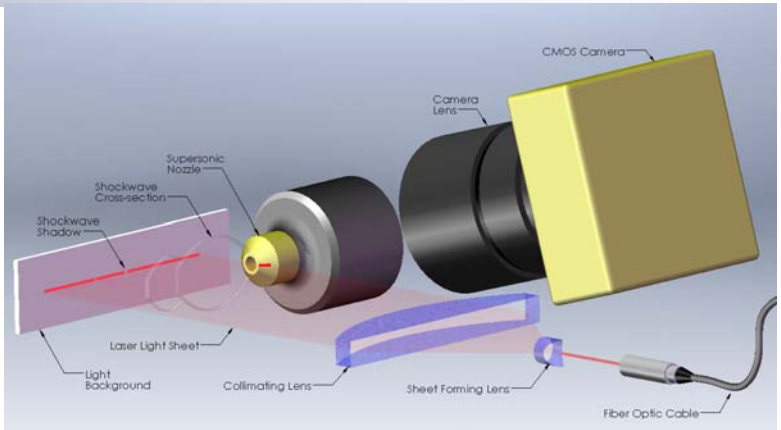
**Develop scanning laser beam shock sensing techniques based on scanning optical beams and laser sheets for on-board flight control and ground test applications;**

**Benefits:**

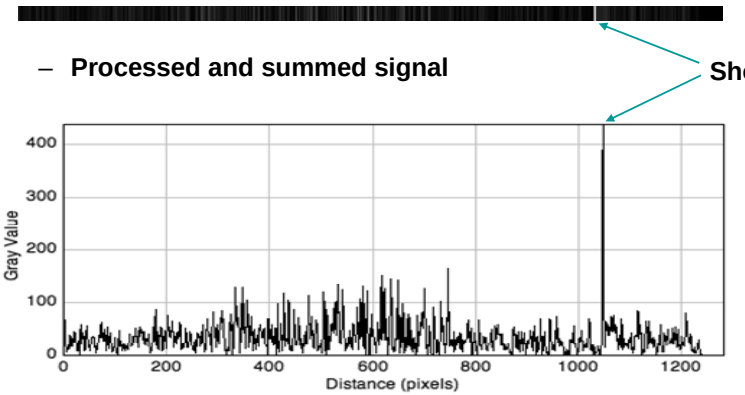
- **Enables to implement facility enhancements for experimental validation of inlet / shock train / isolator measurements;**
- **In-flight shock position sensors enable control of hypersonic vehicles;**

**Impact:**

**Sensing & monitoring of shocks improves vehicle performance & enables the vehicle control through various hypersonic flight regimes.**



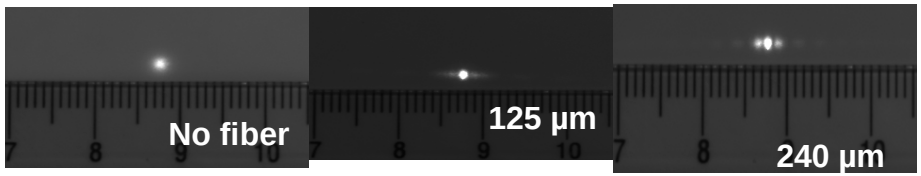

- **CMOS camera read at 2 kHz**
  - **16x1280 pixel FOV**




  - **Processed and summed signal**

- **Resolution: 0.5 pixel ·75mm/1280pixels = 25 microns**

***2 mm Pencil Beam***



# Hypersonic Mass Flux Sensor

*(Mark Wernet, GRC)*

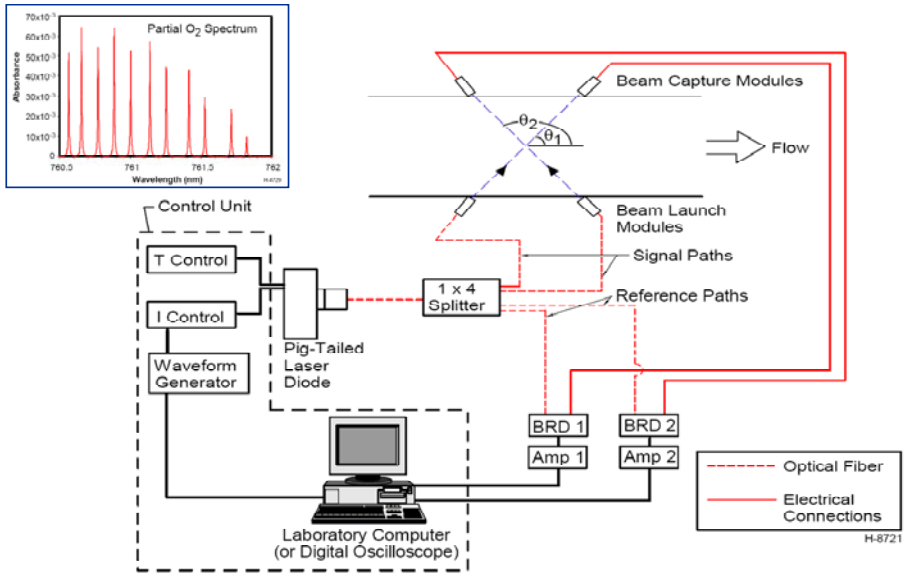
**Application:**

**Based on diode laser absorption of target species in the flow (select $H_2O$ for combustion driven flow facility), can extract Velocity from Doppler shift, Density from line-of-sight absorption, and Gas temperature if needed from ratio of two absorption features.**

**Benefits:**

**Provides real time measurement of mass flux in engine inlets is a critical parameter used to monitor the operating point of hypersonic propulsion systems.**

**Provides the necessary information to validate CFD predictions of hypersonic flows**




*Laser sensor for mass flux (density x velocity)*

**Complemented by an NRA**

# High Temperature Pressure sensors

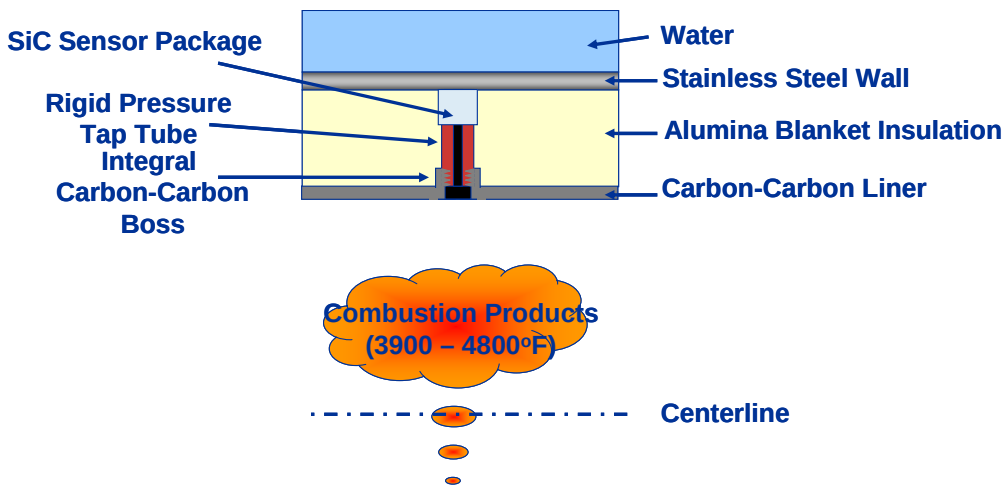
*(Robert S. Okojie, GRC)*

**Application:**

**Direct pressure and velocity measurements in flow path to validate Hypersonic CFD codes**

- **Sensor operation demonstrated at 600 °C under HyFly Project with JHU-APL;**
- **Second generation to be demonstrated at 1000 °C by end of FY08;**
- **Third generation to be embedded in SiC/SiC panel.**

***SiC pressure sensor rated for 600 °C operation***



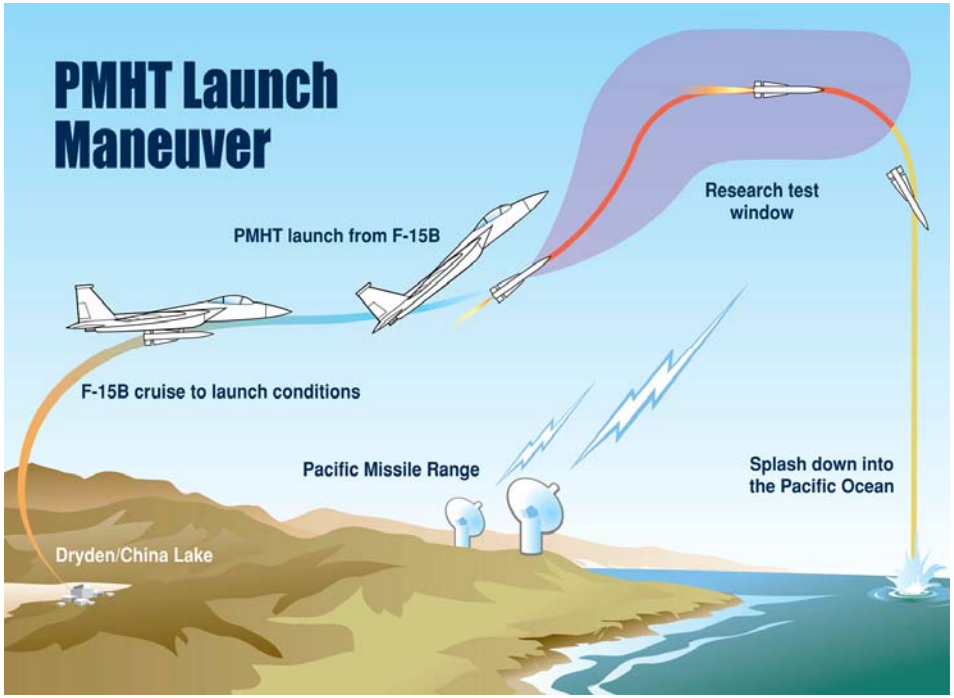
- Diagnostic Technologies
- Sensor Technologies
- **Testbed for Flight Instrumentation Qualification/Validation**
- Investments in New and Emerging Concepts

# Phoenix Missile Studies

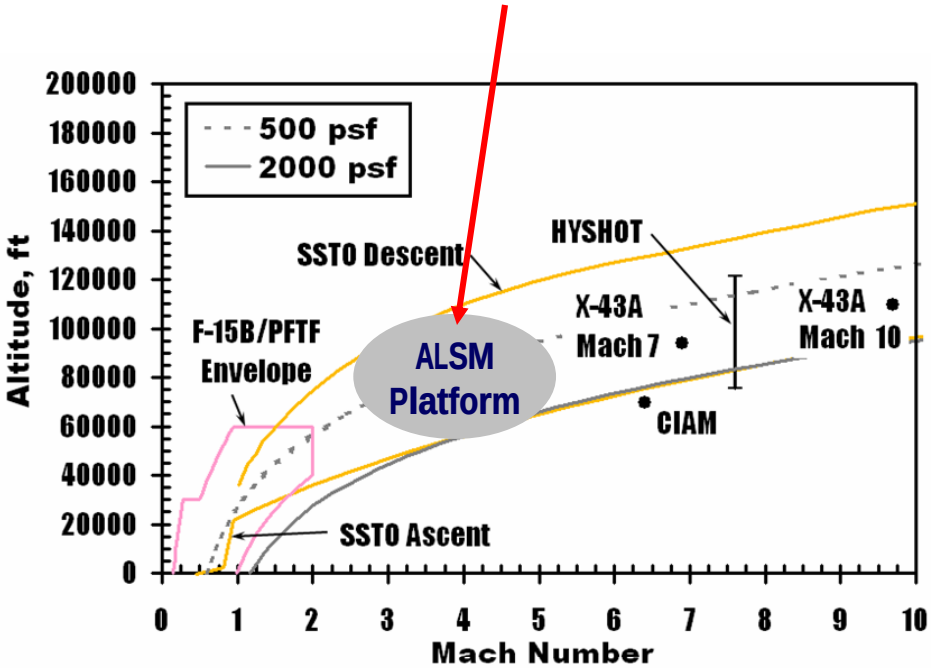
*(Tom Jones, DFRC)*

**Objective:**

**Provide low cost hypersonic research flight test capability to increase the amount of hypersonic flight data to help bridge the large developmental gap between ground testing/analysis and major flight demonstrator X-planes.**




**Phoenix Flight Envelope**



# Phoenix Possible Payloads

- **Aerodynamics**
  - **Boundary layer laminar to turbulent transition experiment**
  - **External burning for transonic drag reduction**
  - **Supersonic parachute testing**
- **Systems**
  - **High speed flush air data system (FADS) validation**
  - **Avionics system flight validation**
- **Materials & Structures**
  - **High temperature seals**
  - **High temp leading edge validation**
  - **High temp instrumentation**
- **Guidance, Navigation, and Controls**
  - **Hypersonic control law validation**
- **Science**
  - **High altitude research**

*All internal components (warhead, old guidance computer, and radar tracker) removed from guidance and armament sections to make space for payload and new guidance computer and INU*

- Diagnostic Technologies
- Sensor Technologies
- Testbed for Flight Instrumentation Qualification/Validation
- **Investments in New and Emerging Concepts**

# NRAs: Investment in New and Emerging Concepts

| Title | Organization | AAP | Prop | M&S | GNC |
|---|---|---|---|---|---|
| Development of MHz frame rate optical diagnostics for hypersonic ground test facilities | THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION | | X | | |
| Combustion Efficiency Measurement for Ground Test and Basic Hypersonic Research | THE RECTOR AND VISITORS OF THE UNIVERSITY OF VIRGINIA | | X | | |
| Hypersonic Mass-Flux Sensing with Fiber-Coupled Tunable Diode Lasers for Ground Test Applications and Flight Evaluation | LELAND JUNIOR STANDFORD UNIVERSITY | X | X | | |
| Simultaneous Dual-broadband CARS and Interferometric Rayleigh Scattering | THE GEORGE WASHINGTON UNIVERSITY | | X | | |
| High-Sensitivity Heat Flux Gage for Calibrated Heat Transfer Measurements | TAO OF SYSTEMS INTEGRATION, INC | X | | X | |
| Protected, High Temperature Optical Fiber Sensors, Gauge Elements and Systems | VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY | | | X | |
| Adaptation of Temperature and Pressure Sensitive Paint Technology for Basic Hypersonic Research | LEATECH, LLC | X | X | X | |

**These NRAs were awarded in 2006, maximum 3 years; New awards to be made in 2007**

# High-Sensitivity Heat Flux Gage For Calibrated Heat Transfer Measurements

*(NRA: Tao Systems, Inc)*

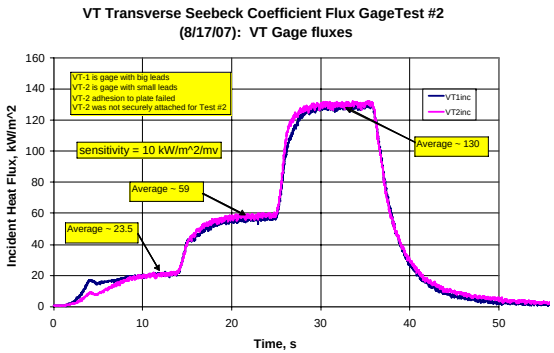
## Objectives

- Develop low/high temperature heat flux sensors (HFS)
  - Improve sensor stability at high heat fluxes and high temperatures
  - Increase sensor sensitivity (signal-to-noise ratio)
  - Increase frequency response

## Approach

- Thermoelectric high temperature HFS
  - Reduce profile to increase frequency response
  - Stable under continuous operation at 1000 $^{o}$C.

**Preliminary Testing: Sandia Labs**




**Stable HFS Testing > 1000 $^{o}$C and High Heat Fluxes**

## Impact

- Increased resolution heat transfer measurement
- Higher frequency response than existing heat flux gages
- High temperature operation and calibration (> 1000 $^{o}$C)

# Summary

**The Experimental Capabilities discipline in the Hypersonics Project has demonstrated its focused efforts to**

- **enhance existing diagnostics and sensor capabilities;**
- **develop new techniques to maturation;**
- **Investing in new and emerging concepts.**

**These efforts have resulted in the generation of new experimental techniques that can be used to more accurately validate theoretical and computational models, and reduction of costly and time-consuming iterative production of hardware .**

# Acknowledgements

**Hypersonic Leadership Team led by**

**Dr. Jim Pittman, Principal Investigator**
**Dr. Neil Cheatwood, Project Scientist**
**Dr. Larry Olson, Project Manager**

**ExCap POCs, on behalf of ExCap group**

**Ernie Fretter, ARC**
**Larry Hudson, DFRC**
**Scott Thomas, GRC**
**Paul Danehy, LaRC**