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13. SUPPLEMENTARY NOTES Viewgraph for the NDIA Conference on Physics-Based Modeling in Design & Development for U.S. Defense, Denver, CO in 5-8 November 2012.					
14. ABSTRACT Combustion instabilities have been observed in nearly every major liquid rocket engine development effort, including the most recent development programs. They are caused by the coupling of the natural acoustic modes of the combustion chamber with the dynamics of the combustion heat release and can lead to catastrophic damage of the internal components of the rocket engine. Rayleigh's criterion states that combustion instabilities are driven when the pressure waves and the heat release are in phase and that the instabilities are damped when they are out of phase. Despite the simplicity of this relationship, the prediction of the occurrence of combustion instabilities has proven to be an enduring challenge because of the inherent complexities in the physics of multiphase turbulent flames. The present paper provides the Air Force Research Lab (AFRL)'s vision and strategy for combustor design tools that can predict combustion stability to help guide the development of the US's next generation liquid rocket engines.					
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AFRL's ALREST Physics-Based Combustion Stability Program

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Dr. Doug Talley

Aerospace Systems Directorate (RQ)
Air Force Research Laboratory



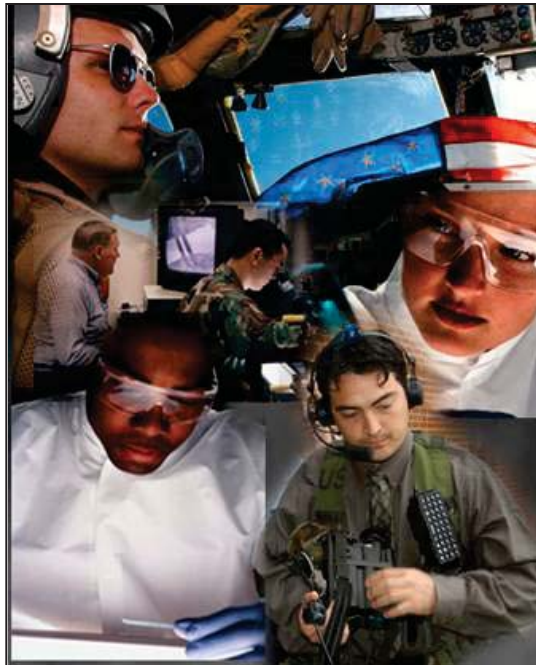
8 November 2012



Air Force Research Lab



Air Force Research Laboratory

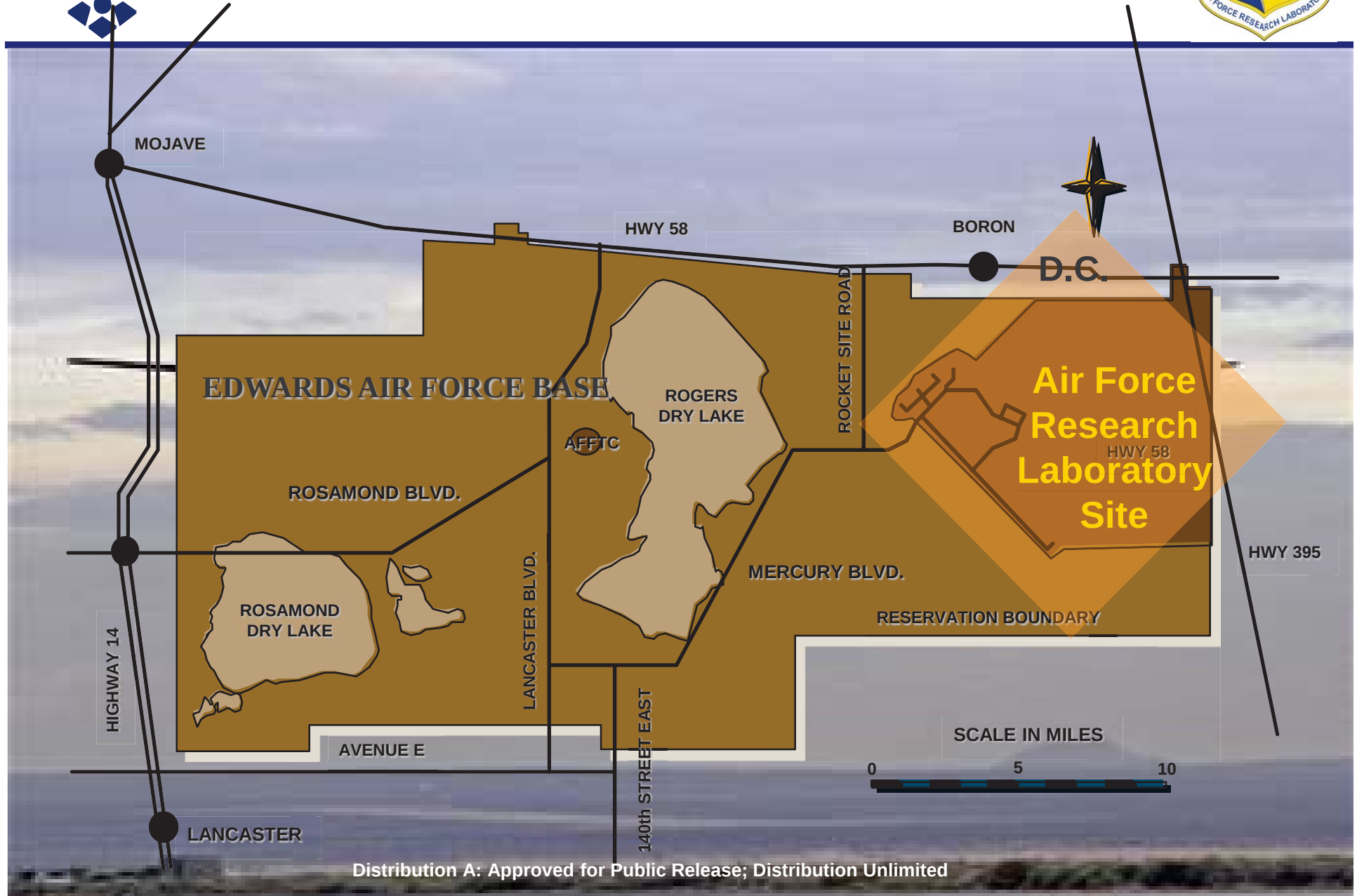


- 10 Major R&D sites across US
- 40 Locations around the World
- 10 Technical Directorates
 - Air Vehicles (RB)
 - Propulsion (RZ)
 - ↓
 - Aerospace Systems Directorate (RQ)

- 5,400 Gov't Employees
- 3,800 On-site Contractors



Edwards Research Site





Facilities



Bench-level Labs



Altitude Facilities

- From micro-newtons to 50,000 lbs thrust



High Thrust Facilities

- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust

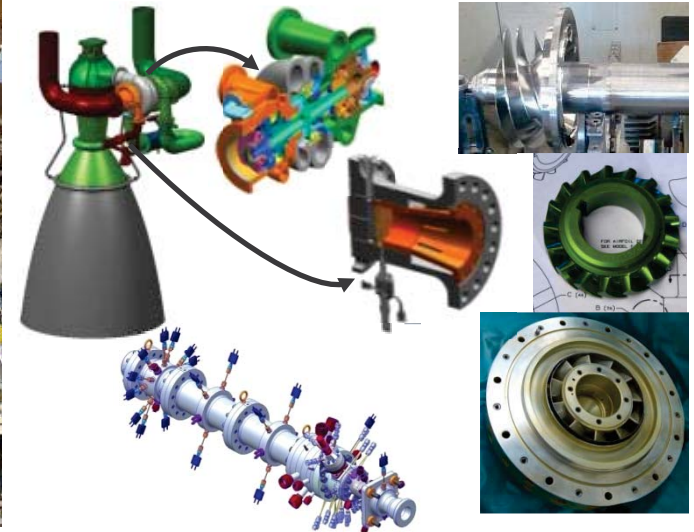




Hydrocarbon Boost

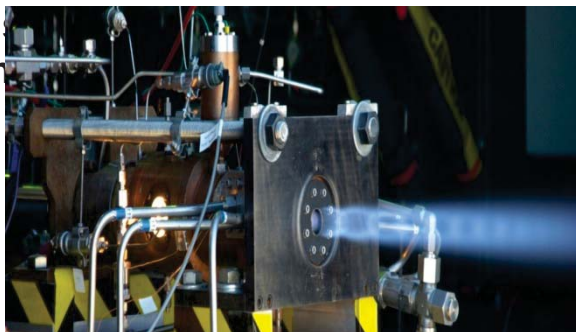


- HCB establishes advanced, modern, domestic LRE Tech Base
 - Required to replace Russian RD-180 on EELV
 - 1st reusable high performance U.S. HC engine
 - Establishes Ox-rich staged combustion (ORSC) tech base for U.S.
 - Help sustain ailing U.S. rocket engine industry tech development base
 - HCB strongly supports SMC/LR American Kerosene Engine project



In-House:

- Building subscale test facility to mitigate combustion devices risk
- Critical combustion research using 219 funds
- Fuel thermal injector design



The WOWs:

- Design, build, test ORSC LOx/Kerosene Liquid Rocket Engine Tech Demonstrator
 - 250K-lbf with high Throttle Capability (SOTA is 2:1) – Enables mission flexibility
 - 100 Life Cycle with 50 cycle overhaul (SOTA is 20) – Exceeds requirement, provides margin
- ORSC is a higher performing engine resulting in a smaller launch vehicle or an increase in delivered payload



What is a Combustion Instability (CI)?



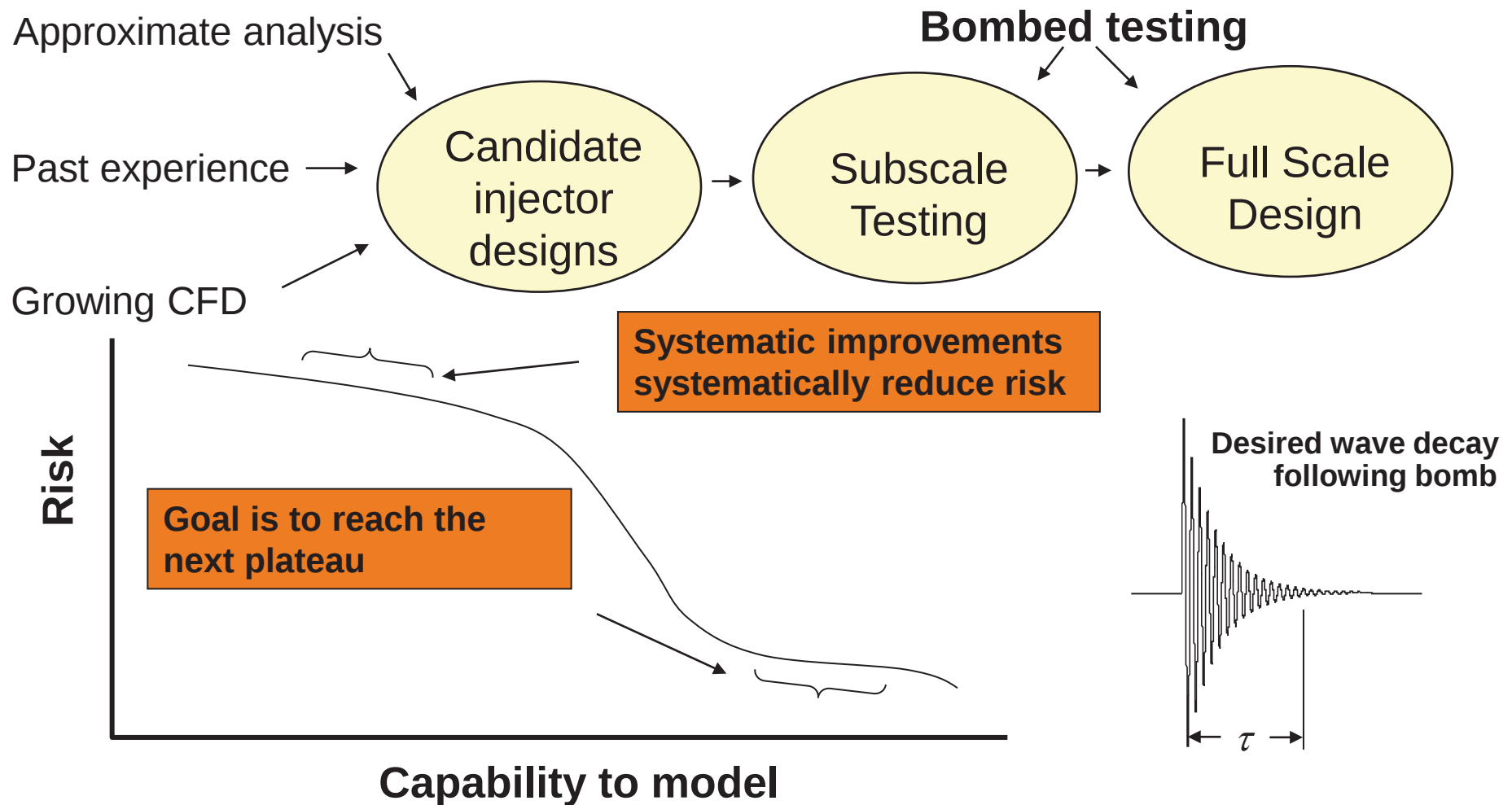
Damaged F-1 engine injector faceplate
caused by combustion instability

“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs”
– JANNAF Stability Panel Draft

- Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.
- Irreparable damage can occur in <1s.
- Combustion instability caused a four year delay in the development of the F-1 engine used in the Apollo program
 - > 2000 full scale tests
 - > \$400 million for propellants alone (at 2010 prices)
- CI has been identified as a major risk factor in the HCB demo and future engine development.



Risk Reduction





Challenges



- **High pressures**
 - Supercritical pressure with cryogenic propellants
 - Challenging to obtain detailed data
- **Turbulence and Combustion**
 - Unsteady dynamics requires LES or hybrid RANS-LES
 - Detailed mechanisms for chemical kinetics
 - Turbulent combustion closures
- **Boundary Conditions**
 - Simulations must include fuel-ox manifolds
- **Data Processing**



Overview of ALREST

(Advanced Liquid Rocket Engine Stability Technology)



OBJECTIVE

- **Develop advanced physics-based combustion stability design tools to reduce the risk of developing combustion instabilities in future Air Force liquid rocket engine development programs.**

APPROACH

- **Fully coordinate with other national efforts to conduct data-centric, multi-fidelity model development.**



Data-Centric Model Development



Anderson (Purdue)

- AFOSR
- NASA CUIP

• **ALREST**

• AFRL

Frederick (UAH)

- NASA CUIP

• AFRL

• **ALREST**

Karagozian (UCLA)

- AFOSR

Leyva, Talley (AFRL)

- AFOSR

• **ALREST**

Cavitt (Orbitec)

- AFRL

• **ALREST**

Santoro (PA State)

- AFOSR (core)

- NASA CUIP

• **ALREST**

Yu (Maryland)

- NASA CUIP

Zinn (GA Tech)

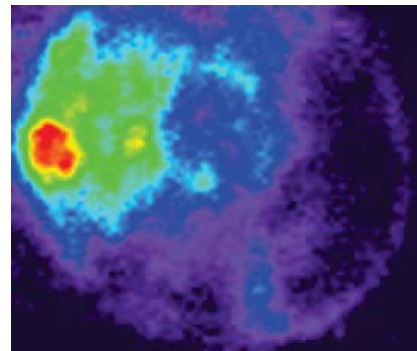
- AFOSR

Nestleroad Engin'ng

- MDA

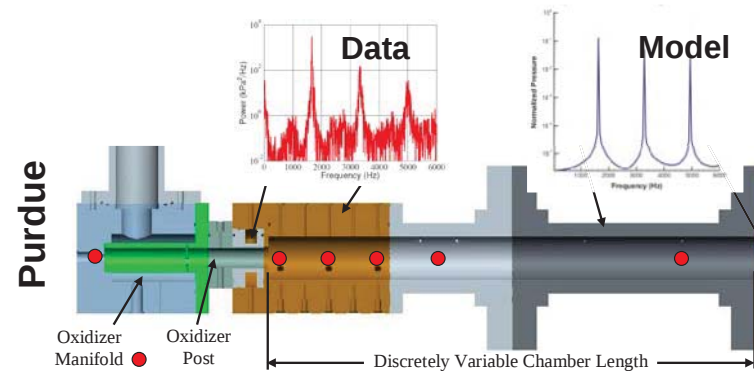
Experiments

Spinning CI

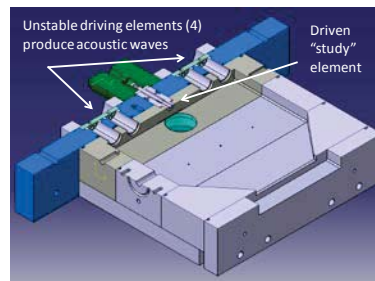


GA Tech

Longitudinal CI

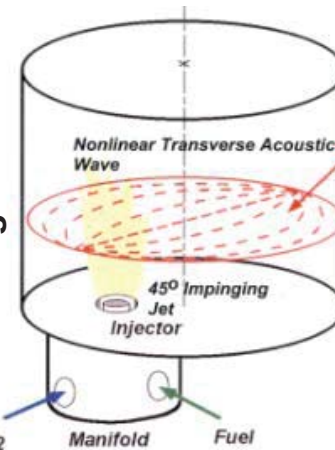


Standing CI



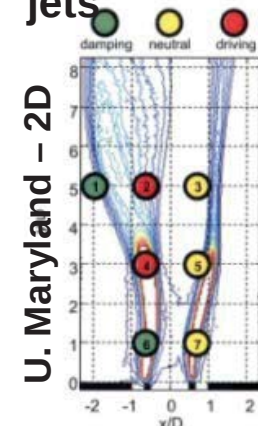
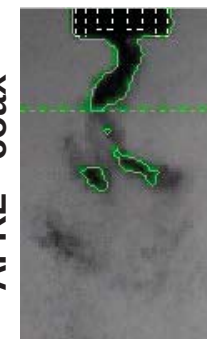
Purdue - multi elem

UAH - single elem



AFRL - coax

Driven jets



Acoustics

HCB will be heavily instrumented to provide CI data

Full Scale (existing and HCB)

Distribution A: Approved for Public Release; Distribution Unlimited





Multi-Fidelity Model Development



Flandro (GTL)

- OSD, AFRL

Heister (Purdue)

- AFOSR, NASA

Merkle (Purdue)

- NASA, AFRL, AFOSR,
ALREST

Muss (Sierra)

- AFRL

Palaniswamy (Metacomp)

- AFOSR, AFRL, MDA
ALREST

Yang (PA State)

- AFOSR, AFRL, MDA
Bellan (JPL)

- AFOSR

- ALREST

Kassoy (U. Colo.)

- AFOSR

Priem consultants

- ALREST

Menon (GA Tech)

- ALREST, AFOSR

Munipalli (HyPerComp)

- ALREST

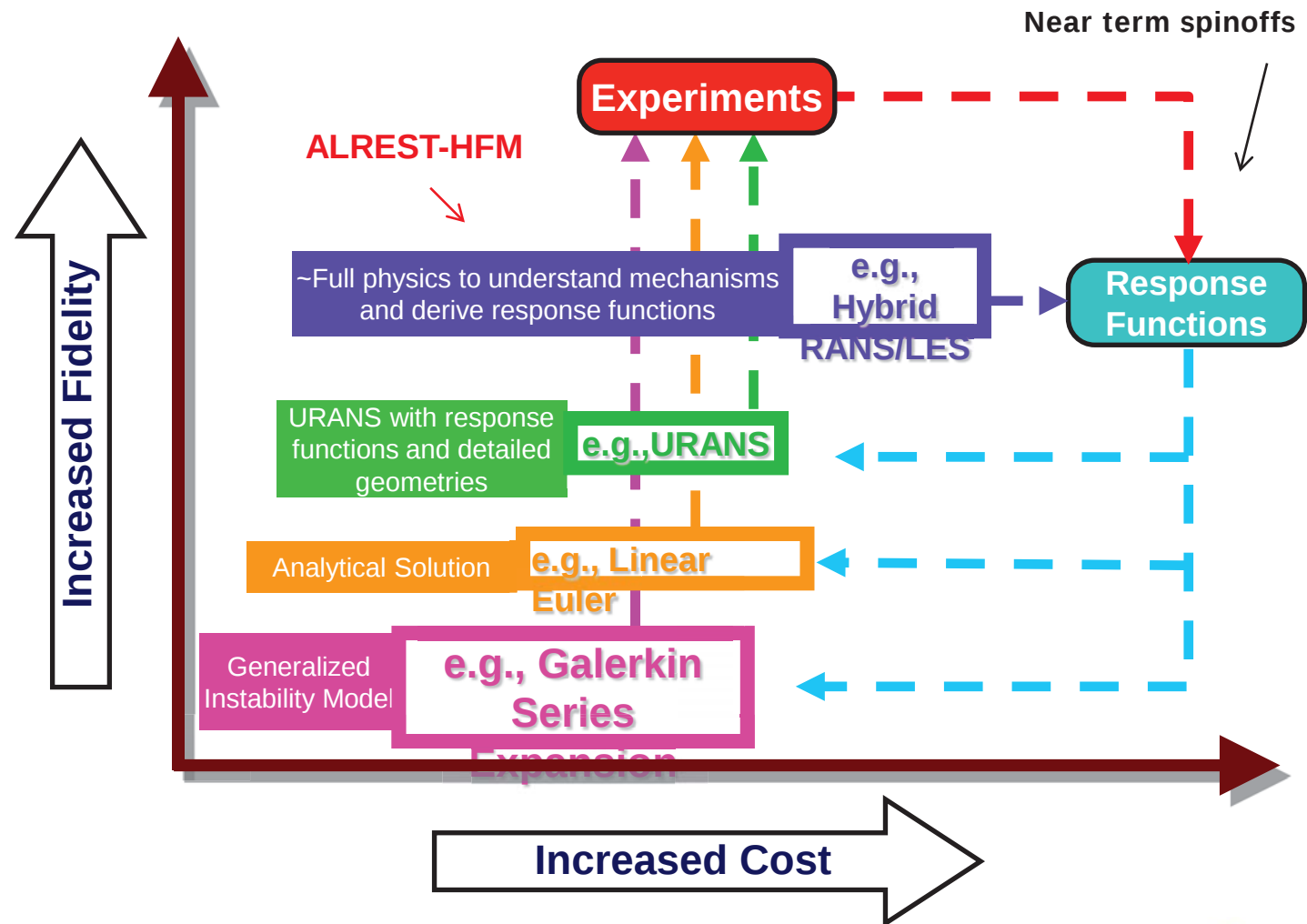
Sirignano, Sideris (UC Irvine)

- AFOSR

Lynch (PWR)

- ALREST

Models





ALREST-HFM (AHFM)



- **ALREST – High Fidelity Modeling** is a six year program to develop high fidelity design tools for combustion stability
 - Central strategy is to take advantage of exponentially growing computational capability as our fastest growing enabling tool.
 - Two independent 3-year phases
 - Selection for phase I does not guarantee selection for phase II
- **Tools will be validated against HCB data and applied to follow-on engine programs.**

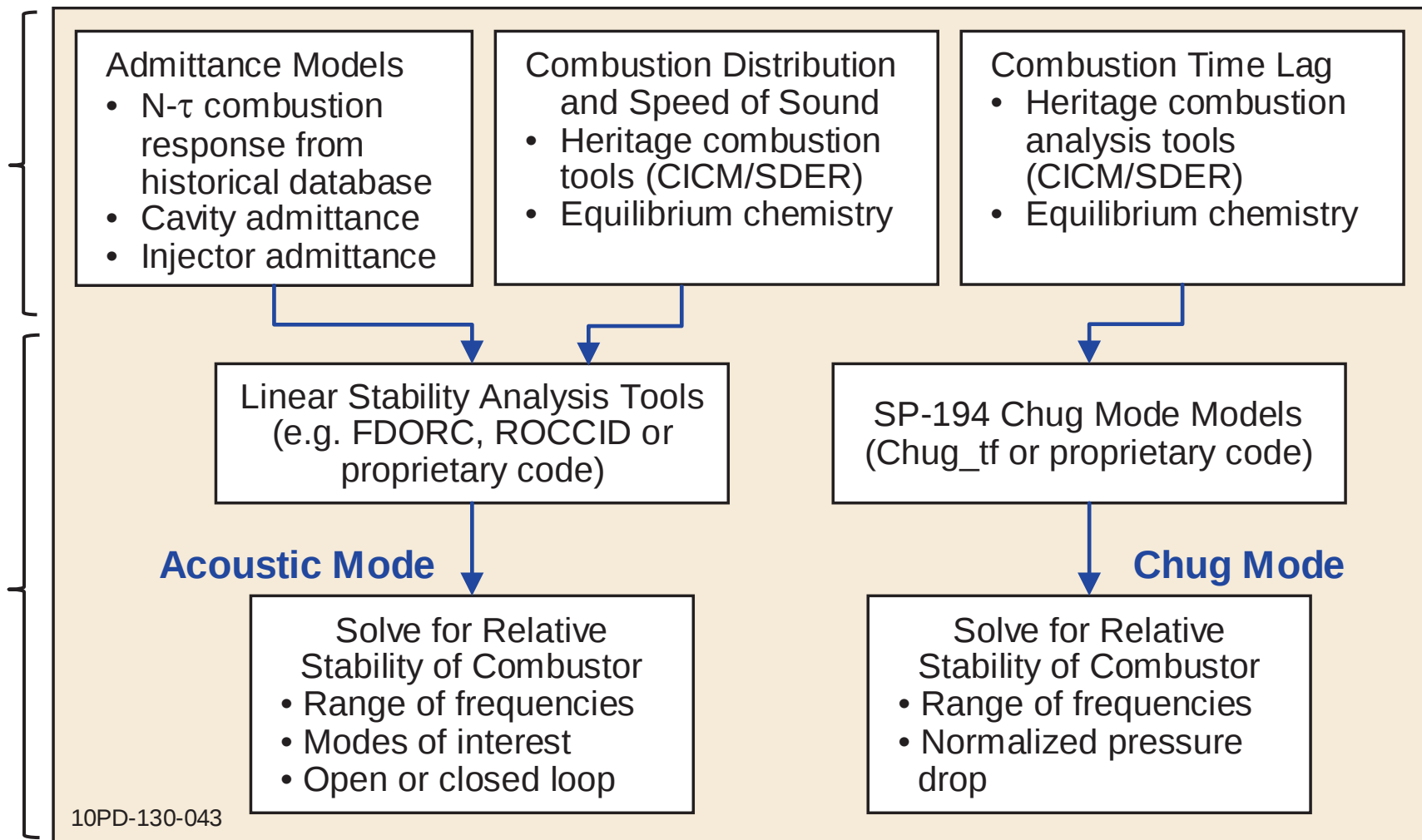


Combustion Stability Design Tools



Current

Industry standard CI tools

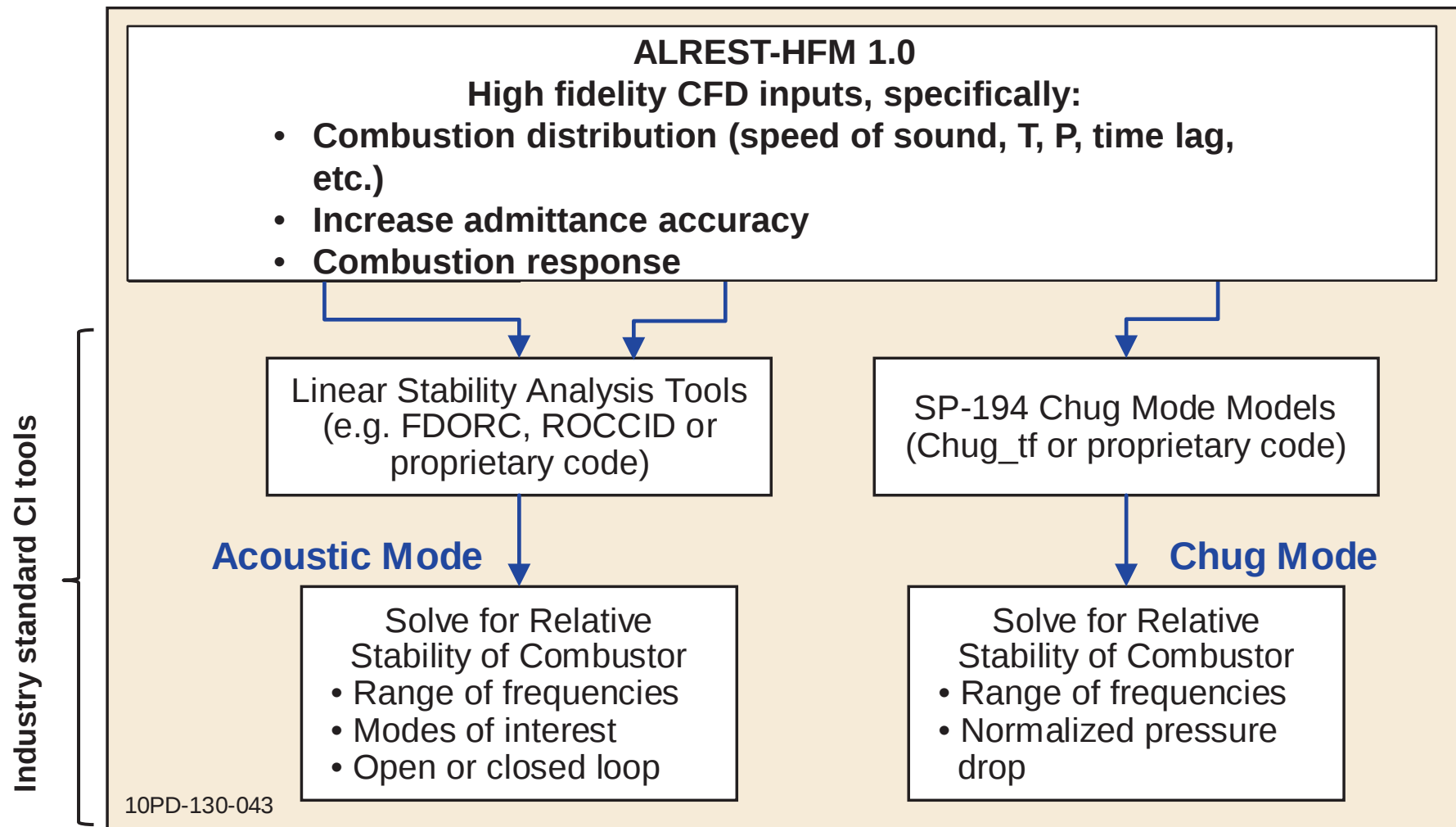




Combustion Stability Design Tools



End of phase I

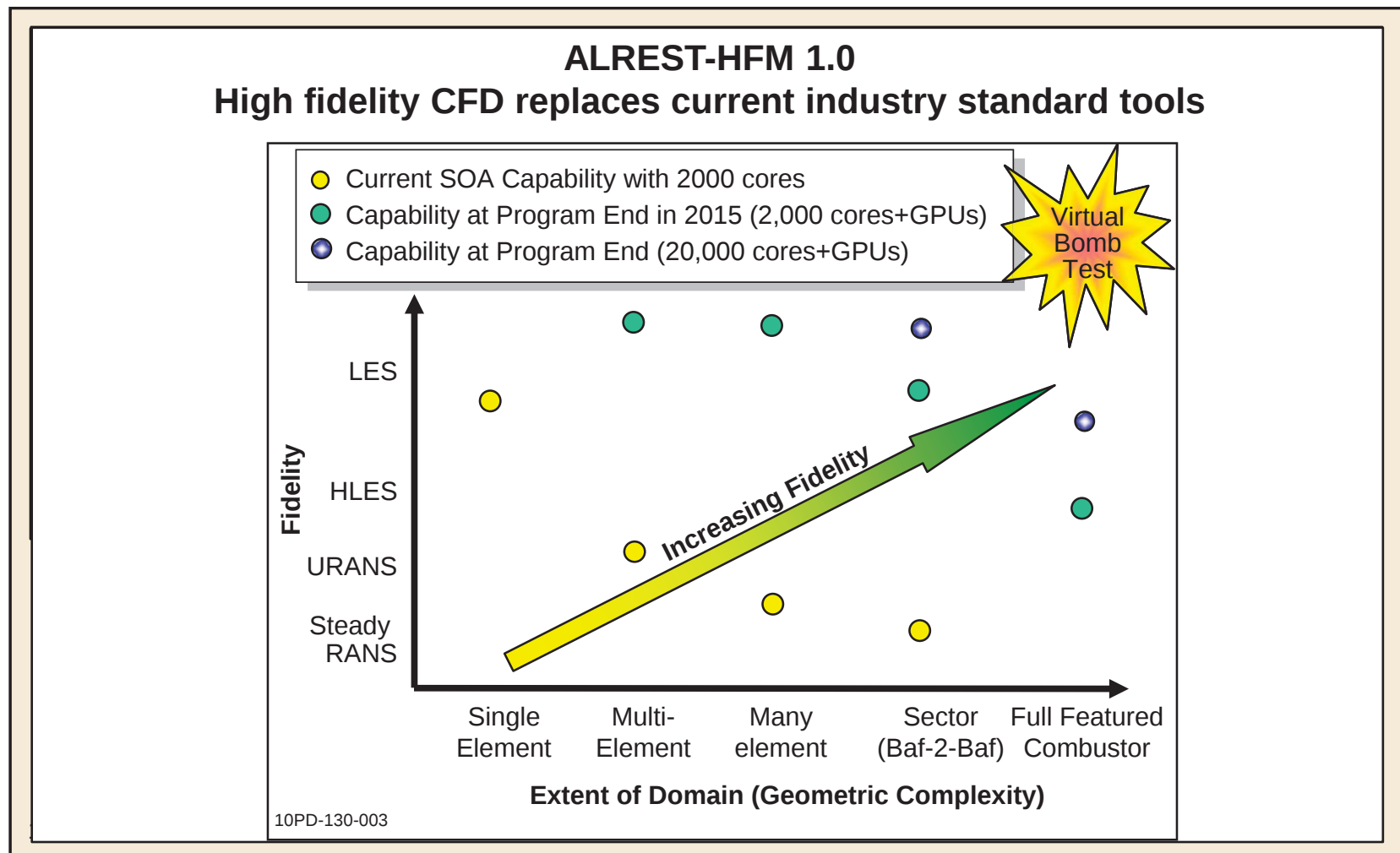




Combustion Stability Design Tools

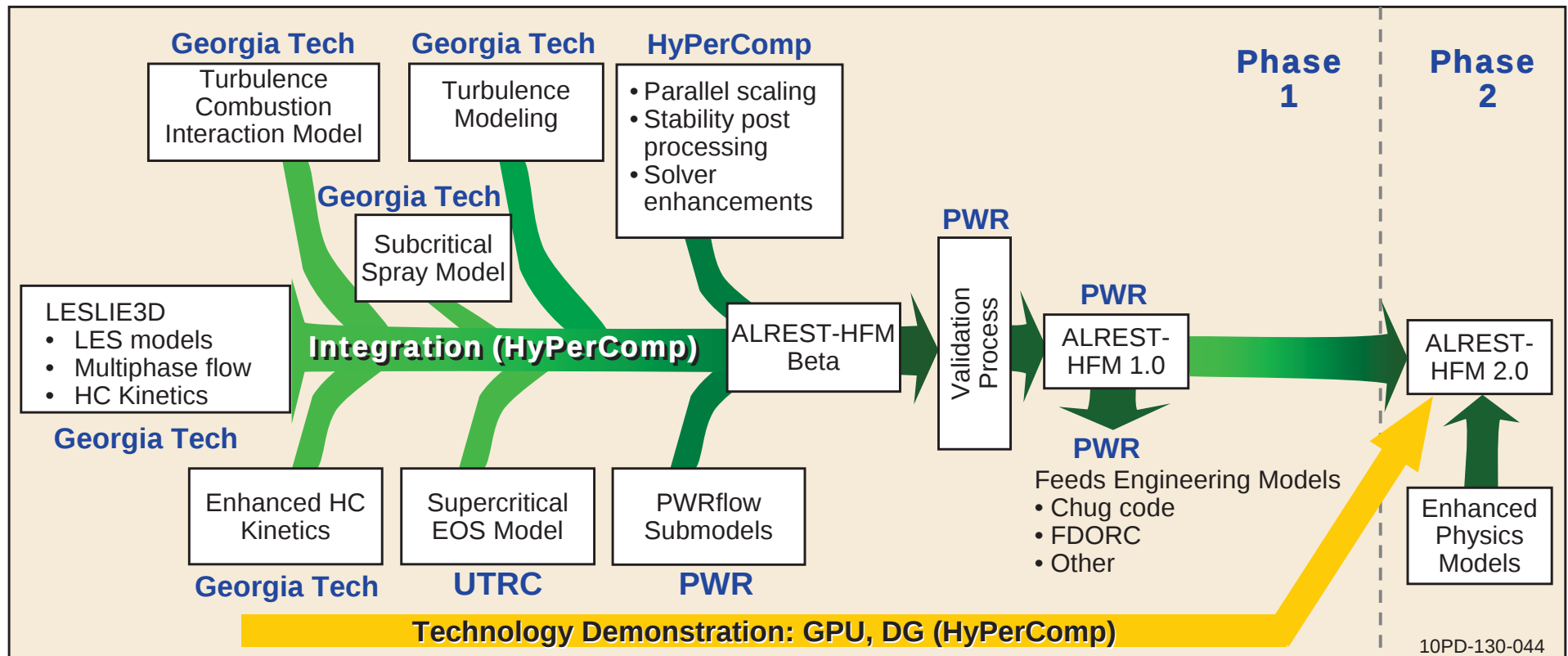


Future vision





Approach



Source code will be delivered and maintained by Hypercomp after the contract ends



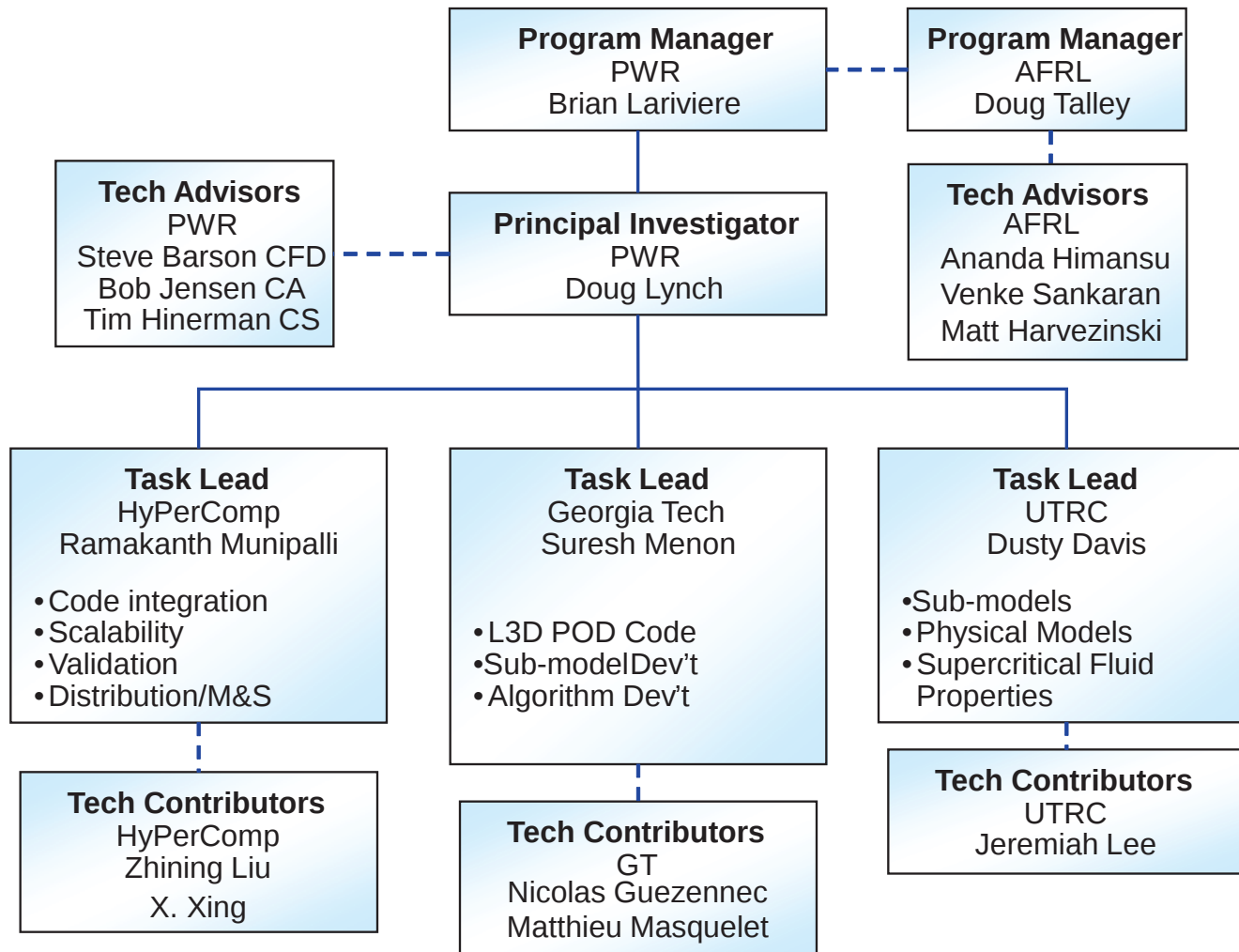
Marriage of PWR PWRflow RANS and Georgia Tech LESLIE3D Codes



	Discretization	Solution Advancement Schemes	Types of Grid	Turbulence Modeling	Kinetics Models	Fluid Properties	Turbulence-Chemistry Interaction Modeling	Discrete Multiphase Modeling	Dispersed Multiphase Modeling
L E S L I E 3 D	Hybrid HLC/E	Currently Explicit Predictor-Corrector Temporal 2nd-Order	Structured; Structured-Unstructured Cartesian	Subgrid Scale K-KL and K- Δ	Variety of Hydrogen and Hydrocarbon Models for Gas Turbines, Ramjets, and LRE's	Mixtures of Calorically Perfect Gases and Mixtures of Peng-Robinson Fluids with Detailed Species Properties	Variety of RANS and LES modeling ranging from flamelets, eddy breakup modeling to LEM (Linear Eddy Modeling)	Detailed Level Set model for drop breakup with interface refinement	Lagrangian Droplet Model with drop breakup and evaporation exercised on gas turbine analyses
P W R f l o w	Cell-Based Limiting with Rusanov, Roe, and FORCE (large density differences) Riemann solvers	Diagonalized and Preconditioned/Nonprec conditioned Point Implicit, Multigrid and Chunk G-S Global Implicit	Unstructured	Goldberg, Menter, and Spalart-Allmaras 1-Equation RANS Models; Anisotropic k- ϵ Model	1- and 2-step global, quasiglobal, and mechanistic models for a variety of hydrocarbons fuels and hydrogen including RP	Perfect Gas, Equilibrium Air, Mixtures of Calorically Perfect Gases and Mixtures of Redlich-Kwong and Peng-Robinson Fluids	Assumed pdf Model based on k- ϵ -g Model in NASA/LaRc Vulcan code	Level Set model for drop breakup employed on some selected problems	Lagrangian Droplet Model with breakup now being tested on gas turbine problems

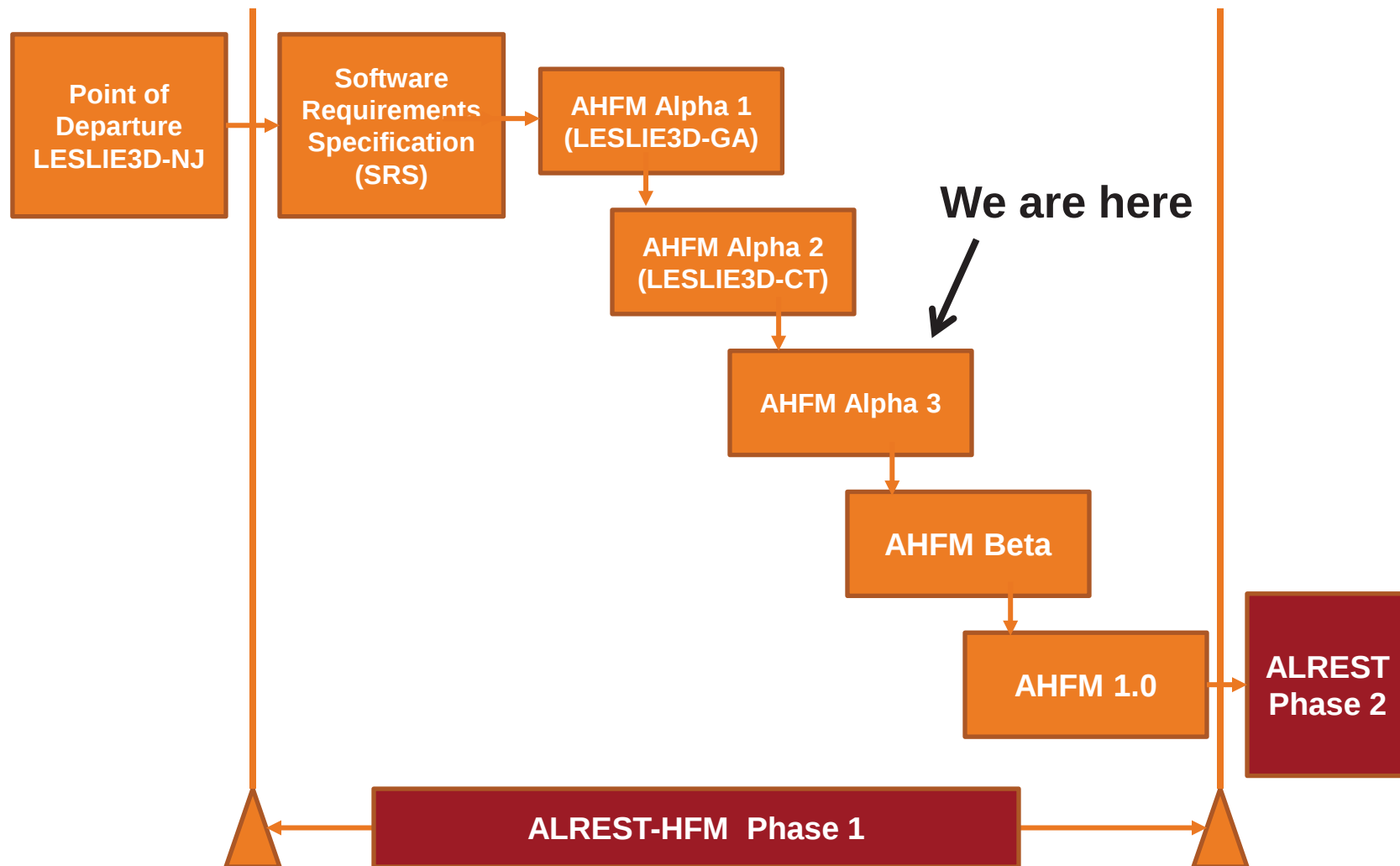


AHFM Dev't Team





Four stages of development





ALREST verification suite



Case No.	Description of Test Case used for Verification
VR-1	Uniform Flows (Run with all available schemes)
VR-1.1	3D Uniform Flow in rotated uniform grid
VR-1.2	3D Uniform Flow in rotated non-uniform grid
VR-1.3	Uniform Flow in a 2-domain uniform grid
VR-2	Simple Scaling Study
VR-2.1	3D Temporal Mixing Layer (TML) with light load
VR-2.2	3D TML with normal load
VR-3	Wave Propagation Accuracy
VR-3.1	Quasi 1D Gaussian pressure pulse traveling in a duct of variable area
VR-3.2	Above with temperature variation
VR-4	Flame Test Cases
VR-4.1	Laminar premixed methane/air flame ($\phi=1$, $p=1$ to 60 atm, 4-step, 8-species, initial solution from GRI)
VR-4.2	Laminar premixed H ₂ /Air flame ($\phi=0.7$)
VR-5	Boundary Condition Test Cases
VR-5.1	Pressure reflection from inflow, non-reflecting exit at outflow
VR-5.2	Above with turbulent inflow
VR-5.3	Above with Calorically (CPG) vs Thermally (TPG) perfect gas models
VR-6	Convection Test Cases
VR-6.1	1D Tests of wave speed with jump in species concentration
VR-6.2	1D Shock tube problem with limiters and artificial dissipation
VR-6.3	1D Gaussian pulse with different flux formulae
VR-6.4	2D convected vortex
VR-6.5	1D Gaussian entropy wave
VR-7	Temporal Mixing Layer
VR-7.1	3D, 1 species Euler CPG mixing layer model
VR-7.2	2D, 2 species CPG model
VR-7.3	Shock Wave Test Cases
VR-7.4	1D Sod shock tube test case
VR-7.5	2D Oblique shock Mach 5, 25 deg wedge
VR-7.6	2D Richtmyer-Meshkov Instability

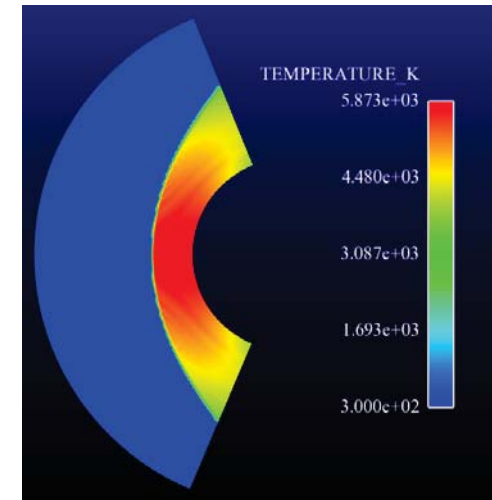
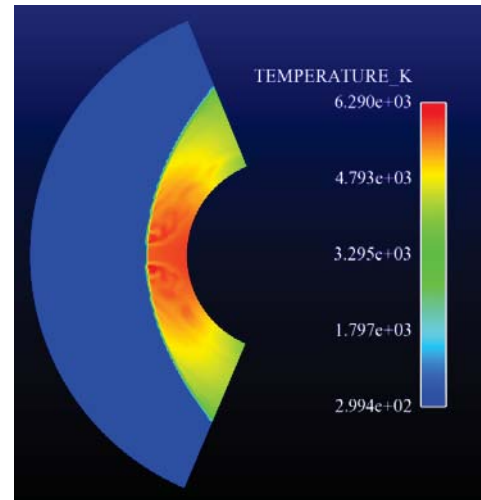
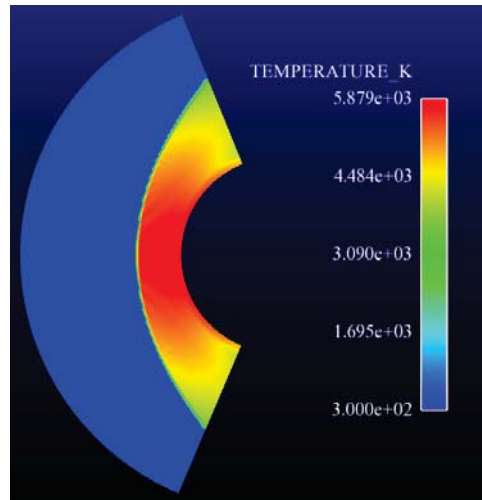
These are the set of “automated test cases” used to verify code integrity was maintained during code dev’t



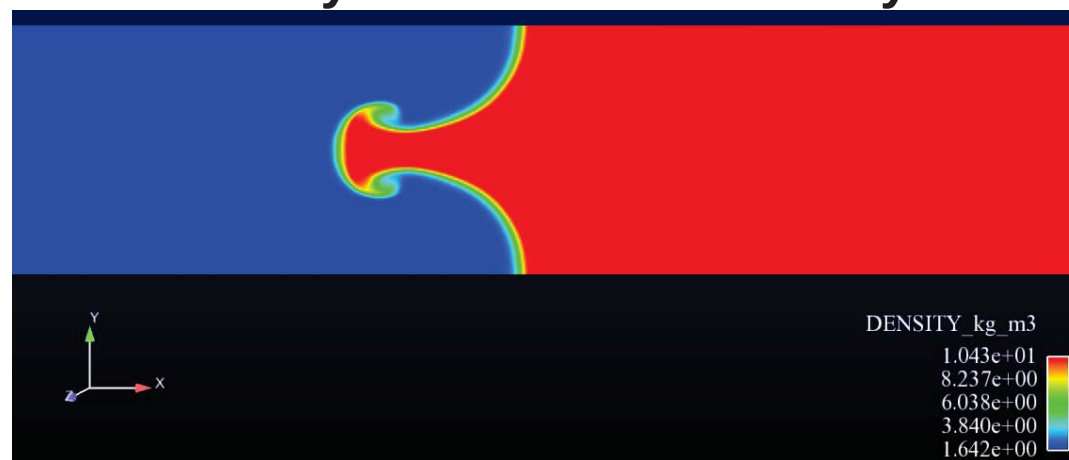
Two of the many verification cases



2D blunt body

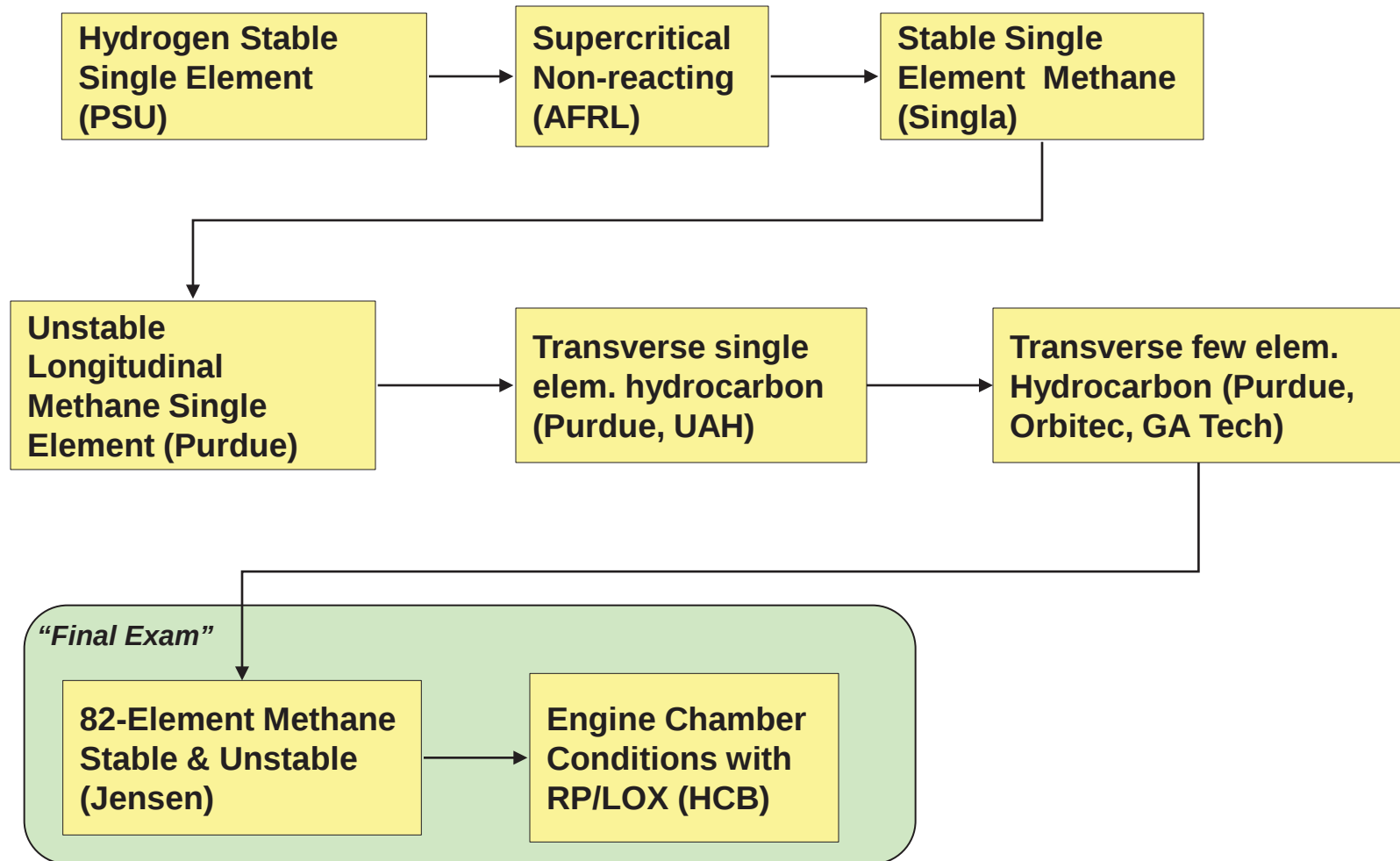


Richtmyer-Meshkov Instability



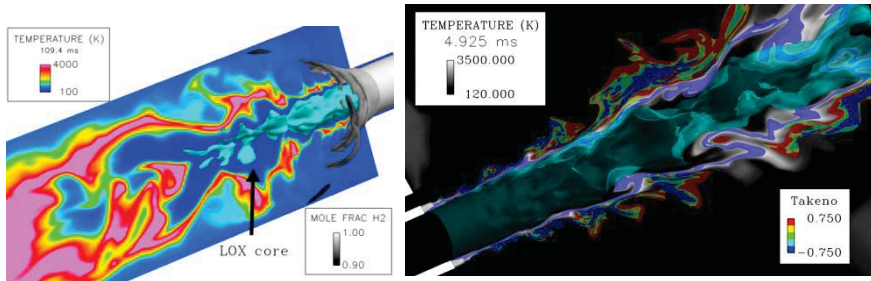


ALREST Validation Cases

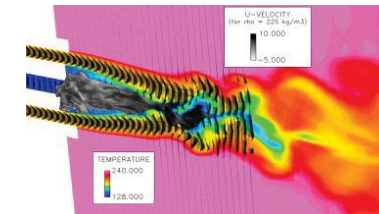




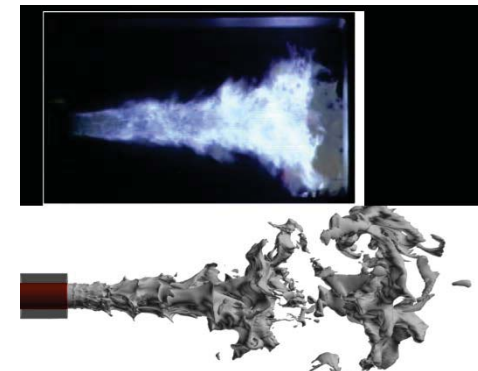
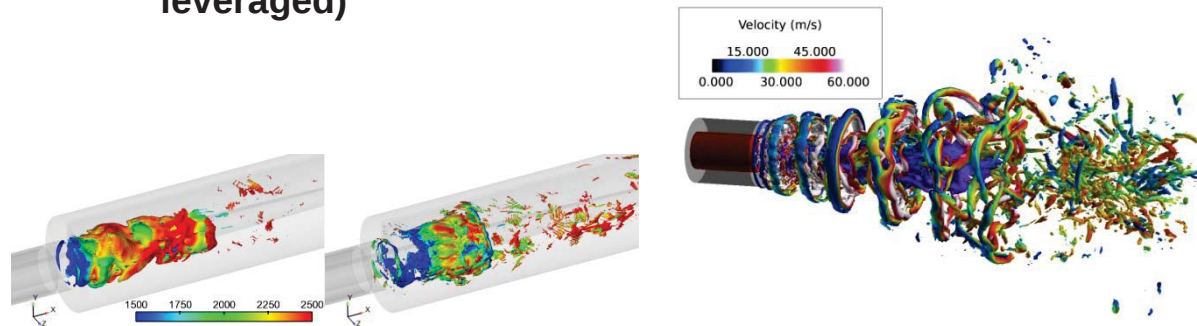
Validation Simulations



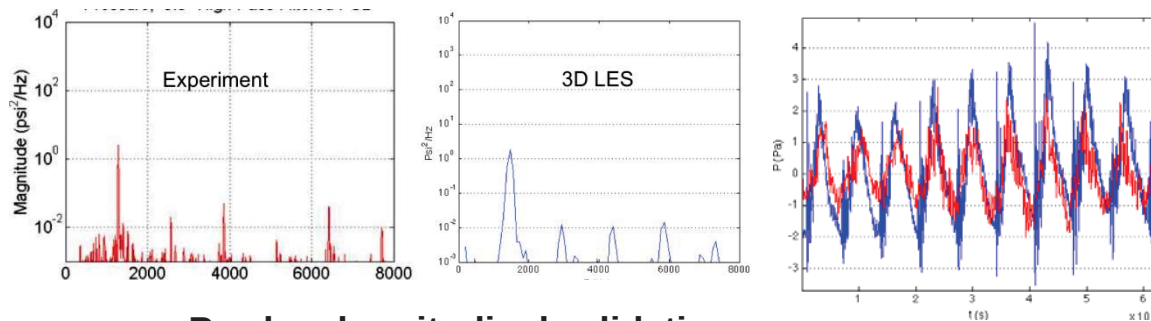
PSU LOX/H2 validation (NASA – leveraged)



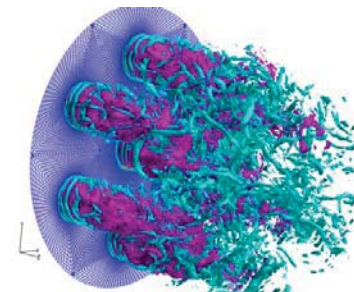
AFRL supercritical data (validation case)



Single element combustion case



Purdue longitudinal validation case



7 element scalability study



AHFM Validation Case: Case 3: CVRC Longitudinal Instability (Yu, et al)



Case Description:

- Case 3: Longitudinal Instability for Single Injector
- Yu et al Completed for Anderson CUIP Task
- Continuous Variable Resonance Combustor
- Oxidizer Post length=

Relevance to AHFM:

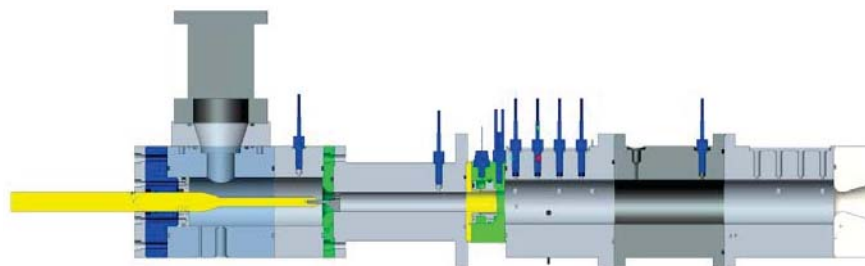
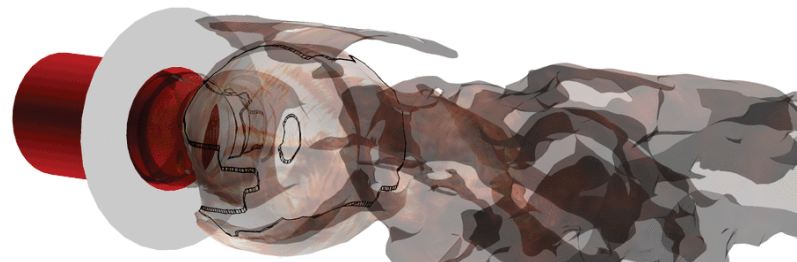
- Longitudinal Instability for Hydrocarbon Combustion under Supercritical Conditions

Key Metric or Success Criteria:

- Frequency and Amplitude Growth of Fundamental Instability and Higher Harmonic/Secondary Modes
- Mode Shapes and Phase

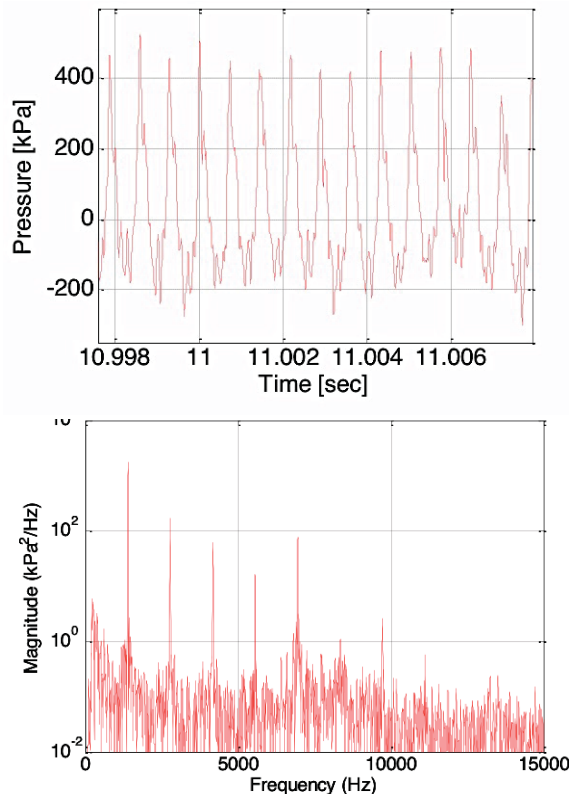
Status:

- Complete; Analyzing Results
Code Version: AHFM- α 1 (LESLIE3D-GA)
Computer System & No. of Cores
Grid Size:
Other Special Characteristics:
- Mixture of Calorically Perfect Gases
 - xx Methane – Oxygen Kinetics



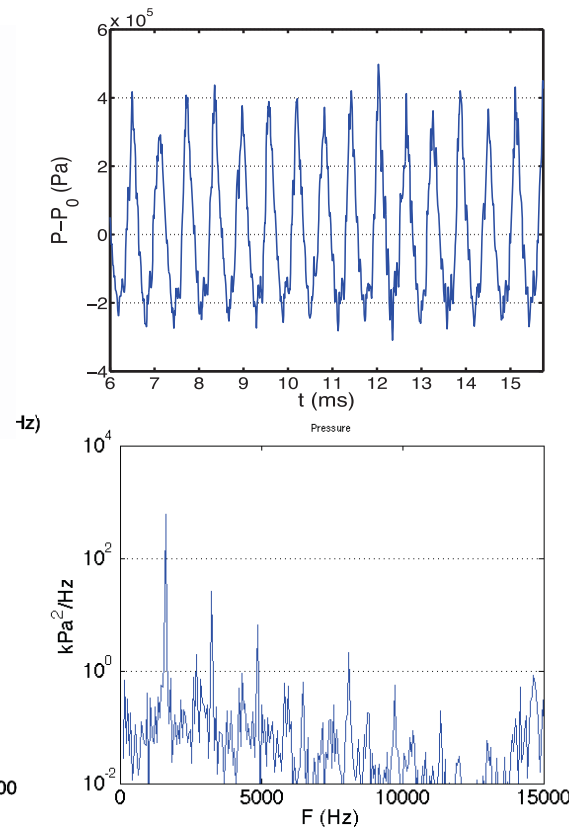


Pressure signal



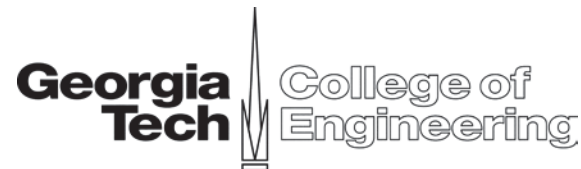
Experiment

36.85 cm



LES

- Good prediction of the peak to peak fluctuations
- Good prediction of trends
- Frequency and amplitude slightly off
 - 200 Hz and x2 respectively
 - Reason still under investigation
- $P_0 = 1.55$ Mpa > $P_{exp} = 1.4$ MPa



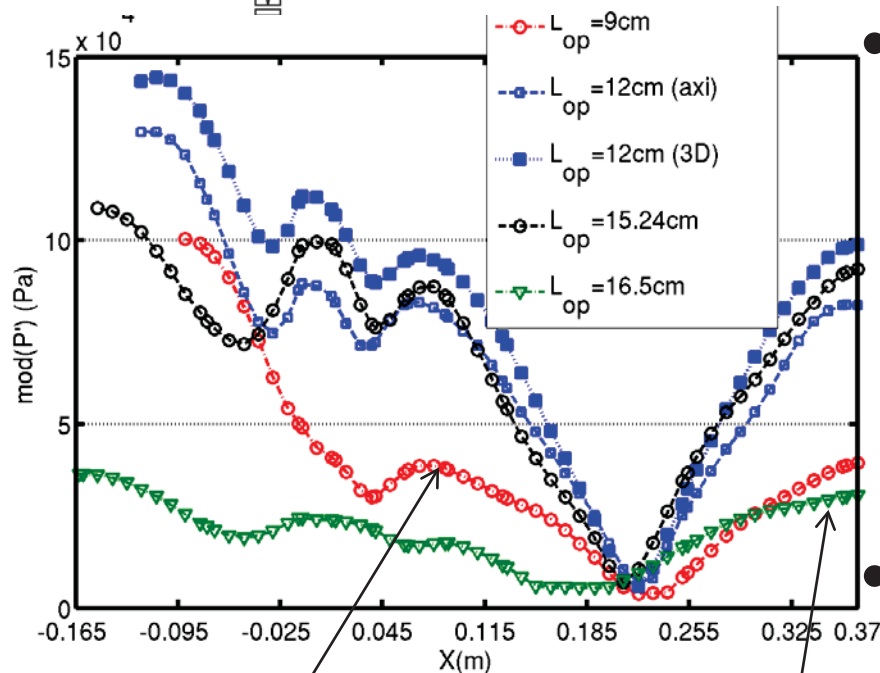


Parametric study with Axi-LES



Georgia
Tech

College of
Engineering



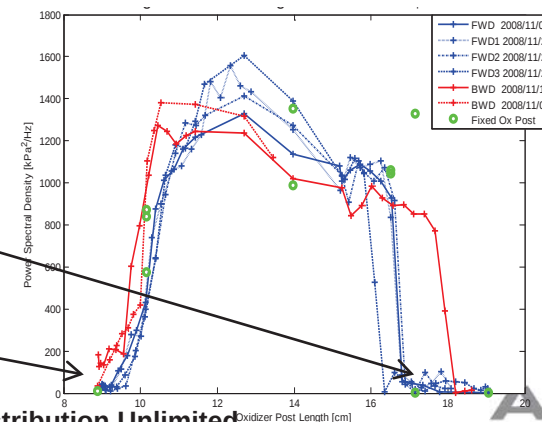
9 cm

16 cm

• Good prediction of the stability domain:

- $L < 9\text{cm}$ and $L > 16\text{cm}$: **strong reduction of acoustics**
- $L > 9\text{cm}$ and $L < 16\text{cm}$: **unstable combustor**

• Underestimation of the amplitude



- Effect of the injector length on the combustor stability



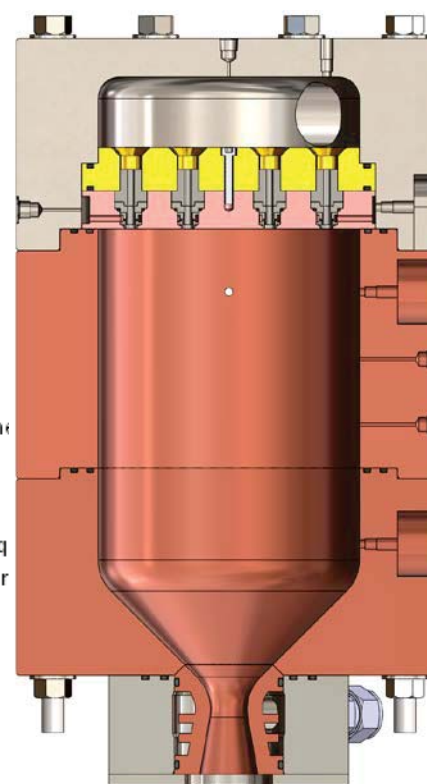
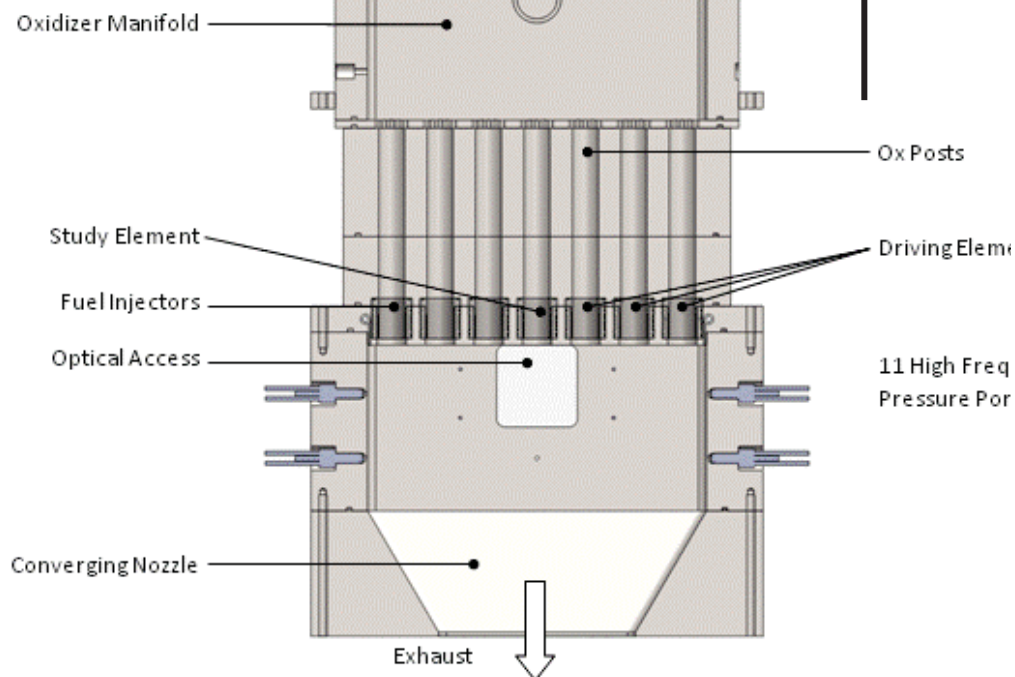
Several-element transverse validation data will come from two phase II SBIRs



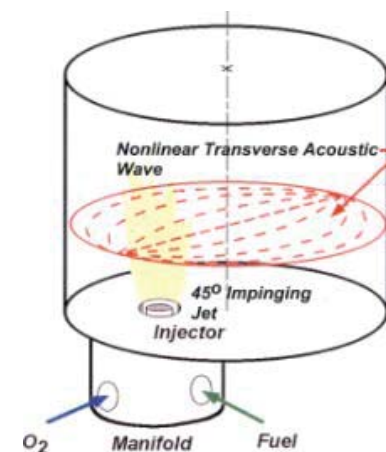
PURDUE
UNIVERSITY

INS
SPACE
LLC

ORBITEC



Scaling

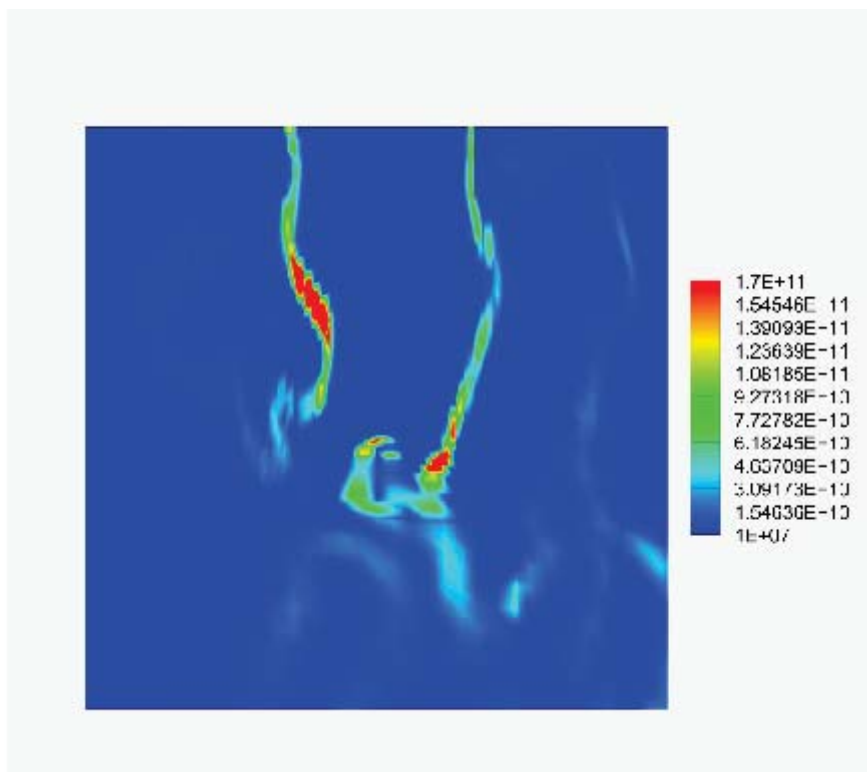




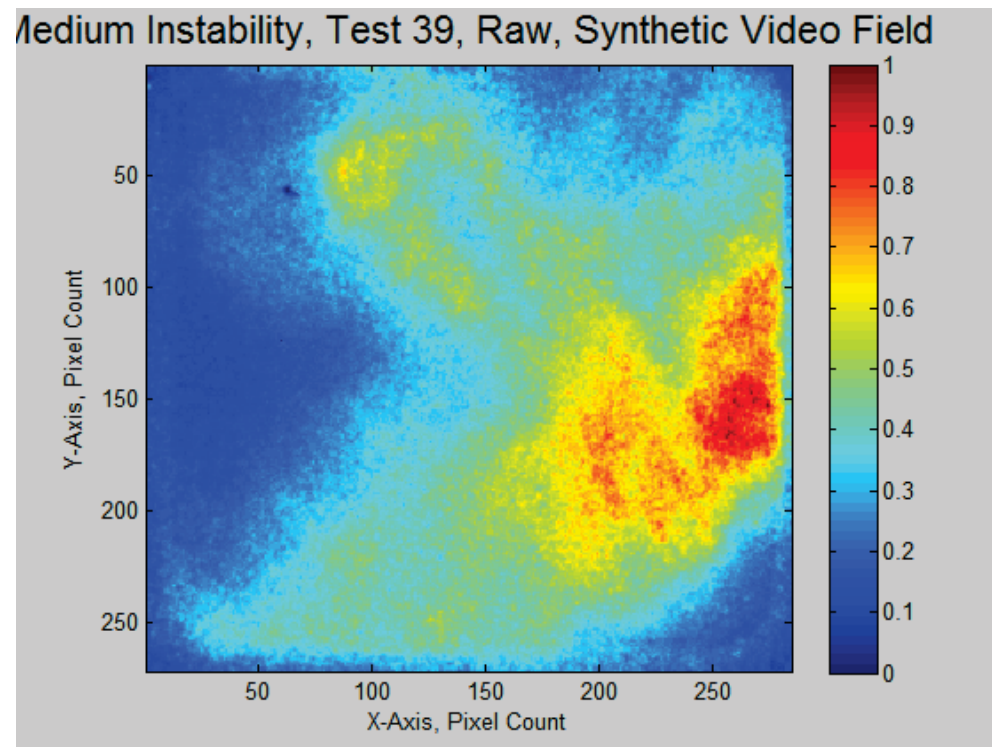
Heat Release



CFD Heat Rate (Watts)

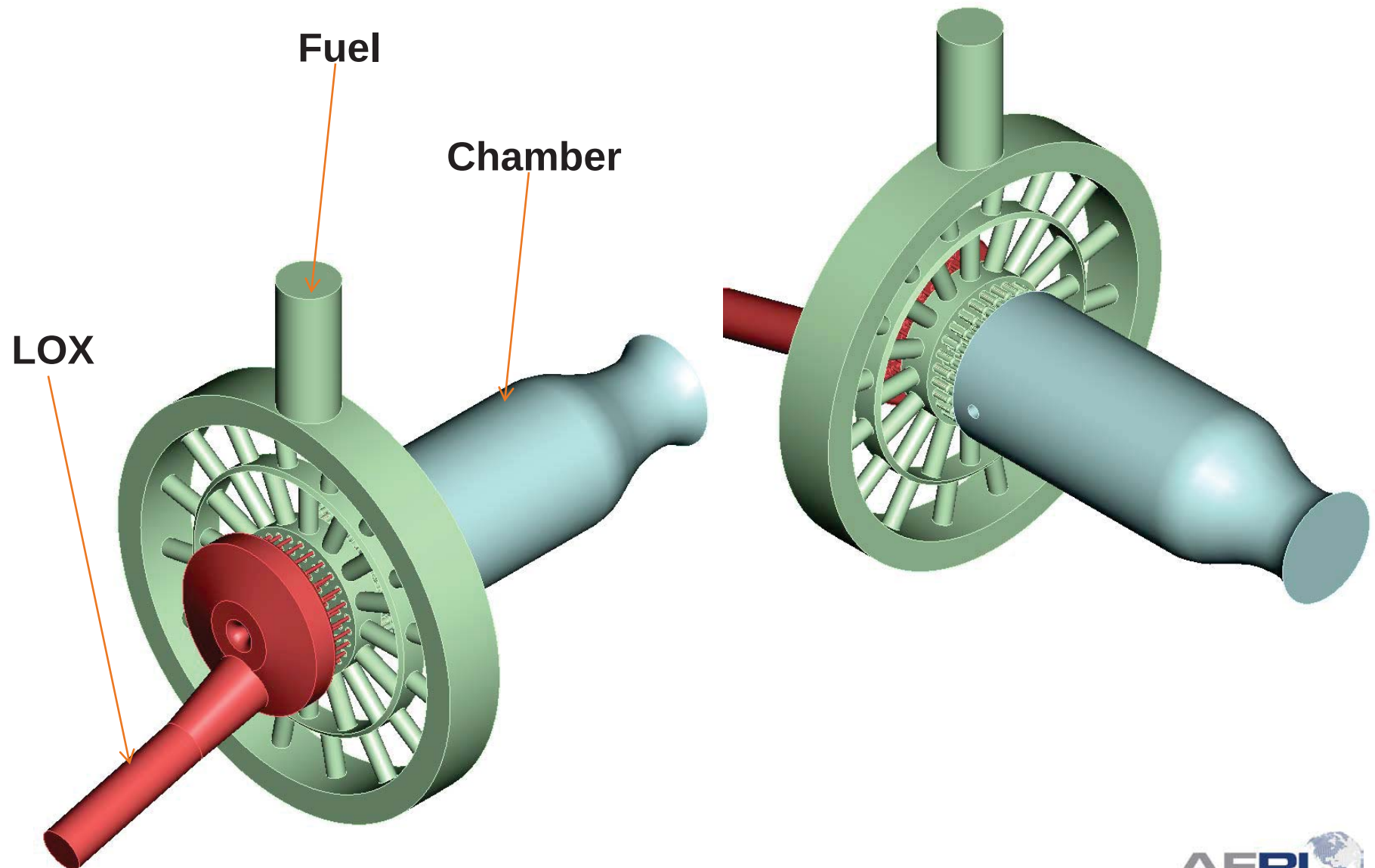


Experiment Video - CH*



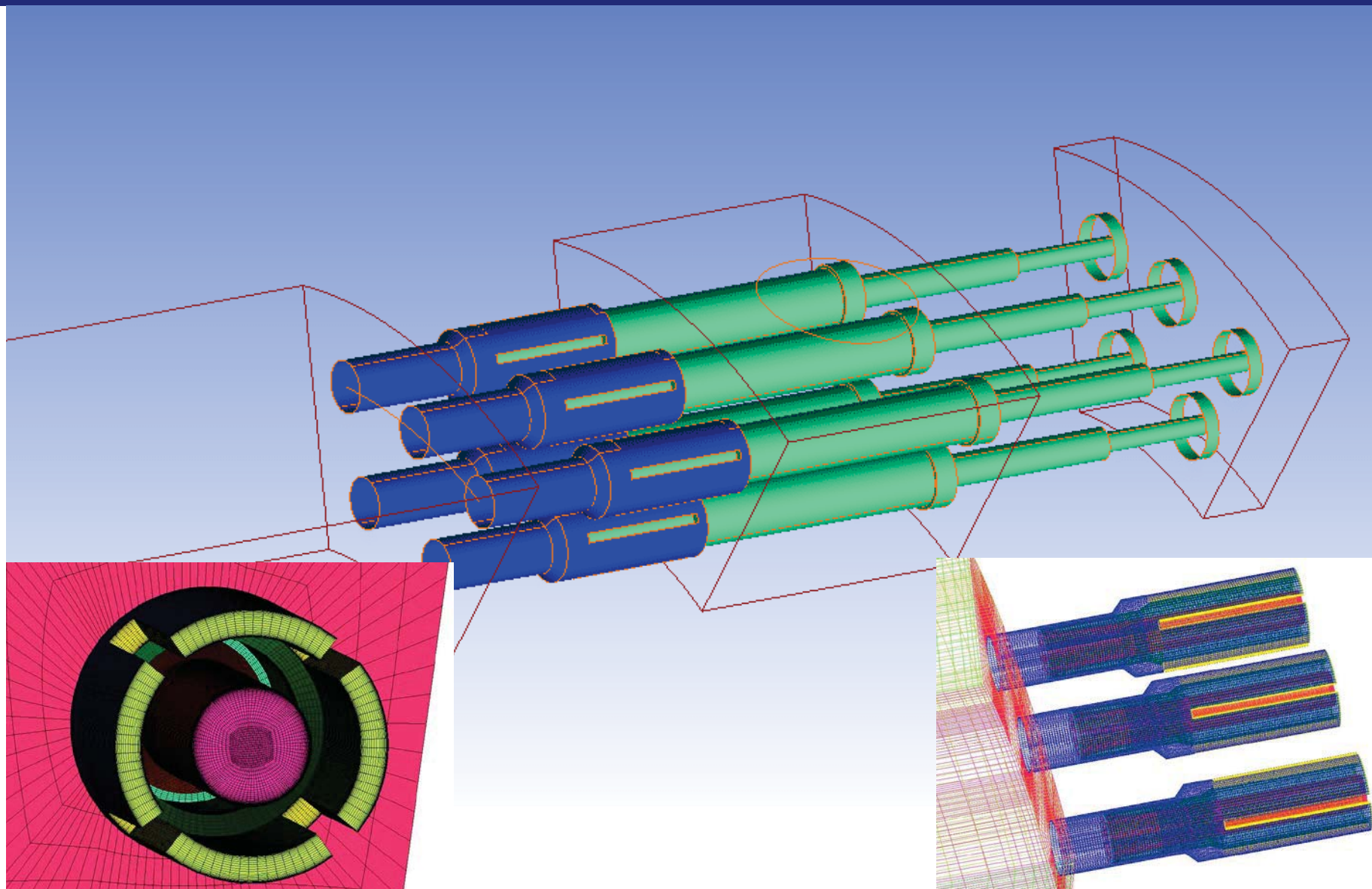


CAD drawing of engine and manifolds





Five Element Sector Mesh





Analytical Methods



Gloyer-Taylor Labs' UCDS suite of tools applied to existing liquid rocket engine data.

$$\frac{dR_m}{dt} = \alpha_m R_m; \quad \alpha_m = \left\{ \begin{array}{l} \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj}} M_{inj} (A_{inj}^{(r)} + 1) \psi_m^2 dS}_{\text{Pressure Coupling}} - \underbrace{\frac{1}{2E_m^2} \iint_{S_N} M_{inj} (A_N^{(r)} + 1) \psi_m^2 dS}_{\text{Nozzle Damping}} \\ + \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj||}} M_{inj} (B_{inj}^{(r)}) \psi_m^2 dS}_{\text{Acoustic Boundary Layer Pumping (ABL)}} - \underbrace{\frac{1}{2E_m^2} \iint_{S_{inj||}} \left(\frac{\delta}{2\gamma M_{inj}} \right)^2 (\nabla \psi_m \cdot \nabla \psi_m) dS}_{\text{Viscous Damping at Injection Surfaces}} \\ - \underbrace{\frac{1}{2\gamma P_0 E_m^2} \iiint_V \rho_0 \mathbf{u}_0 \cdot \langle \mathbf{u}_1 \times \omega_1 \rangle dV}_{\text{Vortex Shedding Effects; Flow-Turning Damping}} - \underbrace{\frac{1}{2\gamma P_0 E_m^2} \iiint_V \rho_1 \mathbf{u}_1 \cdot \langle \mathbf{u}_0 \times \omega_0 \rangle dV}_{\text{Vortex Shedding Effects; Flow-Turning Damping}} \\ + \underbrace{\frac{1}{2\gamma P_0 E_m^2} \iiint_V \left\langle \frac{\mathcal{H}_1 T_1}{T_0} - \frac{\mathcal{H}_0 T_1^2}{T_0^2} \right\rangle dV}_{\text{Distributed Combustion; Heat Release}} + \left\{ \begin{array}{l} \text{(Viscous Losses; Energy Dissipation)} \\ \text{+(Heat Transfer)} \\ \text{+(Particle Damping and} \\ \text{+ (Other Two-Phase Flow Effects))} \end{array} \right\} \end{array} \right\}$$





Summary



- **ALREST**
 - Nationally coordinated data-centric multi-fidelity model development
 - ALREST-HFM is the high-fidelity physics-based platform
 - Validated using relevant rocket data
 - Results are input into lower-fidelity engineering tools
- **Future**
 - More sophisticated physics models
 - Improved combustion diagnostics
 - Modular code and model development
 - Reduced-basis model development