The 2015 Aerothermodynamics, Transition and Turbulence, and MURI Review
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411 B H Goethert Pkwy, Tullahoma, TN 37388

NASA-LaRC Hypersonics Mission Overview

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NASA Hypersonics Recent History

NASA's FAP Hypersonics Project ended in FY12 after 7 years

- **NASA HQ managed** through Aeronautics Research Mission Directorate
- **Extensive NASA funding** (~$60M/year down to ~$25M/year in FY12)
- 7 years of fundamental research and support of DoD programs

Interim model for NASA Hypersonics (FY14/15)

- **Support DoD Hypersonics Programs/Sustain Capabilities**
- **NASA Langley and Glenn managed**
- **Minimal NASA funding**
  - ARMD FAP High Speed: $4.5M/year hypersonics subproject
  - ARMD FAP ATP/AETC: $3.5M/year for 8' HTT and LAL
  - FY15 ARMD Augmentation: $5M (one year)
- **Reimbursable funding model**
  - **Find external customer funding** to maintain in-house Subject Matter Experts and Test Services/Facilities
  - **FY 14/15 Funding stream:** AFRL funding for DoD focused programs. This provides some sustainment for NASA hypersonic critical capabilities
  - **DARPA reimbursable support for TBG and HAWC**
  - **Industry IRAD reimbursable work**

NASA Hypersonics FY14/15

Summary of FY14/15 major activities:

- Fundamental research & tool development
- LaRC 8-ft High Temperature Tunnel Capability sustainment & improvements
- Phase 3 Combined Cycle Engine Rig (Mode Transition)
- Joint AFRL/NASA Systems Analysis capability dev./systems studies
- Aero/Aerothermal and Thermal Structural studies/evaluation for TBG
- Propulsion support of the High Speed Strike Weapon Technology Maturation
- Flight Research support of the Joint US-AUS HIFiRE Program
- Aero/Aerothermal, Propulsion & Materials testing for TBG and HAWC
- Aero/Aerothermal & Propulsion testing for Industry (IRAD)

NASA Hypersonics FY16

- NASA HQ managed through ARMD
  - Advanced Air Vehicles Program (AAVP) (Jay Dryer)
    - Aeronautics Evaluation and Test Capabilities (AETC) (Ron Colantonio)
      - Hypersonics Subproject (Ken Rock)
  - Funding
    - $15M Full Cost
    - Includes $3.5M for:
      - 8-Ft High Temperature Tunnel (8' HTT)
      - Langley Aerothermodynamics Laboratory (LAL)
- DoD Reimubursable support for focused Programs
  - AFRL
  - DARPA
- Industry Reimbursable support

NASA Hypersonics FY16

Planning/Not yet approved

Strategic Thrust

Recapture US Supremacy in hypersonics for future National needs/NASA going to support AF Roadmaps

National Aeronautics Research and Development Plan: In general, the Department of Defense seeks to develop technologies to a level where they can be validated or demonstrated in a relevant environment and ultimately be employed in weapon systems. This validation or demonstration may include flight test, ground test, validated modeling and simulation, and any other means as appropriate to enable the transition of technologies into the development of aviation systems for national security and homeland defense

Outcomes

Outcomes are derived from USAF Hypersonics S&T Roadmaps

- Support the development of necessary technology required to support weapon system AOA (TRL 6) by 2020
- Support the development of necessary technology required to support hypersonic ISR AOA (TRL 6) by 2030
- Support the development of necessary technology required to support hypersonic space access AOA (TRL 6) beyond 2030

Research Themes (RTs): Long term research areas that will enable the outcomes

- Efficient and affordable hypersonic propulsion
- Integrated system concept design and analysis for hypersonic flight
- High temperature, durable materials and structures
- Aerodynamic and aerothermodynamic environment predication capabilities

Technical Challenges (TCs): Specific measurable research commitments w/in the RTs

- Under development

Hypersonics Research Themes

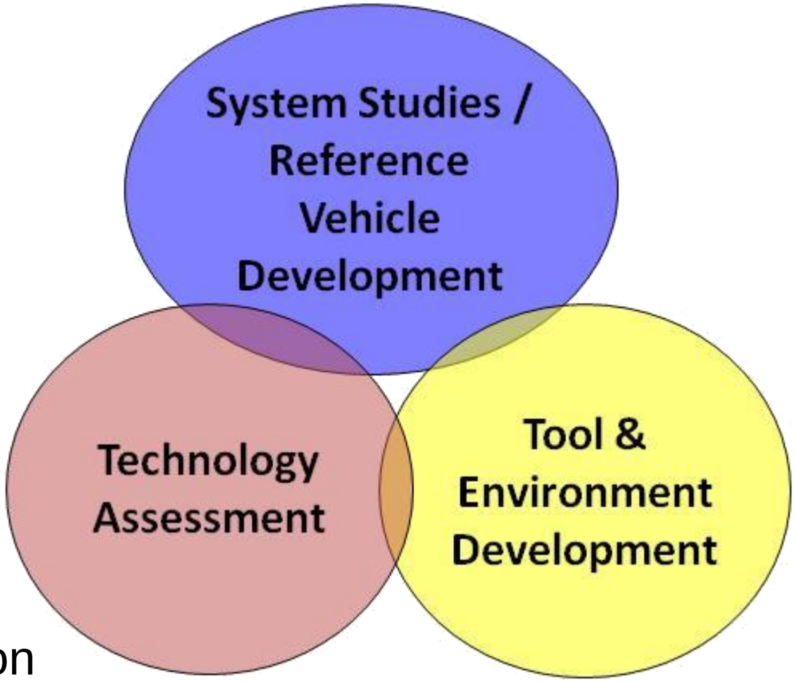
- ❑ Efficient and Affordable Hypersonic Propulsion
  - Develop and demonstrate hypersonic air breathing propulsion technology, tools, and techniques in the areas of Combine Cycle propulsion, scramjet propulsion, and propulsion airframe integrations to enable efficient and affordable hypersonic systems.
- ❑ Integrated System Concept Design & Analysis for Hypersonic Flight
  - Develop and analyze reference vehicle concepts to determine potential system capabilities that establish research & technology goals and to advance design & analysis tools to significantly reduce system uncertainty.
- ❑ High Temperature, Durable Materials and Structures
  - Develop and characterize high temperature materials and structures with application to seals, leading edge materials, thermal protective systems, insulation, and advanced heat exchangers to increase durability of flight structures.
- ❑ Aerodynamic and Aerothermodynamic Environment Predication Capabilities
  - Develop and validate improved aero/aerothermo predication capabilities to reduce hypersonic vehicle environmental uncertainties.

Systems Analysis Role in Hypersonics

1. **Develop and analyze reference vehicle concepts across a range of missions to determine potential system capabilities and to establish research and technology goals and requirements.**

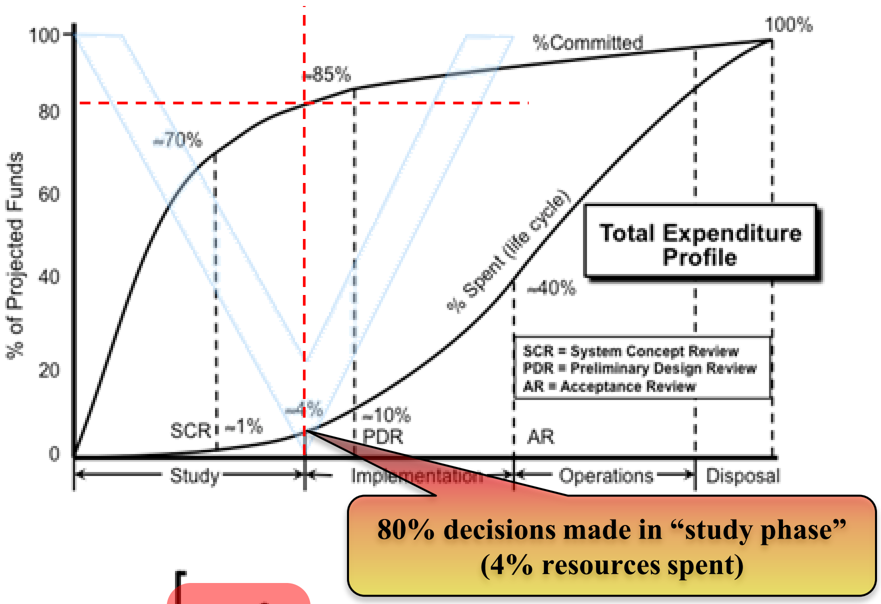
2. **Evaluate technology needs and impacts and provide definitive systems analysis results to decision makers.**

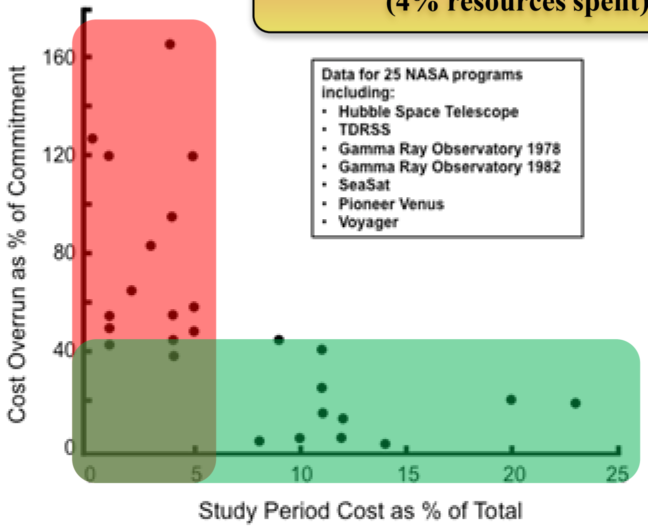
3. **Enhance vehicle level analysis tools and capabilities to facilitate 1. and 2.**
   - Advance integrated analysis capabilities and processes to significantly reduce analysis cycle time, enabling broader design exploration and potential to bring higher fidelity analyses to conceptual level.
   - Develop higher fidelity multi-discipline tools and analysis to provide reduced order models and validation for integrated environment analysis.



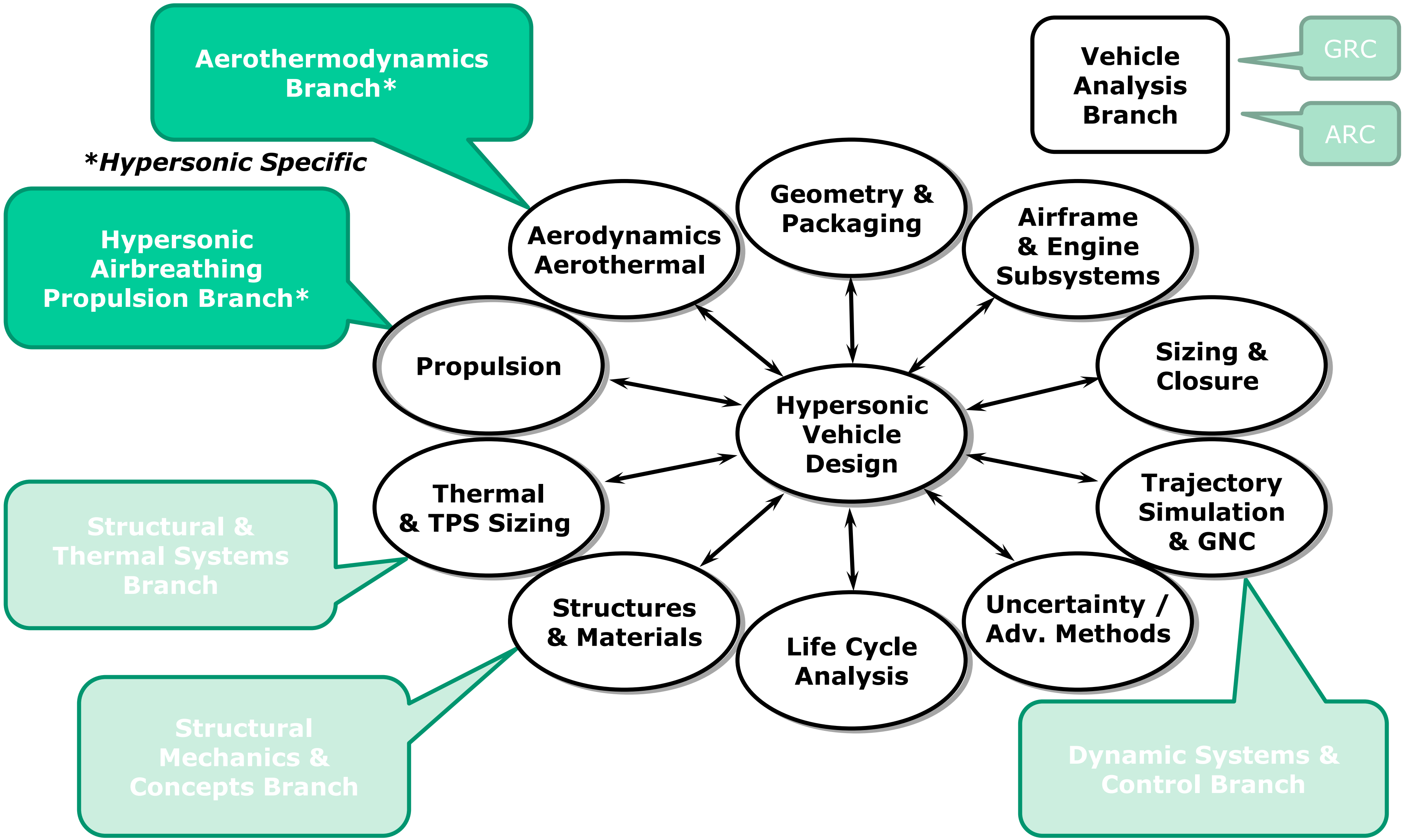
Benefits of Early Investment & Gov't Involvement

- **NASA flight programs have enjoyed substantially more success when government engineers & researchers are integral parts of the executing team (X-43, ARES-1X, MLAS, MER)**
- **Gov't team can provide**
  - Non-proprietary baseline design to guide R&D and improved requirements (pre / Phase A)
  - Independent analysis of contractor designs (Phase A)
  - Perform smart buyer function (contract award)
  - Evaluate system level performance pre & post flight





Hypersonic System Analysis Disciplines



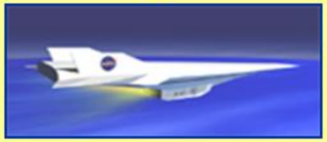
Vehicle Analysis Branch

- **Perform conceptual and preliminary design and analysis of high speed atmospheric flight and space transportation system concepts and related technologies, from the point of origin to the final destination and over the entire life cycle.**
  - Home to hypersonic airbreathing vehicle design
  - Unique “systems” perspective
- **Disciplines**
  - Aerodynamics
  - Weights & sizing
  - Aerothermal & TPS
  - Flight Mechanics
  - Structures
  - System Level Modeling / Configuration
  - Uncertainty Quantification
- **Honest broker / independent technical review**
  - History of performing independent technical review role for NASA HQ and other government agencies
- **Relevant Hypersonic Experience**
  - X-43A,B,C,D - X-33, X-34, X-37 - NASP
  - Access to Space - M10 Dual Fuel - Shuttle
  - Hypersonic vehicle & missile designs for Army, AF, Navy

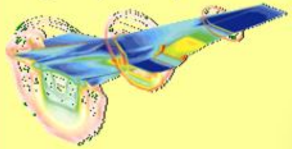
Flight Mechanics Analysis Capabilities

- **Mission Feasibility & Trajectory Optimization**
  - Design of constrained 3DOF & 6DOF trajectories that optimize vehicle performance & meet mission requirements
- **Multidisciplinary Performance Analysis**
  - Techniques that couple trajectory design & other discipline methods
  - Component Loads/Load Distribution
  - Vehicle strength requirements from trajectory-based loads analysis
- **Uncertainty Studies**
  - Application of Monte Carlo trajectory analysis to understand and assess the impact of mission uncertainties
- **End-to-End Flight Simulation**
  - High-fidelity 6DOF simulations for concept definition and detailed performance analysis
  - Guidance & control design and testing
  - Operational missions and day-of-launch support
- **Stage Separation Modeling**
  - Simulation of complex stage separation problems that include constrained relative motion and aerodynamic interference effects
- **Range Safety & Footprint Analysis**
- **Trajectory Reconstruction**

Hyper-X



- Trajectory Development



- Separation Analysis
- Control System Verification
- Vehicle Sizing Studies
- Propulsion flow-path development support

- Mishap Investigation
- Two Successful Test Flights

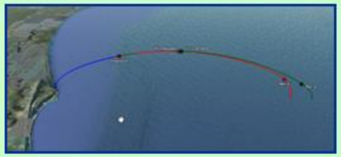
MLAS

- Concept Definition
- Motor sizing
- Trajectory Development
- Control System Design
- Parachute Analysis

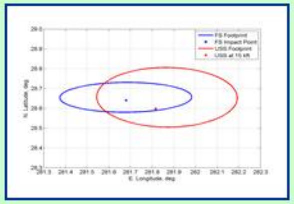
- Concept of Operations
- Separation studies
- Re-contact & Proximity Analysis
- Successful Test Flight

Ares I-X

- Trajectory Development
- Flight Loads Assessment
- Separation & Reentry Analysis
- Trajectory Reconstruction

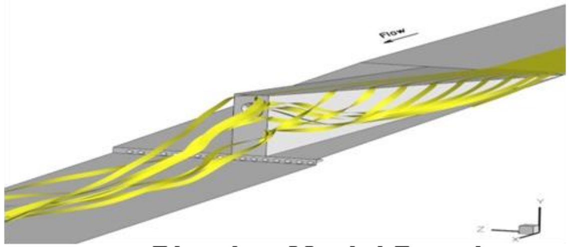


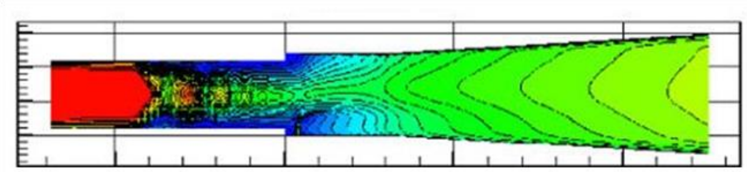
- Range Safety/Footprint Analysis



- Mission Operations Support
- Successful Test Flight

Hypersonic Airbreathing Propulsion Branch



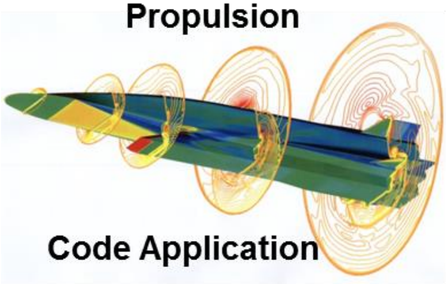


Physics Model Development, Numerical Methods, and Code Development

Experimental Airbreathing Propulsion

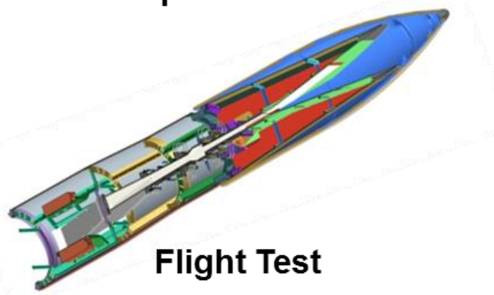
MISSION
Conduct multidisciplinary research to develop advanced technology for hypersonic airbreathing propulsion systems for aerospace vehicles.

Vehicle Configuration Development and Optimization



Code Application

Combined Functional Disciplines for Mission Success



Flight Test

Enhanced Injection and Mixing Project

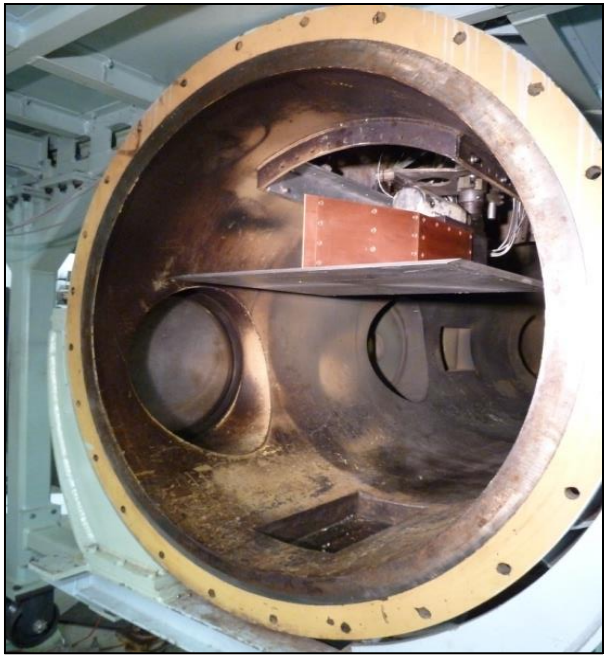
- Goal is to improve scramjet performance and design capability relevant to flight Mach > 8

- Objectives:
  - To increase knowledge and understanding of the fundamental physics governing fuel-air mixing relevant to the hypervelocity flight regime.
  - To develop strategies for improving injector performance (increased mixing efficiency, reduced/optimized losses/drag).
  - To develop the functional relationships between mixing efficiency, losses (i.e. total pressure loss, drag) and flowpath geometry (i.e. combustor length, injector spacing) (e.g. McClinton et al. 2002)

Research Approach

Combined experimental and computational approach

- Experiments in Langley Arc-Heated Scramjet Test Facility (AHSTF)
  - Helium injection into Mach 6 airflow
  - Cold flow (T_t=1310 to 1760°R)
  - Injectors mounted on open plate
  - In-stream measurements
    - Gas sampling (helium mole fraction)
    - Pitot pressure
    - Total temperature
  - Fuel plume visualization via nitric oxide planar laser-induced fluorescence (NO PLIF)

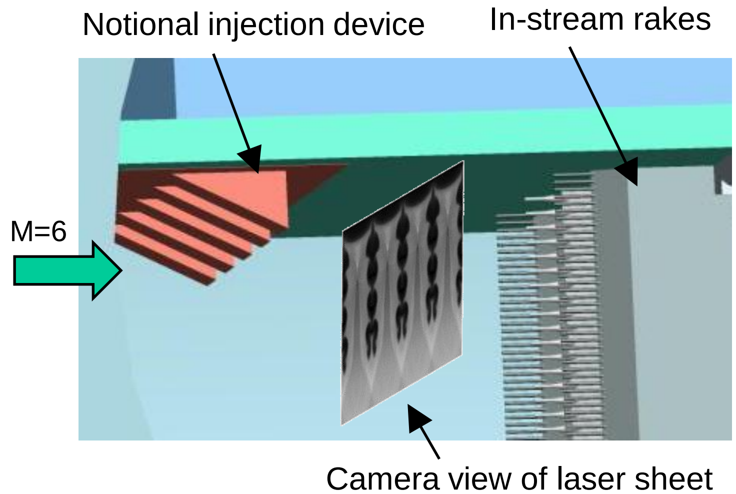


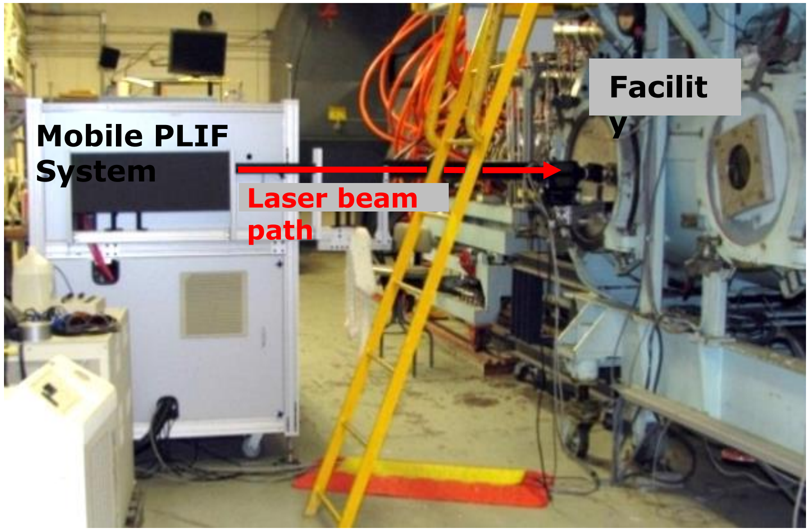
Test article installed in AHSTF with bulkhead and nozzle removed

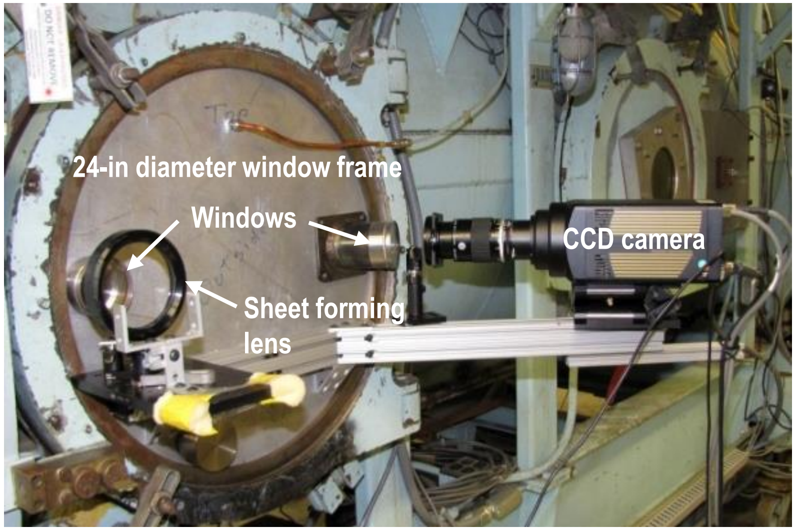
- CFD (using VULCAN-CFD code)
  - Provides details of flowfield otherwise unobtainable from experiment.
  - Needed to compute performance metrics (mixing efficiency, total pressure recovery, stream thrust potential).
  - Reynolds averaged simulations calibrated with experimental data.
  - Large eddy simulations (LES) for select cases for higher fidelity and unsteady flow details

Flow Visualization via NO PLIF

- Nitric oxide (NO) naturally present in facility air as a result of arc heating
- Will act as in-situ flow tracer that can be imaged using planar laser-induced fluorescence (PLIF).
- Fuel plume will be visualized by the *absence* of fluorescence.







Mobile PLIF system and optics as set up in AHSTF for NO PLIF Demonstration Tests

VULCAN-CFD Overview

- **VULCAN-CFD is a hybrid Structured/Unstructured 3-D compressible flow solver**
  - Solves the Reynolds-Averaged or Spatially filtered (LES) equations governing thermal equilibrium/non-equilibrium gases with chemistry
  - Supports any combination of FNS and/or PNS solution procedures
  - Parallelized via domain decomposition using portable MPI libraries
  - Currently supports 36 boundary conditions
  - Arbitrary C0 and non-C0 block to block connectivity supported
  - Variety of turbulence closure models (LEVMs, ARSM, hybrid RAS/LES, dynamic SGS closures)
  - Generalized chemistry treatment (finite rate with allowances for arbitrary reaction orders and pressure-dependent kinetics, CARM)
  - Collaborative development environment with continuous regression testing
  - Portable to a wide class of Unix/Linux architectures
  - Suite of post-processing tools specific to high-speed propulsion

- **VULCAN-CFD is available to US Citizens (ITAR) and a reasonable level of support is offered as well**
  - VULCAN-CFD is used extensively by government, industry and academia for scramjet flowpath analysis
  - On the order of 10 new requests per year are processed

Role of CFD in Scramjet Development

- **CFD has historically been used primarily as an analysis tool**
  - 3-D steady-state RAS (parabolized versions for some analyses)
  - Turbulence modeled using eddy viscosity/gradient diffusion concepts
  - Chemical reactions handled via reduced finite rate kinetics (or possibly mixing controlled kinetics)
  - Turbulence-chemistry interactions typically ignored
  - Acceptable time to solution is measured in days ➔ weeks

- **Limitations as an analysis tool**
  - Uncertainty related to turbulence model is often dominant
  - Crude chemistry → Flame-holding limits can not be obtained
  - Unsteady effects (which can be important) are ignored
  - Best used to describe performance during “robust” operation

- **VULCAN-CFD development activities addressing these limitations**
  - Scale-resolving simulation capabilities
  - Flamelet / Progress Variable (FPV) combustion models

Scale-Resolving Development Activities

- **The hypersonics project NRA program together with a substantial in-house activity transformed VULCAN-CFD into capable tool for scale-resolving simulations**
  - Advanced hybrid RAS/LES formulations
  - Low-dissipation numerics
  - Recycling/Rescaling for specification of resolved turbulence at inflow boundaries
  - Paper highlighting these capabilities won "Best Paper" at 2012 AIAA JPC
- **Dynamic SGS closures have recently been implemented**
  - Classic Germano approach that assumes structural similarity between the sub-grid stresses and test filter stresses
  - Heinz approach (Physics of Fluids, Vol. 24, 2012) that assumes structural similarity between the sub-grid stresses and the Leonard stresses
- **Approximate methods to simulate resolved turbulence at inflow boundaries are on-going**

Flamelet/Progress Variable (FPV) Combustion Model

- **FPV combustion models account for finite rate chemistry with a greatly reduced number of scalars that must be tracked**
  - Drastic reduction in the computational cost (and numerical stiffness) as compared with full finite rate kinetic treatment
- **Formally investigated the applicability of a FPV combustion models for scramjet combustion applications**
  - *a priori* analyses performed using the HIFiRE Direct Connect Rig (HDCR) to assess the fundamental assumptions associated with the FPV combustion model
  - This information was used to determine how best to parameterize the FPV formulation for the highly compressible reacting flow environment present in scramjet engines
- **The FPV formulation has been implemented into VULCAN-CFD and is currently being tested (*a posteriori*) for the HDCR flowpath**
- This activity is the focus of a Ph.D research effort funded through the NSTRF program

Hybrid Structured/Unstructured Capability

- **One of our Hypersonics Project NRA activities resulted in the development of a hybrid structured/unstructured capability into VULCAN-CFD**
  - This project was extended (2 year no-cost extension), so the final software was delivered after the end of the NASA Hypersonics Project
  - Development activities since then have merged this capability with the production release and this capability is currently under-going beta-testing.

- **This capability is unique in that it allows VULCAN-CFD to retain the efficiency of its existing structured grid framework, while only utilizing an unstructured framework when local geometry constraints demand it.**