Use, Assessment, and Improvement of the Loci-CHEM CFD Code for Simulation of Combustion in a Single Element GO_2/GH_2 Injector and Chamber

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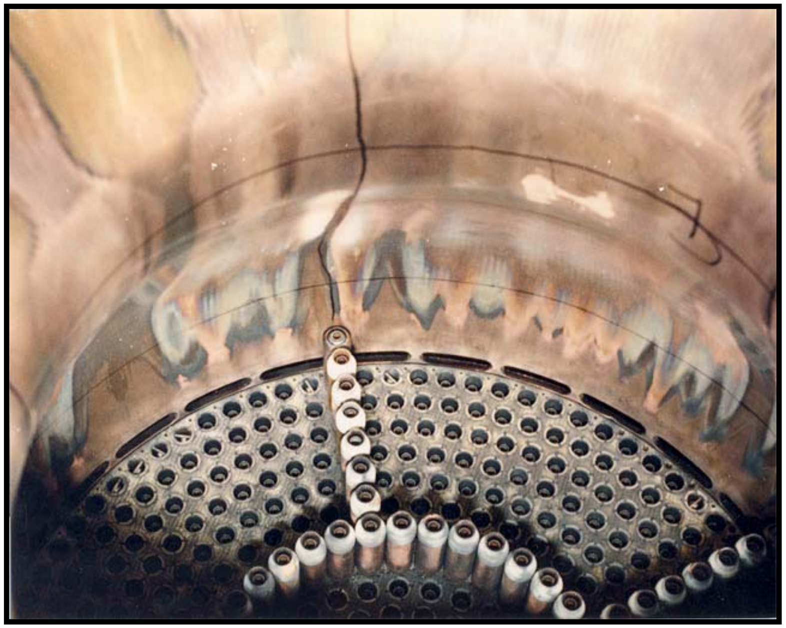
Summary Statement

This presentation documents one part of a continuing effort at Marshall Space Flight Center (MSFC) to use, assess, and continually improve CFD codes to the point of material utility in the design of rocket engine combustion devices.

Background – Need for Improved Tools

The Need for Improved Injector Design Tools

- **Issues with current injector design tools**
  - 1-D, empirical
  - Result in costly, time consuming test, fail, fix development program



Environments are 3 dimensional

- **Requirements for new injector design tools (Simulation Readiness Level)**
  - **Fidelity**-must be able to calculate performance & 3-D environments as a function of injector design details and flow physics
  - **Robustness**-must be able to produce large numbers of solutions over a parametric space during the design phase
  - ***Accuracy***- must be demonstrated to yield quantitative results

From: *Reference 1*

Background – Combustion Devices Roadmap

The combustion CFD technology effort at NASA/Marshall Space Flight Center is guided by a Combustion Devices CFD Simulation Capability Roadmap. The Roadmap objective is:

To develop, verify, and validate Computational Fluid Dynamics (CFD) tools for use in multi-disciplinary simulations of the liquid rocket engine TCA hardware ignition, performance, thermal environments, and combustion stability so to affect the TCA design in a timely manner.*

- If CFD is to be used as an injector design tool, code developers & code users must address this key issue:

  How should confidence (i.e. demonstrated accuracy capability) in simulations and modeling for design be critically addressed, and where necessary, improved?

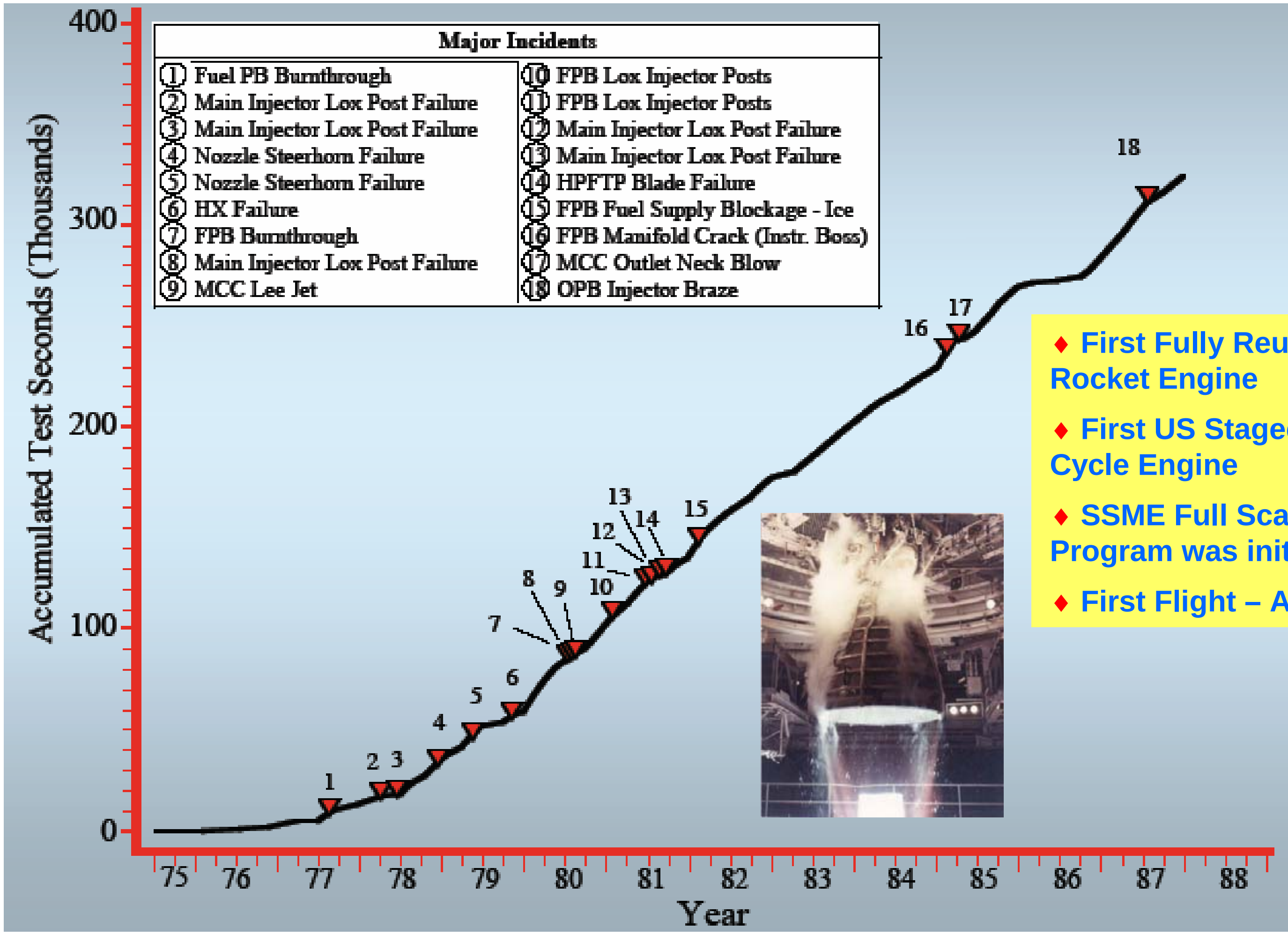
- Verification & Validation of computational solutions are the primary means to quantify and build this confidence

  * - TCA stands for Thrust Chamber Assembly

(Reference 1)

Background – SSME History

Why are new TCA design tools required? Look at the SSME development--

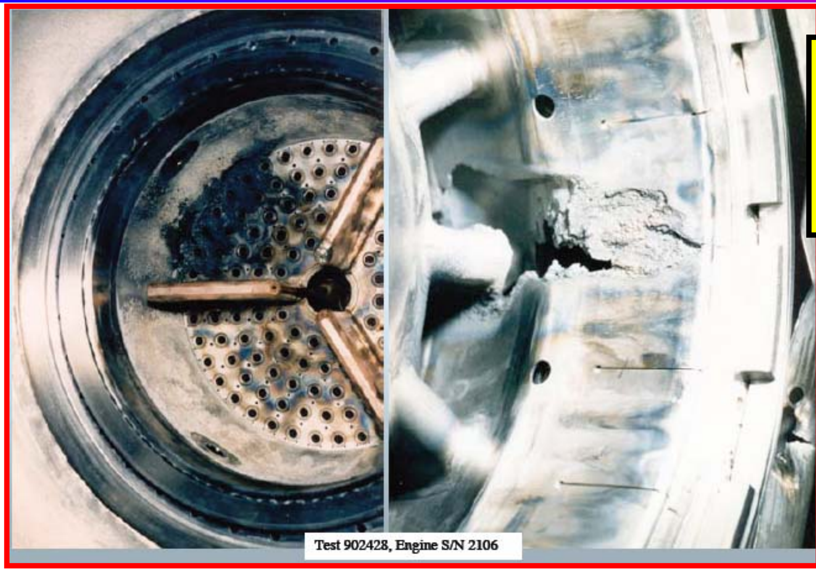


- ♦ **First Fully Reusable Cryogenic Rocket Engine**
- ♦ **First US Staged Combustion Cycle Engine**
- ♦ **SSME Full Scale Development Program was initiated in April 1972**
- ♦ **First Flight – April 1981**

Note: All SSME information from—

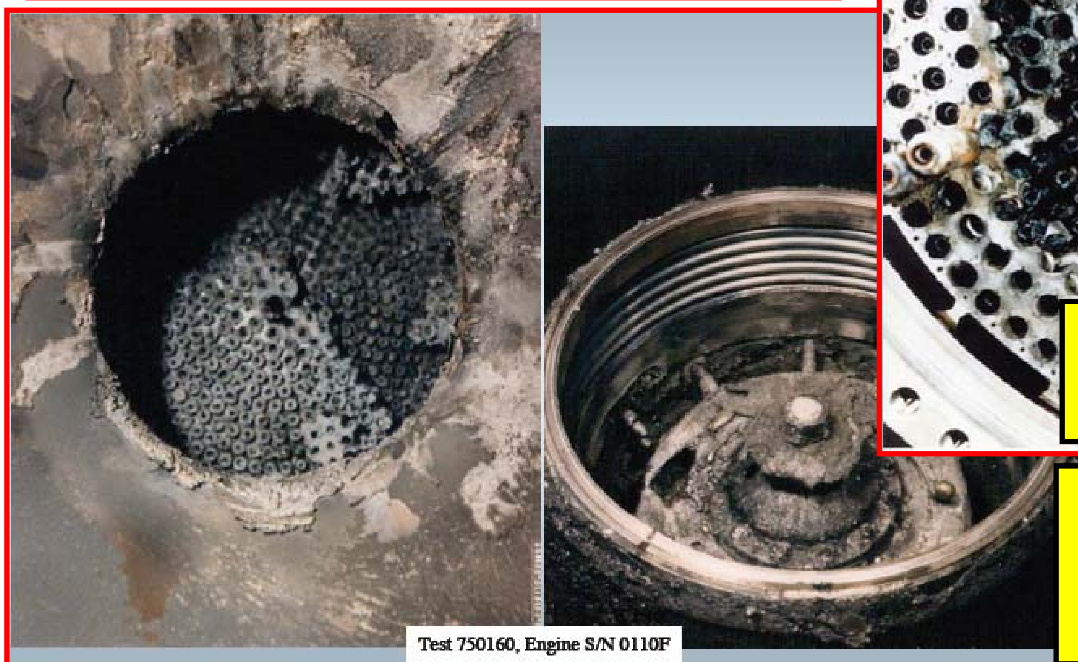
"Combustion Devices Failures During Space Shuttle Main Engine Development," Goetz, O. K., Monk, J. C., 5th International Symposium on Liquid Space Propulsion Long Life Combustion Devices Technology, Chattanooga, TN, 2003 (*Reference 2*)

Background – SSME History



Oxidizer Preburner
Failure at 188 sec.
July 1, 1987

Main Injector Failure at 233 sec.
July 15, 1981

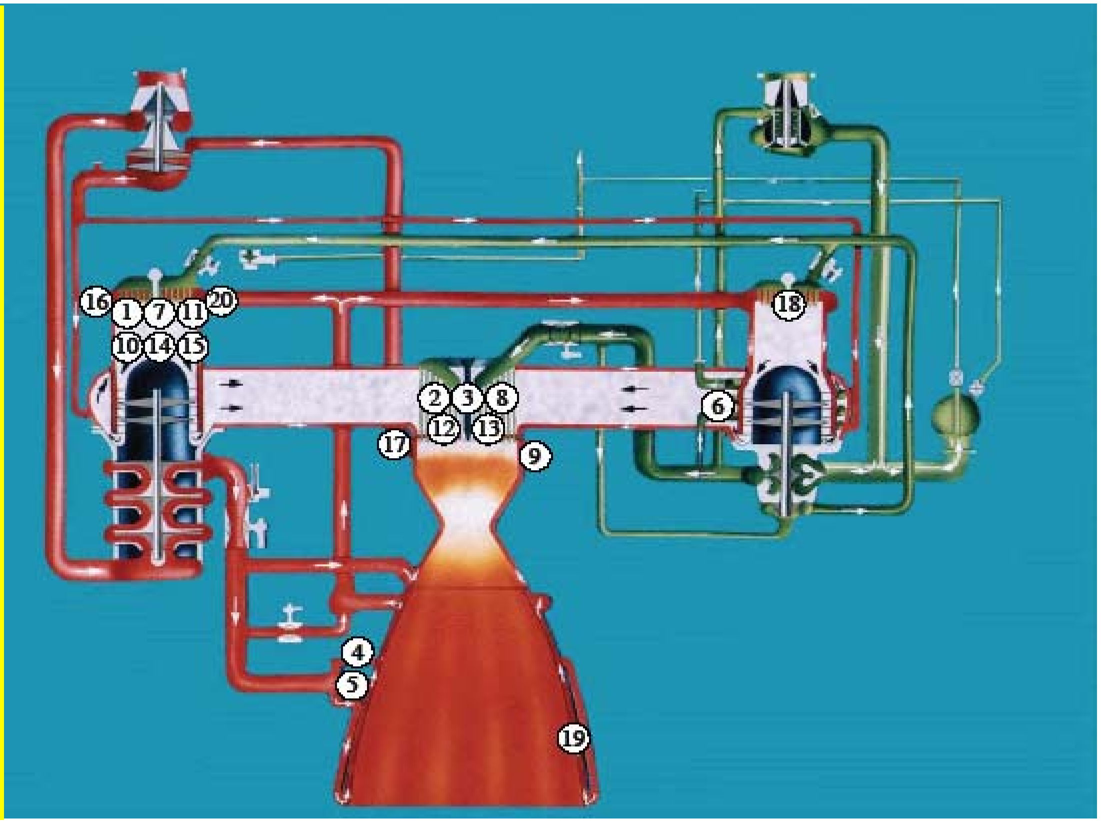


Fuel Preburner
Failure at 3.6 sec.
February 12, 1982

Background – SSME History

Injector design is the heart of this overall vision

- **The large majority (~80%) of Combustion Devices failures occur in the injector**
- **Injector design details and physical processes occurring here govern:**
  - Ignition
  - Performance
  - Environments in the entire combustor or TCA
  - Stability



The design space that contains an injector with reliable ignition characteristics, high performance and stable operation with sufficiently benign environments has historically been located only after several time consuming and costly design, test, fail cycles. *This is a direct consequence of modeling very complex flow phenomena with relatively simple, empirical tools.*

Background – 2 Parallel Thrusts

- Marshall is a Space Flight Center, so we must support Programs with the current, albeit limited capability for injector design

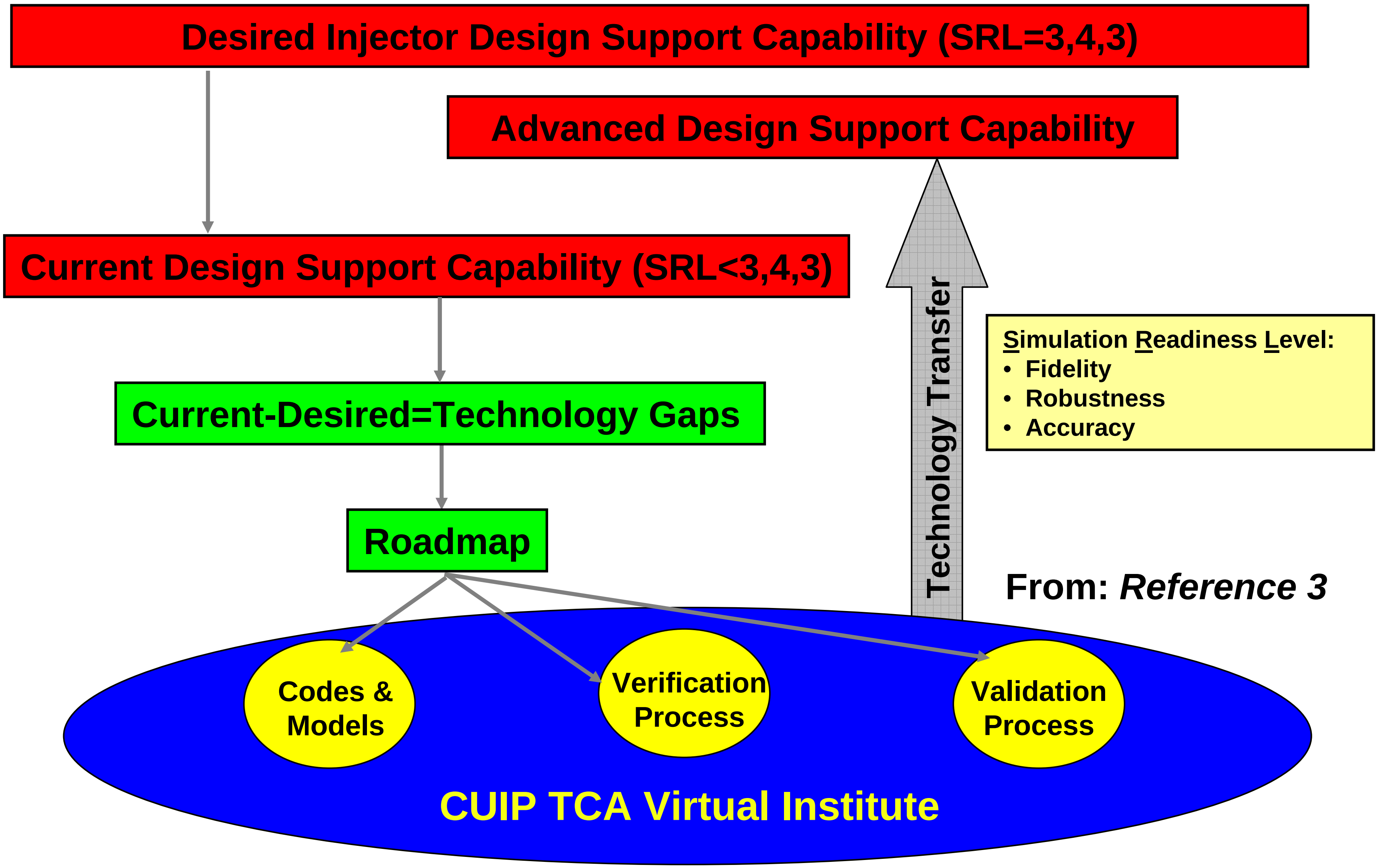
At MSFC, we must maintain 2 parallel thrusts

- Program Support
- Technology Development

- CFD-based Thrust Chamber Assembly (TCA) design tool improvement is a long-term, fairly high risk effort with potentially very high payoff
- Ultimately, these improved tools needs to reside with the engine contractors
- At this point, the risk is more than the engine contractors are willing/able to manage
- It is NASA's job to lower the risk by continued development

From: *Reference 3*

Background - Technology Integration



CUIP - Constellation University Institutes Project TCA - Thrust Chamber Assembly

Application to Vision for Space Exploration

- The ultimate purpose of the efforts documented is assessment and further improvement of the Loci-CHEM code, to facilitate its development into a viable tool for the design of Liquid Propellant Engines used in the Vision for Space Exploration
  - J-2x LOX/Hydrogen engine (starting now)
    - ARES I (Crew Launch Vehicle) 2nd Stage
    - ARES V (Cargo Launch Vehicle) 2nd Stage
  - RS-68 X 5
    - ARES V 1st Stage
  - Lunar Lander / Lunar Take-off Engine
    - LOX / Methane
  - Thrust Vector / Roll Control Engines
  - Igniters

Computational Tool: Loci-CHEM

- **Loci-CHEM:**
  - Finite-volume flow solver for generalized grids
    - Developed at Mississippi State University in part via NASA and NSF funded efforts
    - CHEM uses high resolution approximate Riemann solvers to solve finite-rate chemically reacting viscous turbulent flows. (Details are presented in the CHEM user guide, Ref.4)
  - Density-based computational fluid dynamics (CFD) algorithm
    - Preliminary implementation of pre-conditioning is available and is used extensively here
    - Preconditioning methods for chemically reacting flows are still an area of active research
      - very important component in the continuing development of Loci-CHEM.
  - Two-Equation Turbulence Models
    - Wilcox's k-ω model (KW)
      - Has non-physical sensitivity to the free-steam k and ω values
    - Menter's Baseline Model (BSL): Blended model: k-ω near the wall, k-ε away from the wall
    - Menter's Shear Stress Transport Model (SST)
      - Also a blended model based on Menter's BSL: (k-ω near the wall, k-ε away from the wall)
      - general purpose model that is reasonably effective at predicting flow separations
  - Parallelism is supplied by the Loci framework (Ref. 5)
    - exploits multi-threaded and MPI libraries to provide parallel capability
  - Loci-CHEM is quite scalable
    - approximately 90% parallel efficiency on to 64 CPUs on the axisymmetric simulations that were part of this effort.

Test Description

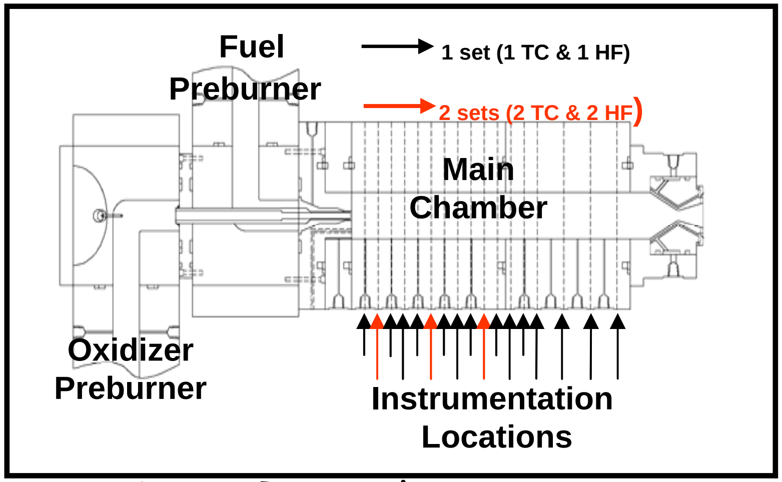
Experimental Program to lead toward better understanding of heat flux to the Chamber Wall

- Single element shear coaxial injectors were tested as part of the Staged Combustion Injector Technology (SCIT) program
  - to obtain benchmark quality data for CFD Code Validation
  - Gaseous Oxygen and Gaseous Hydrogen
  - performed at the Pennsylvania State University's (PSU) Cryogenic Combustion Laboratory (CCL)
    - Reference 6

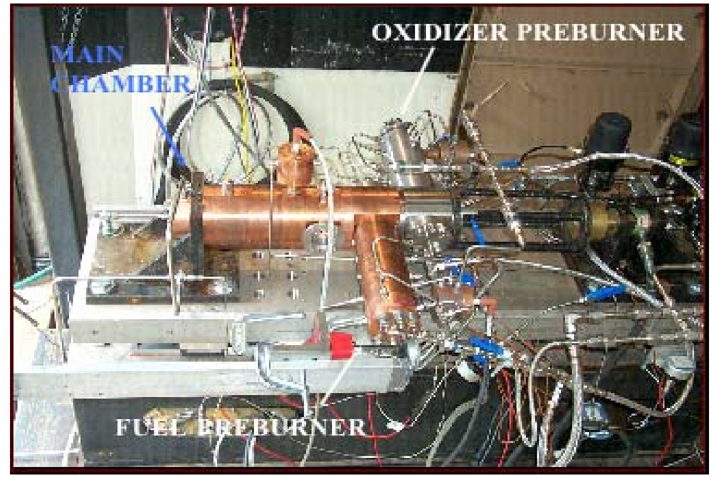
  The Chamber is heavily instrumented for wall temperature and heat flux measurements
    - Allows several types of experiments to be conducted
      - Hot propellants when Pre-Burners are Used
      - Ambient temperature propellants via operation without the pre-burners
    - Instrumentation stations can be moved around from one test to another; allowing different sections of the combusting gases to be instrumented in more detail
- Data was taken over a range of chamber pressures for propellants injected at both ambient and elevated temperatures (8 cases)

Test Description

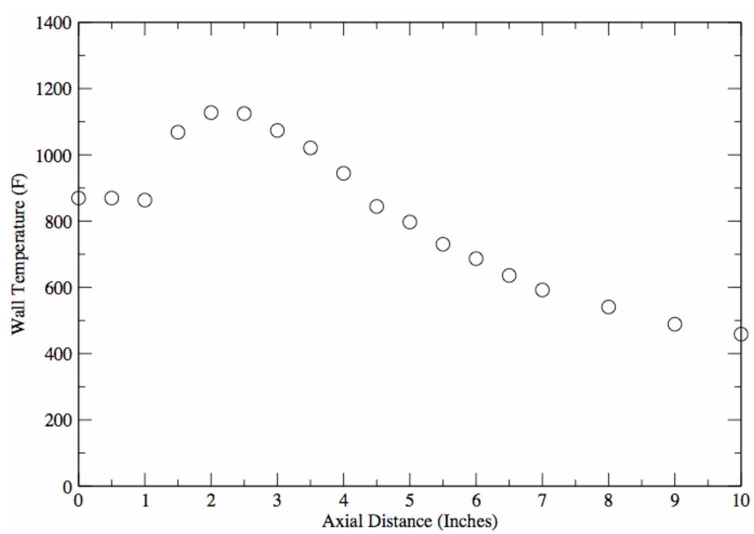
Experiment Modeled—Penn State University



Test Rig Schematic



Test Rig Photo



Sample Measured Wall Temperatures Boundary Condition

CFD Simulations - Cases Run

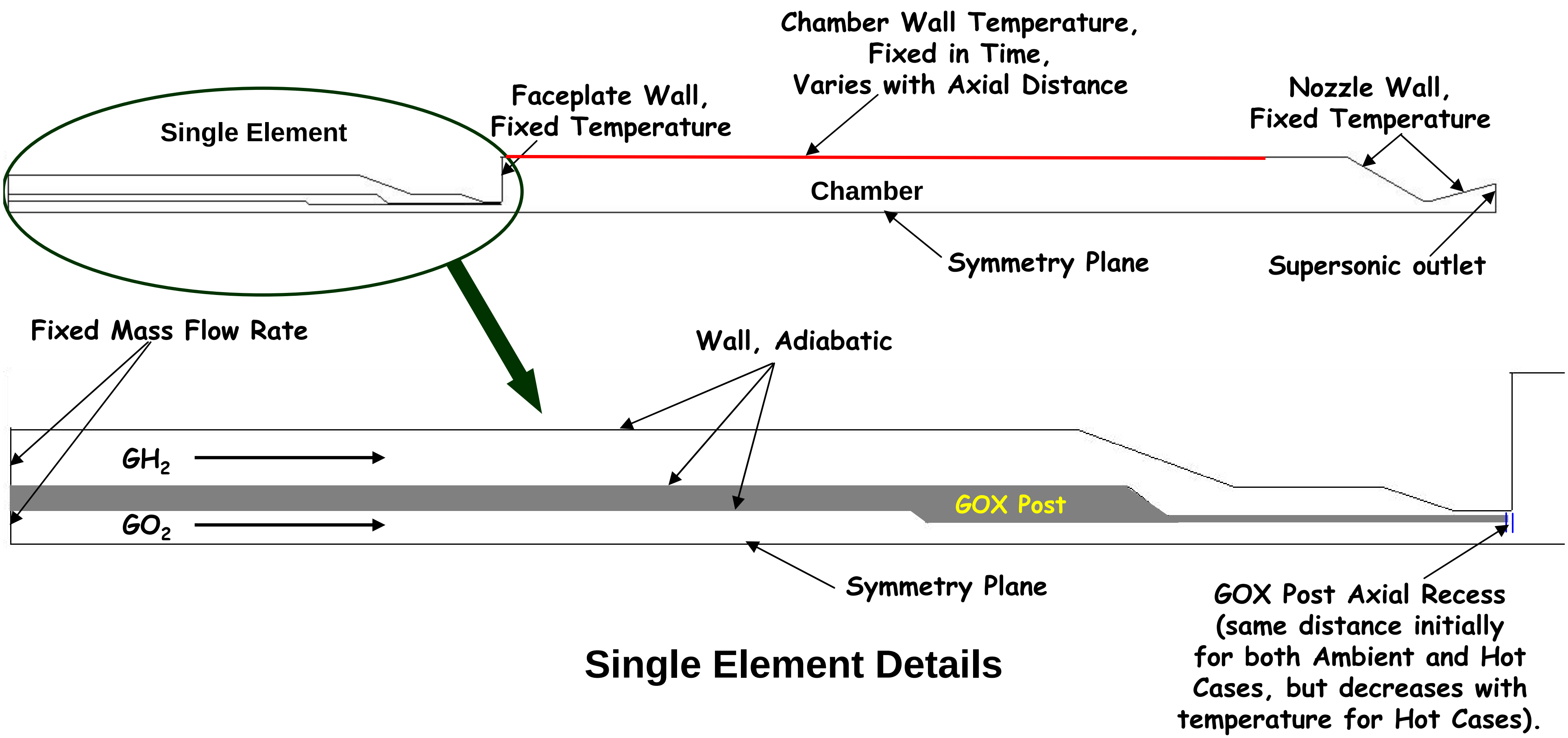
Summary of CFD Simulations Compared to Test Data				
Propellant Temps	Nominal Chamber Pressure (psia)			
	300	450	600	750
~Ambient (no Pre-Burners) (30 - 70 F)	X	X	X	X
Hot (with Pre-Burners) (750 – 1000 F)	X	X	X	X

The full set of simulations were conducted after an extensive set of simulations on one case (750 psia, hot propellants)

- grid independence study on hybrid grids (with and without local refinement)
- Several two-equation eddy viscosity low Reynolds number turbulence models were also evaluated as part of the study
- Effect of Pre-Conditioning was also assessed
- Reference 7

CFD Simulations – Boundary Conditions

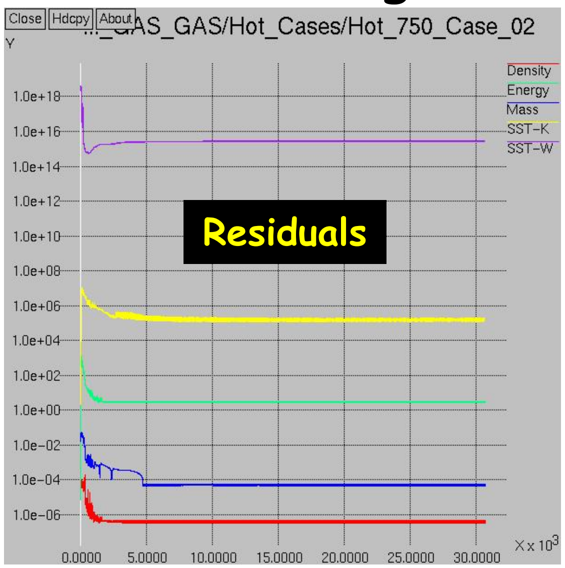
Computational Boundary Conditions

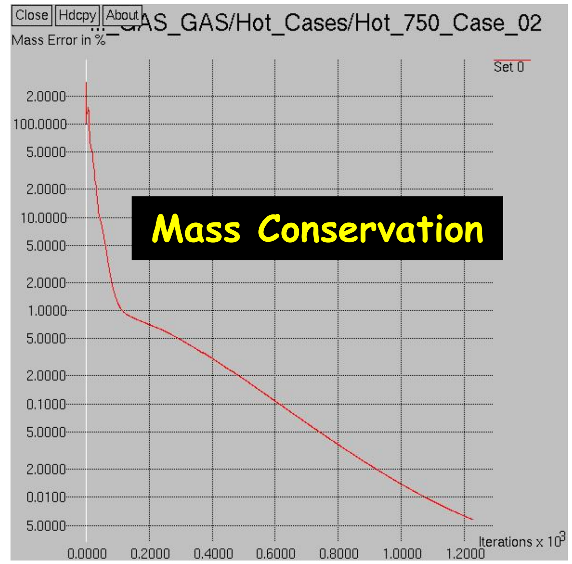


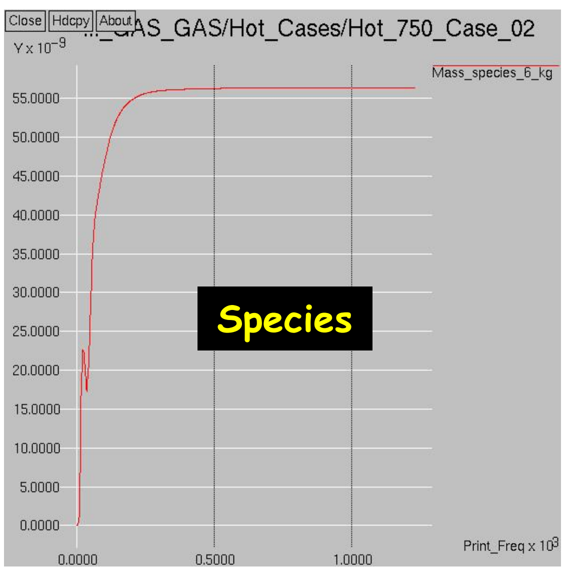
Single Element Details

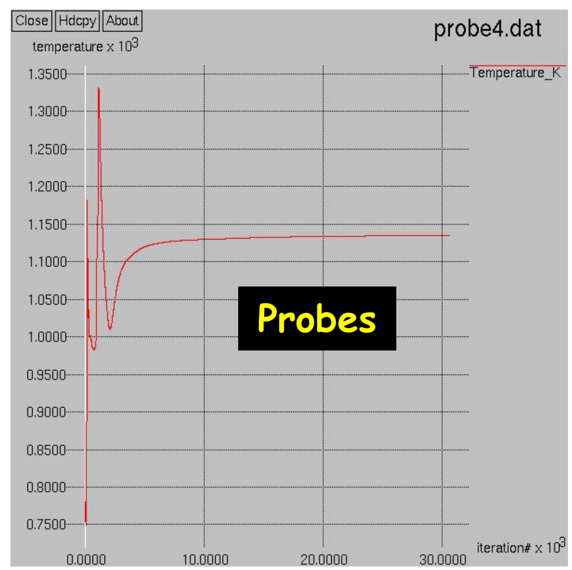
CFD Simulations – Typical Results

- **Iteration Convergence**



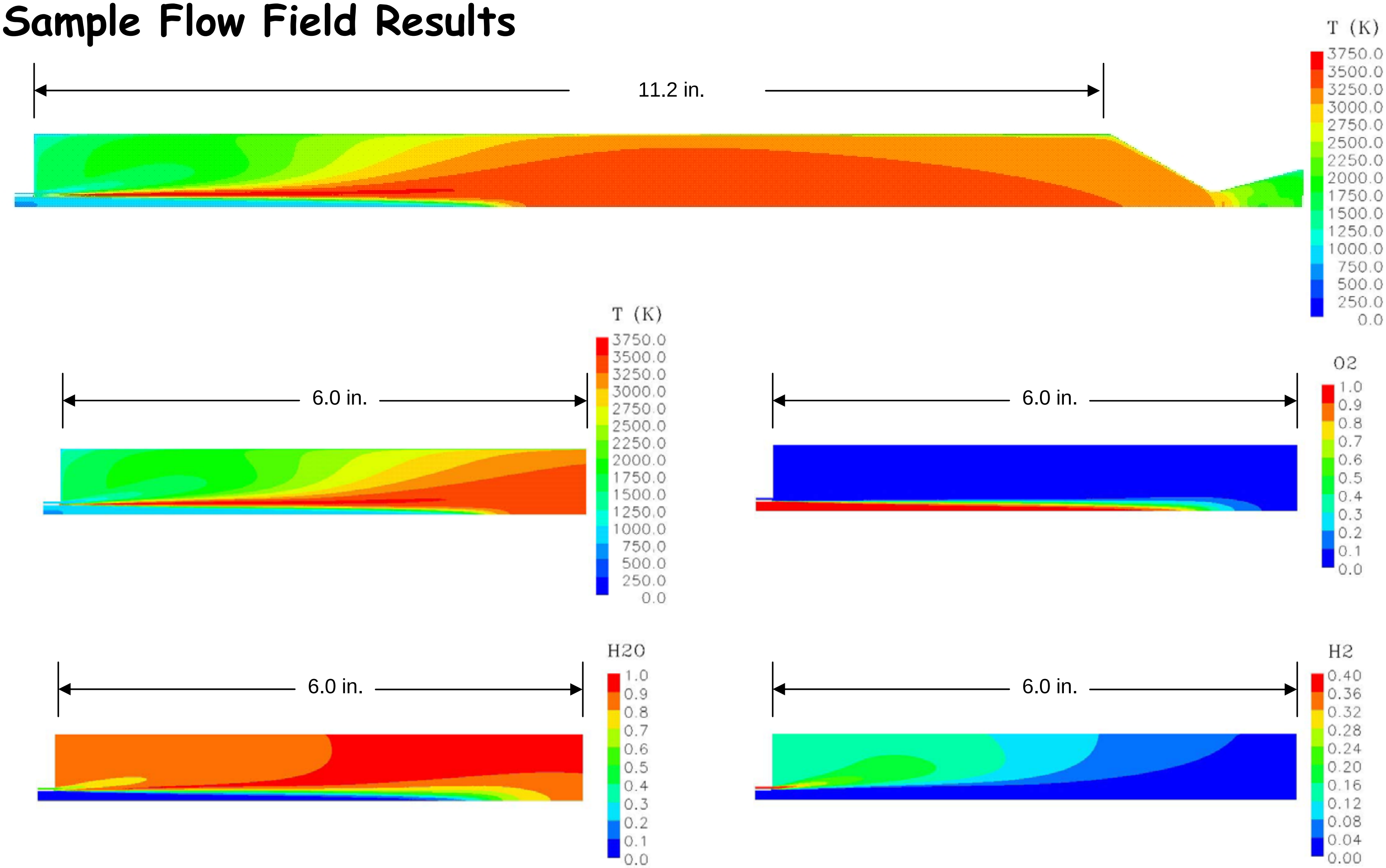




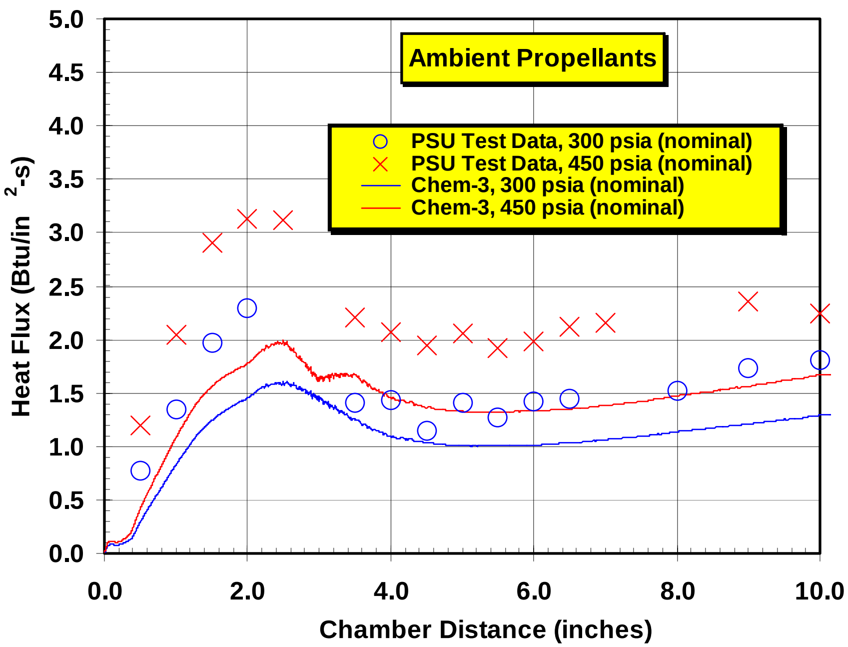


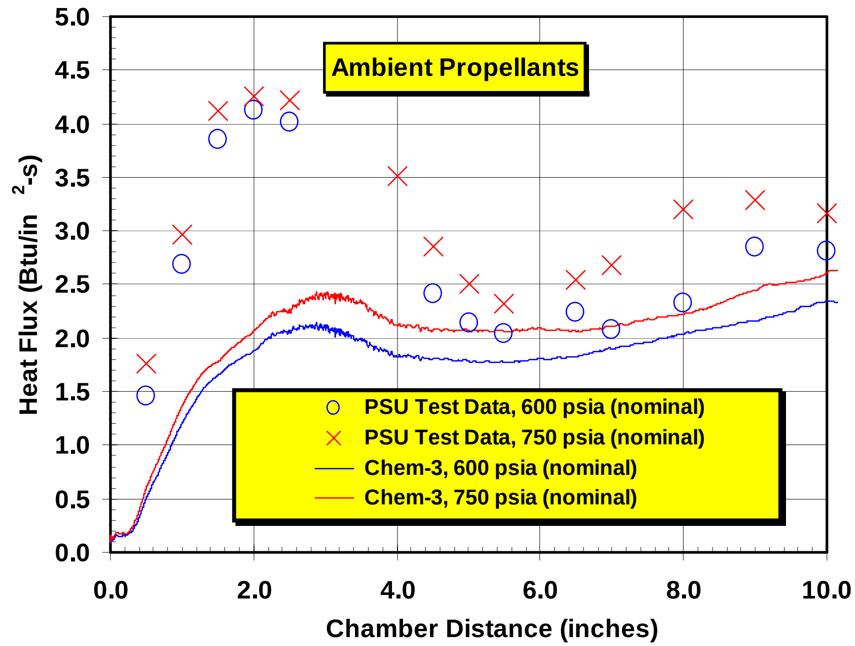
CFD Simulations – Typical Results

Sample Flow Field Results



Results - Ambient Propellants

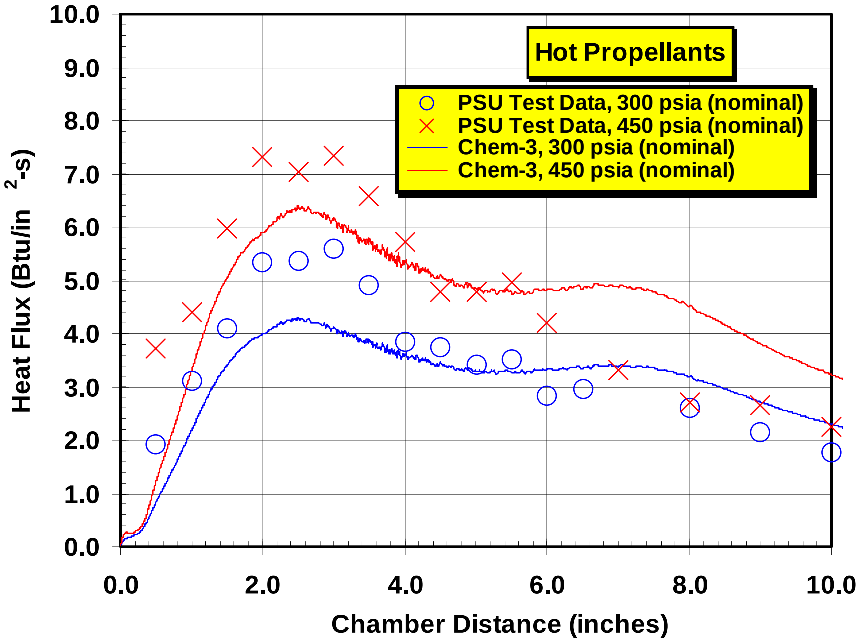


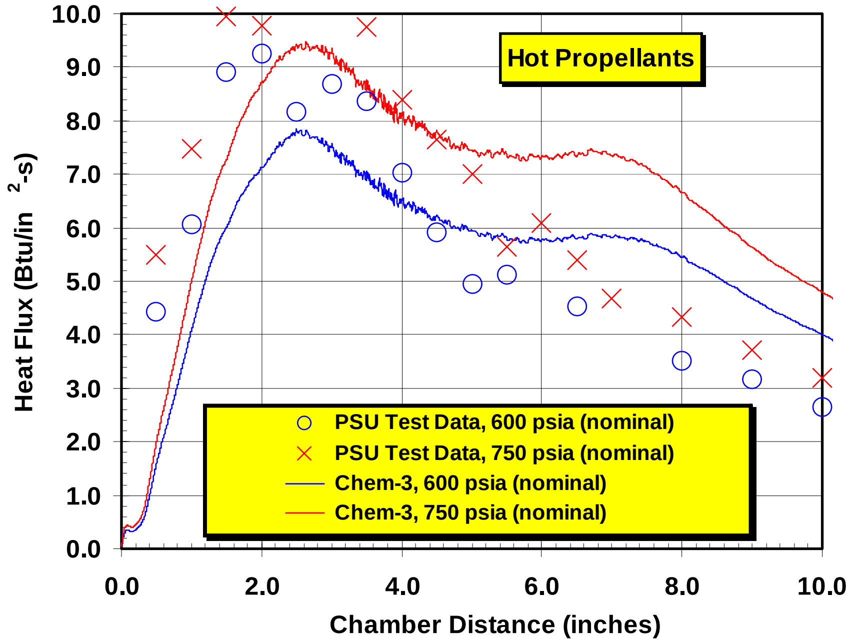


<u>Total Heat Transfer to Chamber Wall (Heat Flux Integrated over 10" Chamber Wall)</u>

- CHEM-3 prediction is 27% **lower** than test data for 300 psia case
- CHEM-3 prediction is 33 – 36% **lower** than test data for remaining cases

Results - Hot Propellants (Pre-Burner)





Total Heat Transfer to Chamber Wall (Heat Flux Integrated over 10" Chamber Wall)

- CHEM-3 prediction is 6% **lower** than test data for 300 psia case
- CHEM-3 prediction is 2% **higher** than test data for 450 and 600 psia cases
- CHEM-3 prediction is 6% **higher** than test data for 750 psia case

Conclusions

- All solutions with Loci-CHEM achieved demonstrated steady state and mesh convergence
- Overall, Loci-CHEM….
  - For the hot propellant (Pre-Burner) Cases
    - Satisfactorily predicts heat flux rise rate and peak heat flux
      - <u>This is important for design</u>
    - Significantly over-predicts the downstream heat flux
    - Predicts total heat transfer to the chamber wall (heat flux integrated over chamber length) within about 6%
  - For the ambient propellant Cases
    - Significantly under-predicts peak heat flux and downstream heat flux for the ambient cases
    - Significantly under-predicts total heat transfer to the chamber wall for the ambient cases
    - <u>Does not predict consumption of all oxygen in the fuel-rich combustion chamber</u>
      - The chamber pressure is also significantly under-predicted compared to test data, mainly due to not combusting all oxygen

Recommendations for Future Work

- On-going Efforts
  - Further Investigation of Mixing Phenomena and Turbulence Models
    - Suspect Inadequate Mixing caused Ambient Cases to not fully consume O2
  - Determine the cause of the over-prediction of downstream heat flux
- Near-Term Efforts
  - Uncertainty and Sensitivity Analysis of test data (CUIP)
  - Continue mesh studies in the direction of coarser grids (for production)
  - Run the problem in the unsteady mode
- Long-Term Efforts
  - Further decomposition of the problem into unit physics problems (CUIP)
    - Series of simple, representative jet problems
    - Series of simple, representative heat transfer problems

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