THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

AFRL's ALREST Physics-Based Combustion Stability Program

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AFRL/RQ

8 November 2012

Air Force Research Lab

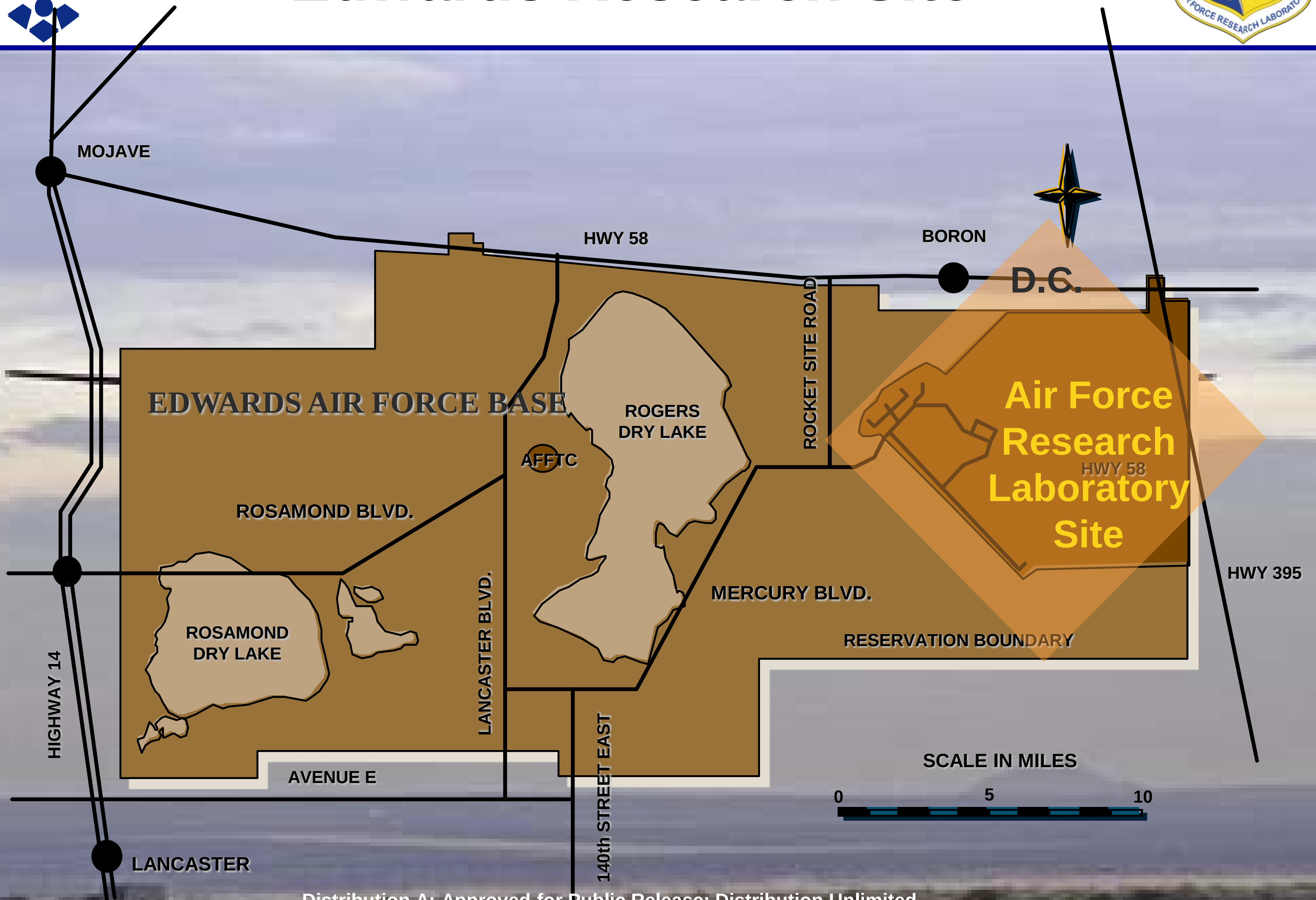
Air Force Research Laboratory

- 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



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Facilities

Bench-level Labs


Altitude Facilities

- From micro-newtons to 50,000 lbs thrust

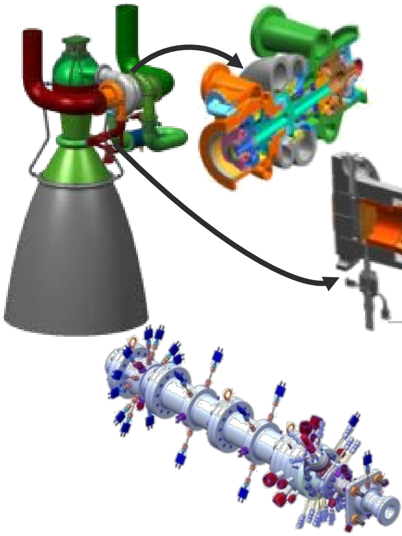
High Thrust Facilities

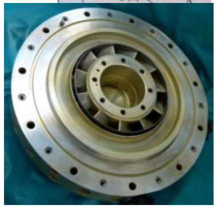
- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust



Hydrocarbon Boost

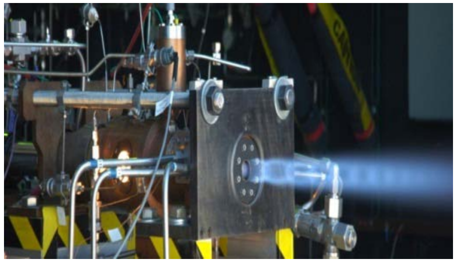
- **HCB establishes advanced, modern, domestic LRE Tech Base**
  - **Required to replace Russian RD-180 on EELV**
  - **1st reusable high performance U.S. HC engine**
  - **Establishes Ox-rich staged combustion (ORSC) <u>tech base</u> for U.S.**
  - **Help sustain ailing U.S. rocket engine industry tech 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 stability**
- **Injector design**
- **Preburner mixing**
- **Combustion Stability**



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 <u>increase in delivered payload</u>**

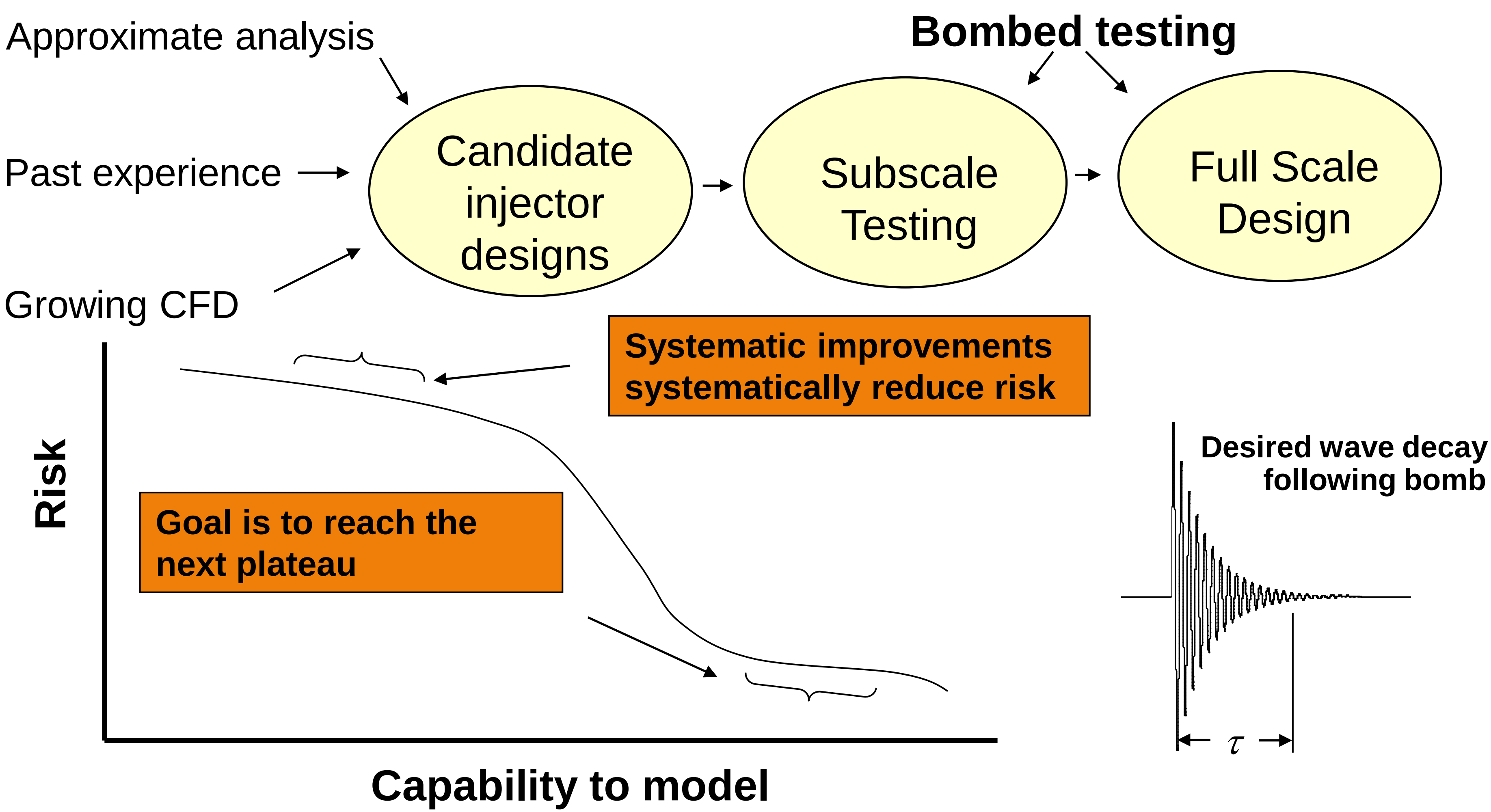
What is a Combustion Instability (CI)?

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 *<u>organized</u>*, *<u>oscillatory</u>* motion in a combustion chamber *<u>sustained by combustion</u>*.**
- **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 <u>major risk factor</u> 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 and 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

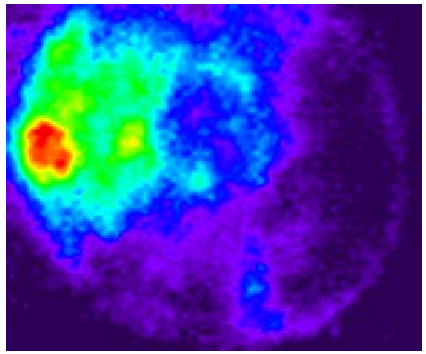
Zinn (GA Tech)
- AFOSR

Nestleroad Engin'ng
- MDA

Experiments

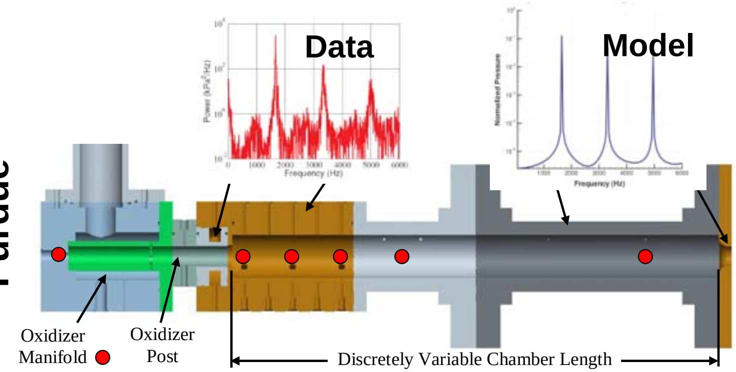
Spinning CI

GA Tech



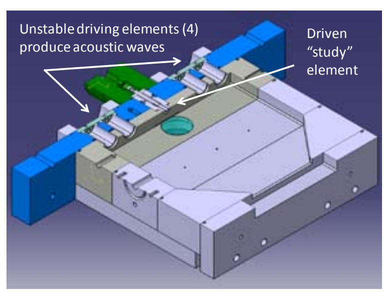
Longitudinal CI

Purdue

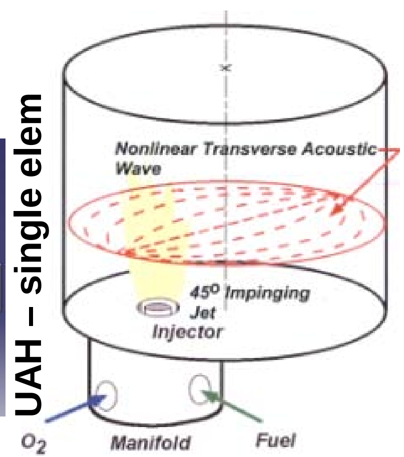


Standing CI

Purdue – multi elem

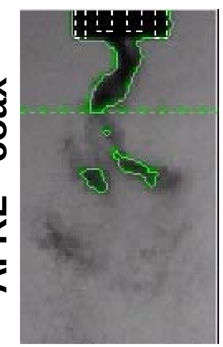


UAH – single elem

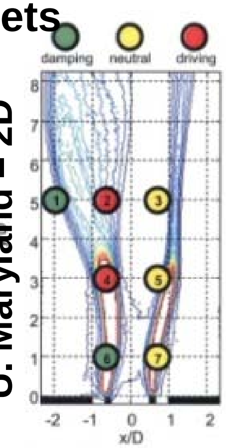


Driven jets

AFRL - coax



U. Maryland – 2D



Acoustics

HCB will be heavily instrumented to provide CI data

Full Scale (existing and HCB)

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AFRL

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**

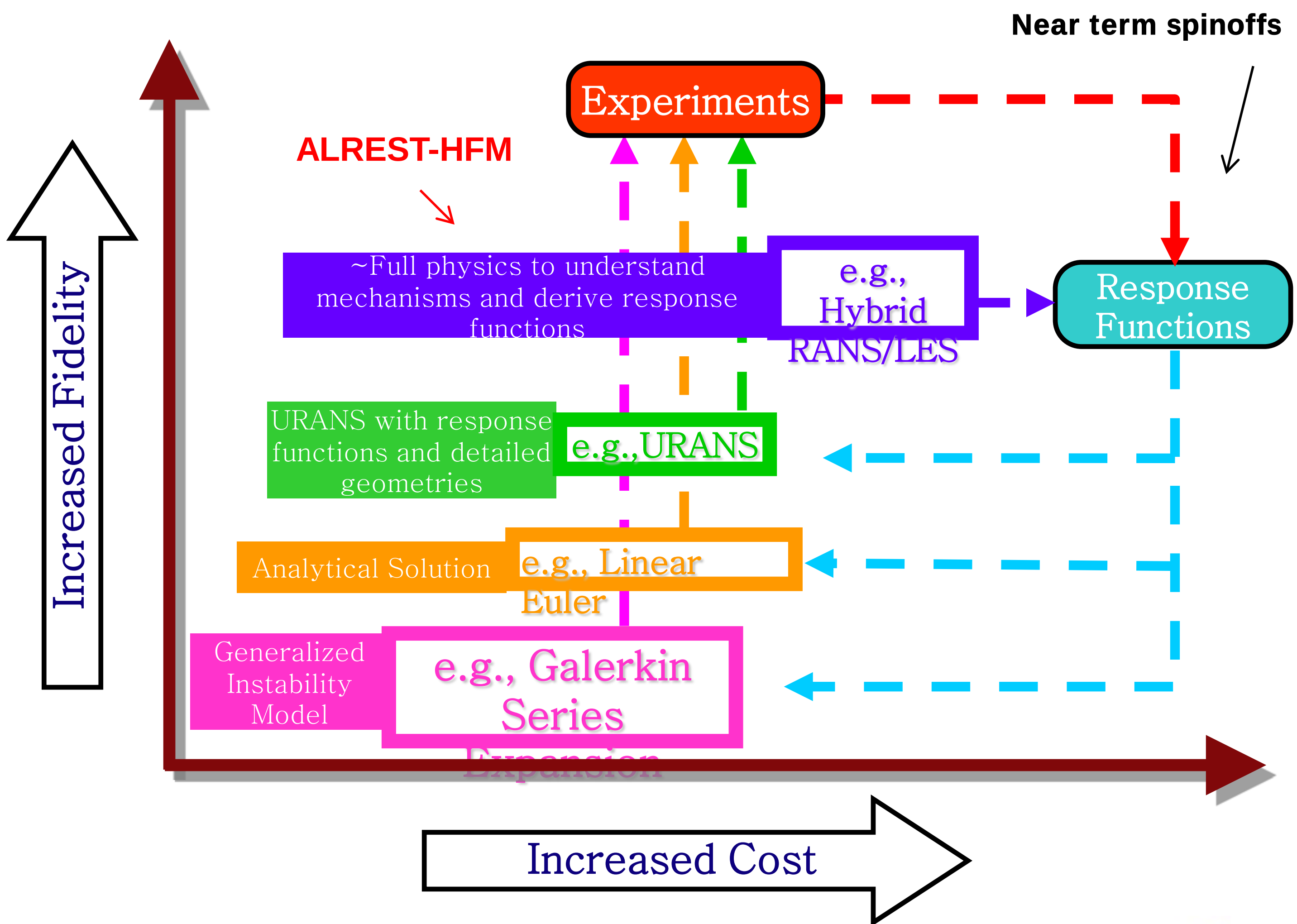
Menon (GA Tech)
- **ALREST, AFOSR**

Munipalli (HyPerComp)
- **ALREST**

Sirignano, Sideris (UC Irvine)
- **AFOSR**

Lynch (PWR)
- **ALREST**

Models

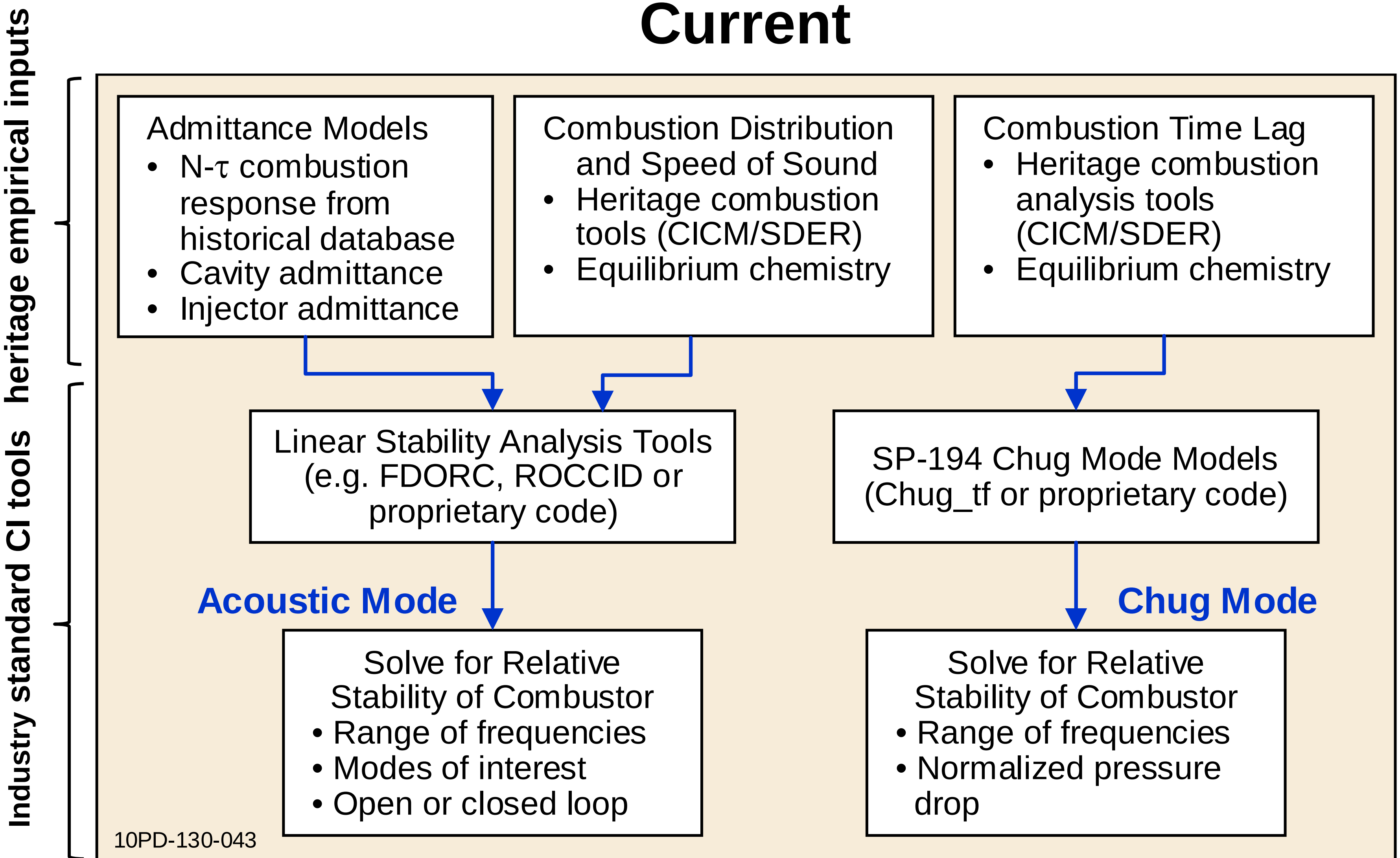


ALREST-HFM (AHFM)

- **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



Combustion Stability Design Tools

End of phase I

ALREST-HFM 1.0
High fidelity CFD inputs, specifically:

- **Combustion distribution (speed of sound, T, P, time lag, etc.)**
- **Increase admittance accuracy**
- **Combustion response**

Linear Stability Analysis Tools (e.g. FDORC, ROCCID or proprietary code)

SP-194 Chug Mode Models (Chug_tf or proprietary code)

Acoustic Mode

Solve for Relative Stability of Combustor
- Range of frequencies
- Modes of interest
- Open or closed loop

Chug Mode

Solve for Relative Stability of Combustor
- Range of frequencies
- Normalized pressure drop

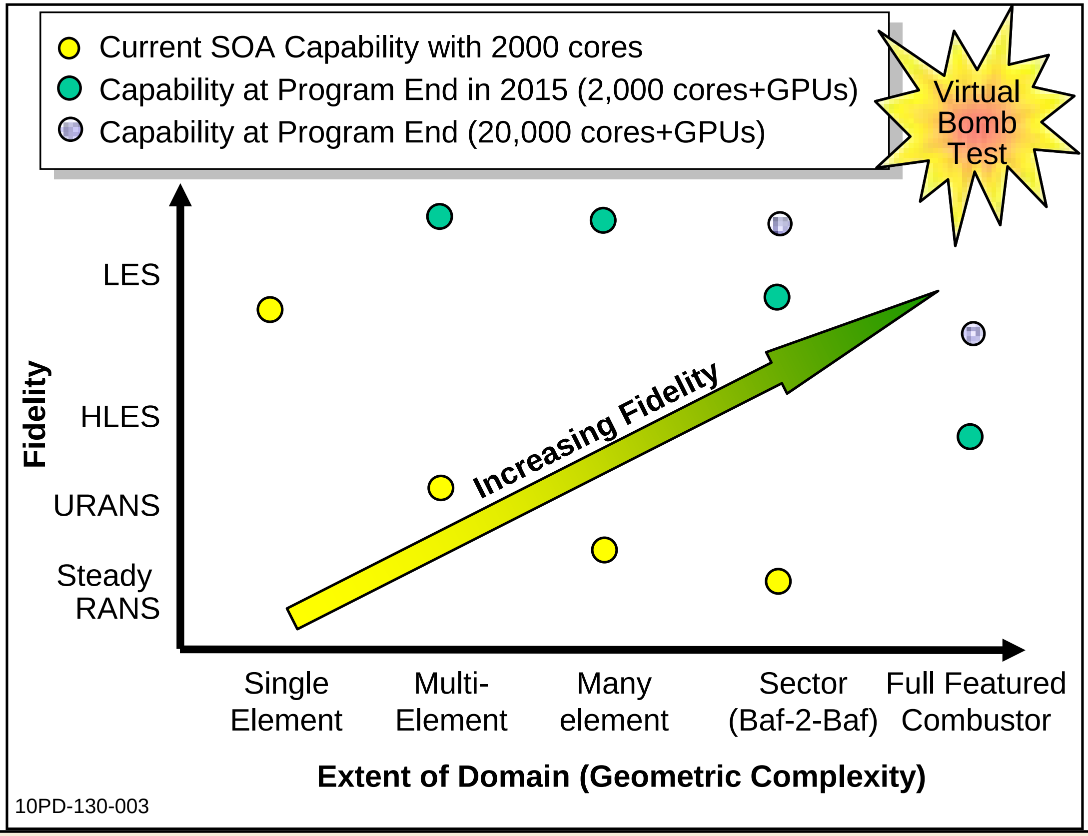
Industry standard CI tools

10PD-130-043

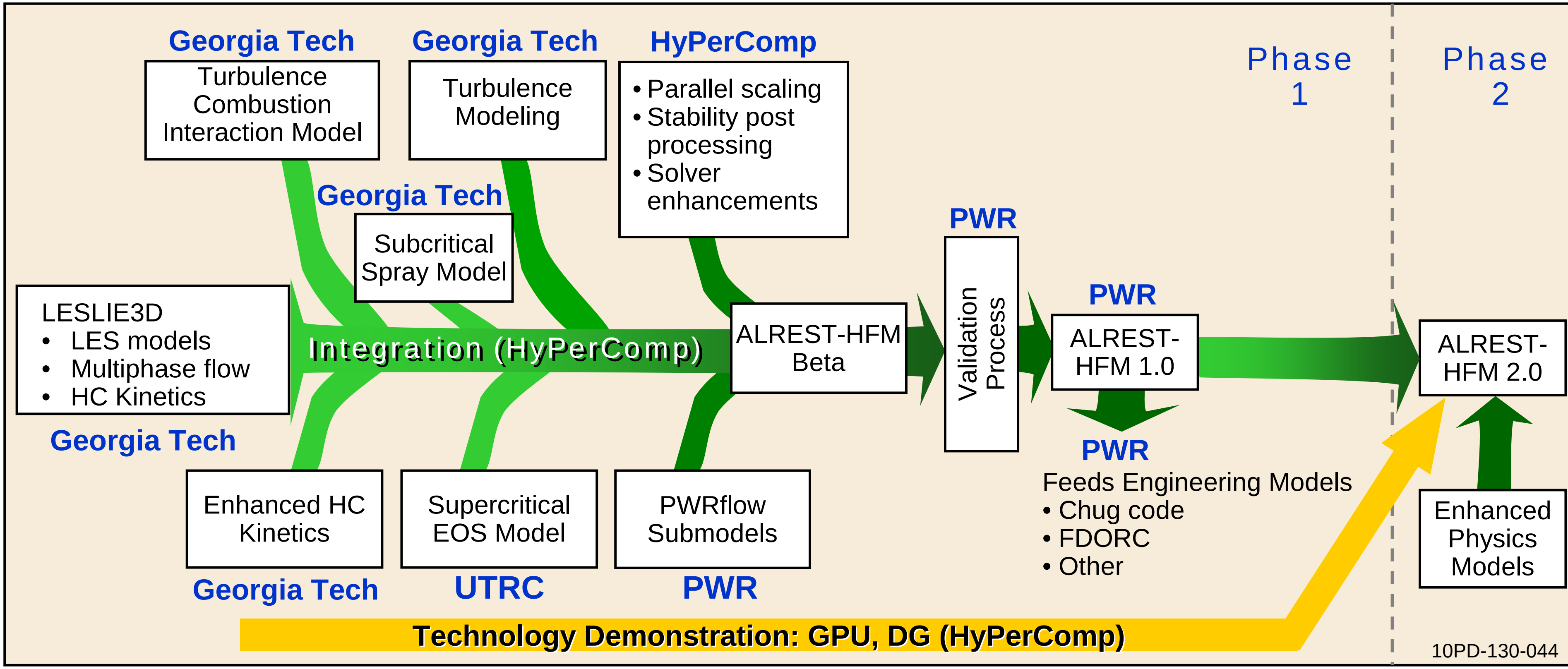
Combustion Stability Design Tools

Future vision

ALREST-HFM 1.0
High fidelity CFD replaces current industry standard tools



Approach



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

AHFM Dev’t Team

Program Manager
PWR
Brian Lariviere

Program Manager
AFRL
Doug Talley

Tech Advisors
PWR
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Bob Jensen CA
Tim Hinerman CS

Principal Investigator
PWR
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Tech Advisors
AFRL
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Matt Harvezinski

Task Lead
HyPerComp
Ramakanth Munipalli

- Code integration
- Scalability
- Validation
- Distribution/M&S

Tech Contributors
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X. Xing

Task Lead
Georgia Tech
Suresh Menon

- L3D POD Code
- Sub-modelDev’t
- Algorithm Dev’t

Tech Contributors
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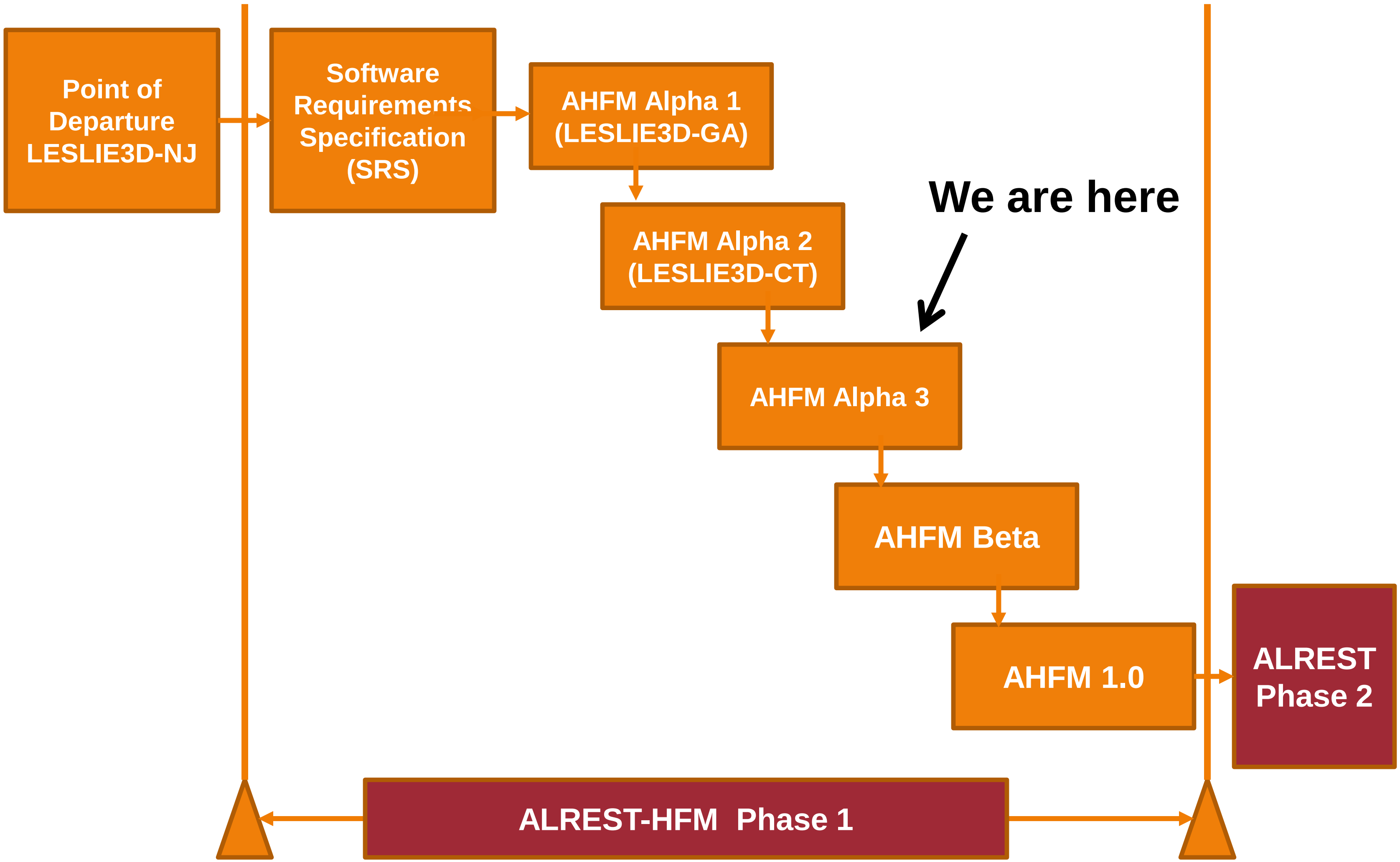
Nicolas Guezennec
Matthieu Masquelet

Task Lead
UTRC
Dusty Davis

- Sub-models
- Physical Models
- Supercritical Fluid Properties

Tech Contributors
UTRC
Jeremiah Lee

Four Stages of Development

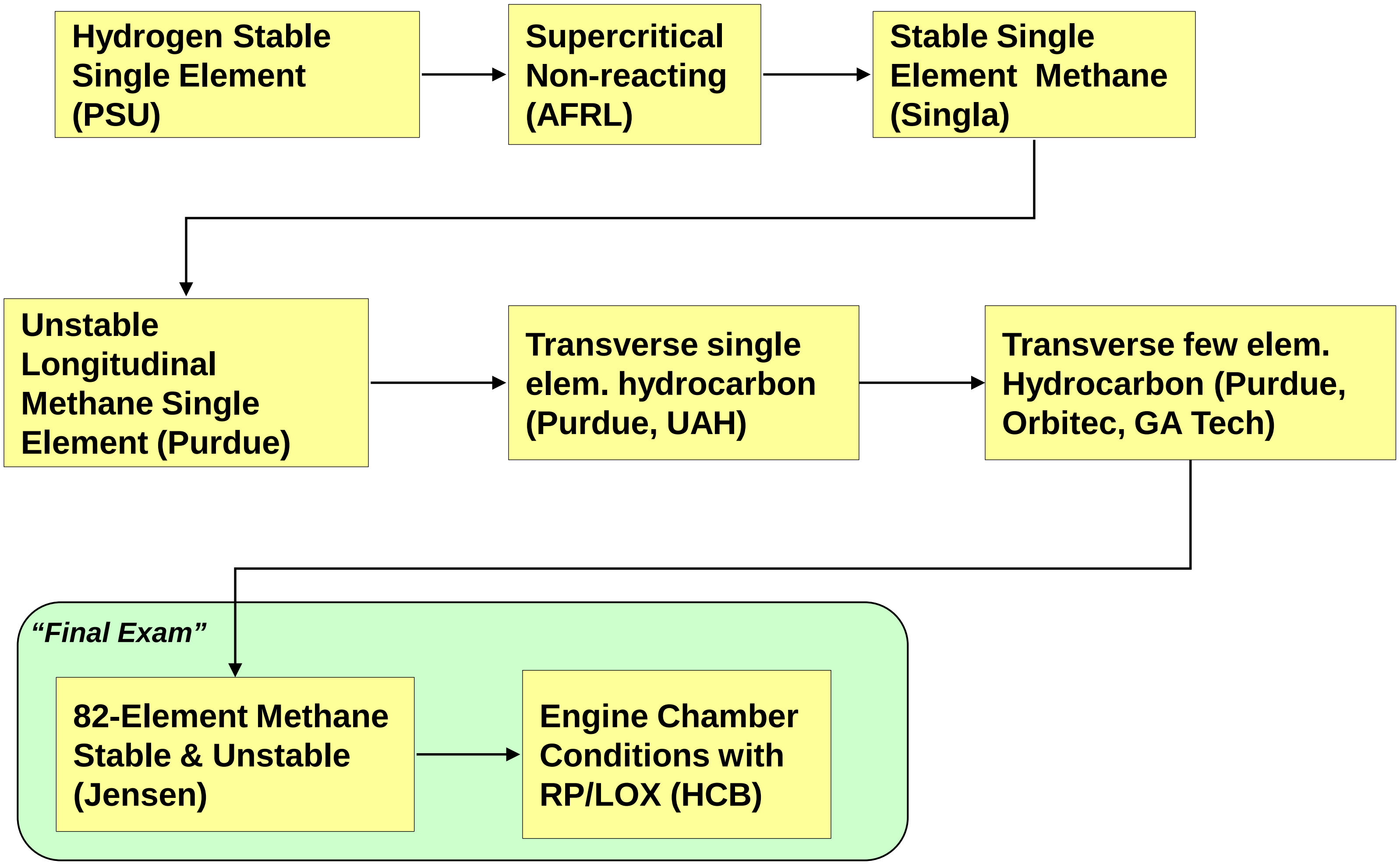


ALREST Verification Suite

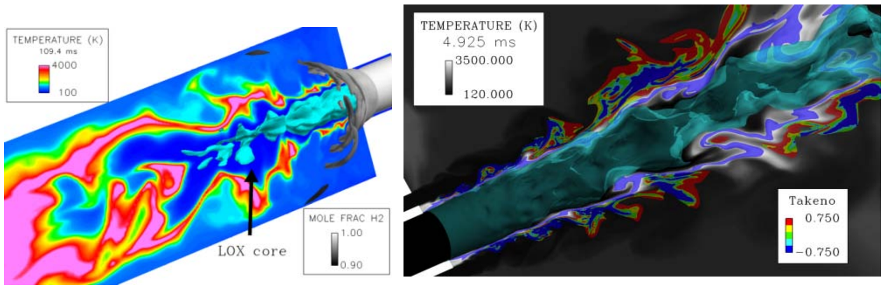
Case No.	Description of Test Case used for Verification
VR-1	**Uniform Flows (Run with all available schemes)**
VR-1.1	3D Uniform Flow in rotated uniform grid
VR-1.2	3D Uniform Flow in rotated non-uniform grid
VR-1.3	Uniform Flow in a 2-domain uniform grid
VR-2	**Simple Scaling Study**
VR-2.1	3D Temporal 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 H2/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 Gaussial 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

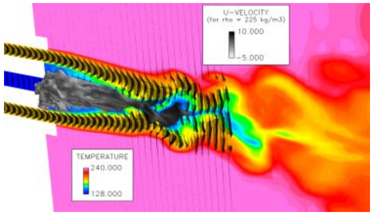
ALREST Validation Cases



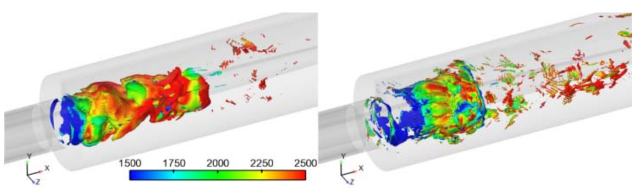
Validation Simulations

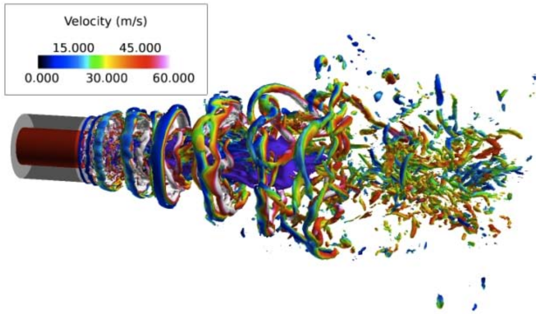


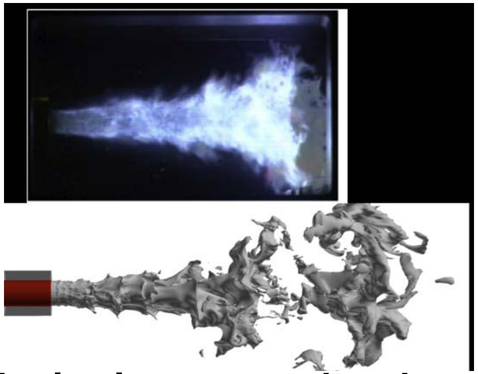
PSU LOX/H2 validation (NASA – leveraged)



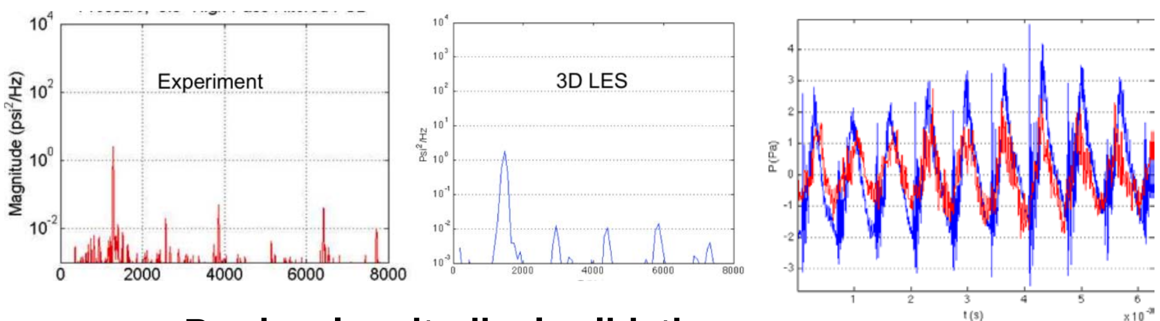
AFRL supercritical data (validation case)



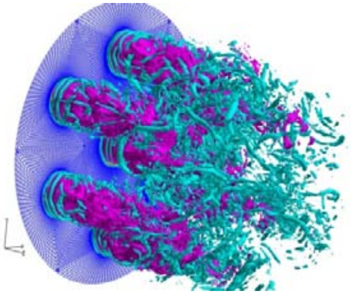




Single element combustion case



Purdue longitudinal validation case



7 element scalability study

CVRC Longitudinal Instability

Case Description:

- Longitudinal instability for single Injector
- Continuous Variable Resonance Combustor
- Self-Excited Combustion Instabilities
- Gas-gas shear coaxial injector element

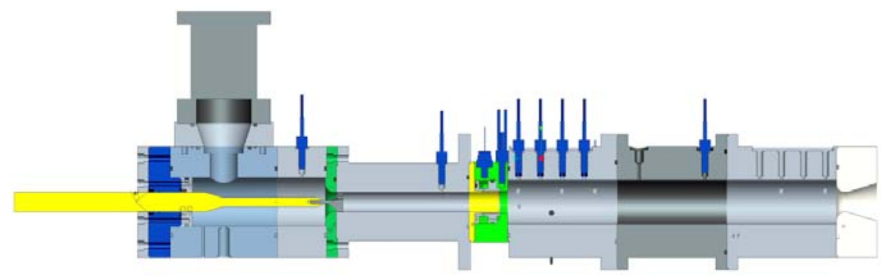
Relevance to AHFM:

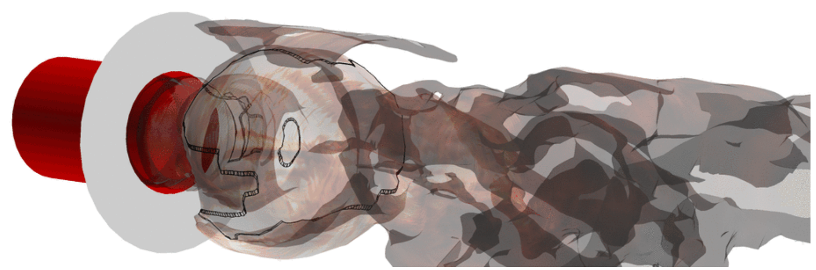
- Longitudinal Instability for Hydrocarbon Combustion under Supercritical Conditions

Key Metric or Success Criteria:

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

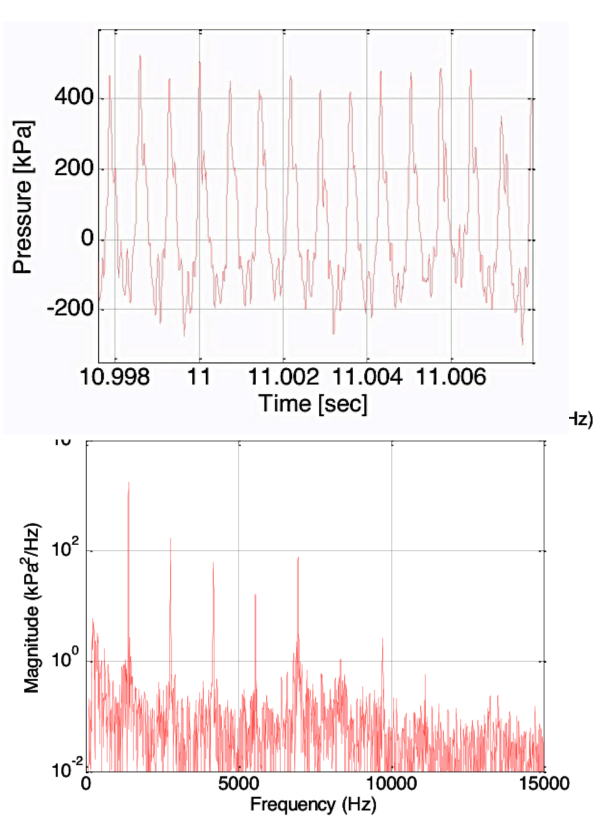
PURDUE UNIVERSITY



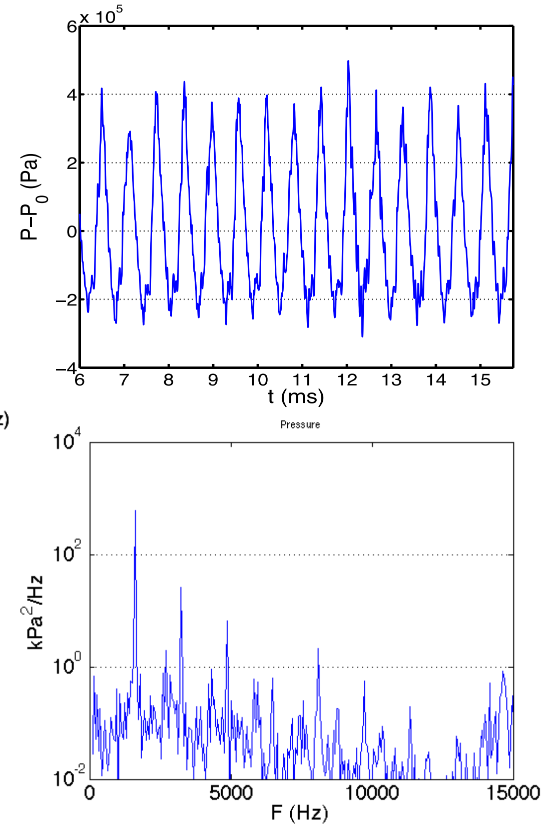


AFRL

Pressure Signal



Experiment

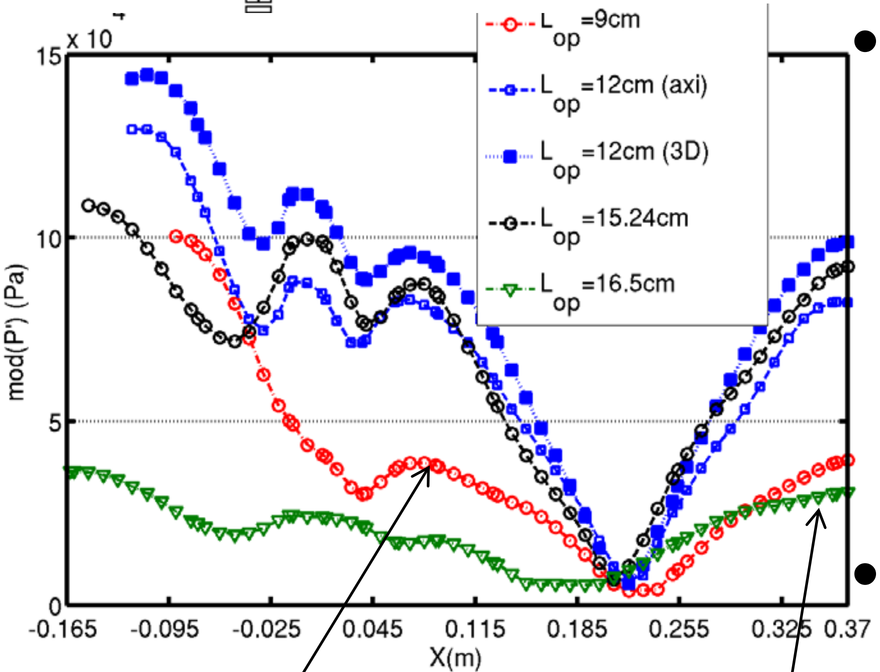


LESLIE

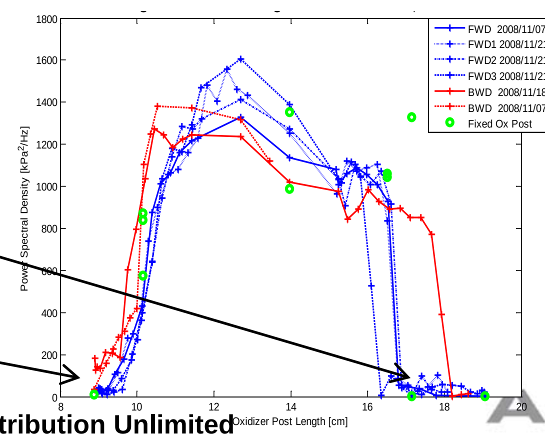
- Good prediction of the peak to peak fluctuations
- Good prediction of trends
- Frequency and amplitude slightly off
  - 200 Hz and x2 respectively
  - Reason still under investigation
- P_0=1.55 Mpa > P_{exp}=1.4 MPa

Georgia Tech College of Engineering

Parametric Studies



- Good prediction of the stability domain:
  - L<9cm and L>16cm: **strong reduction of acoustics**
  - L>9cm and L<16cm: **unstable combustor**
- Underestimation of the amplitude

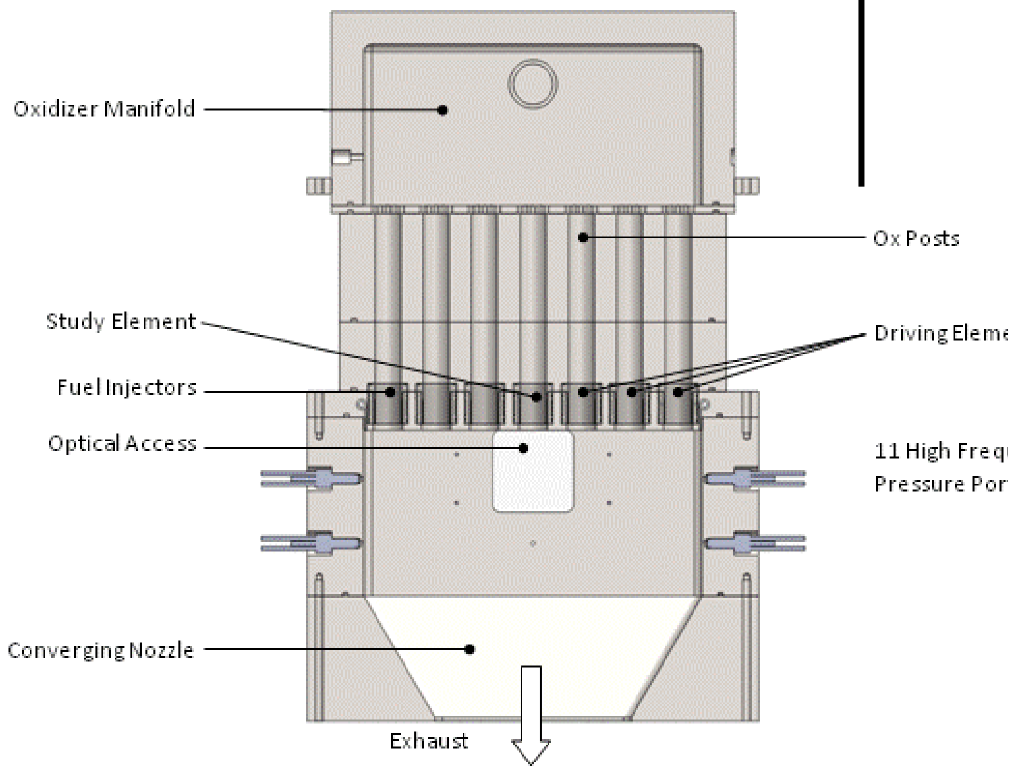


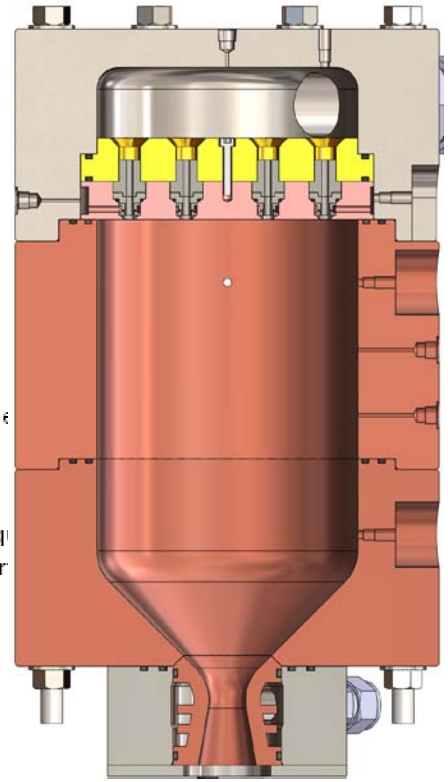
9 cm

16 cm

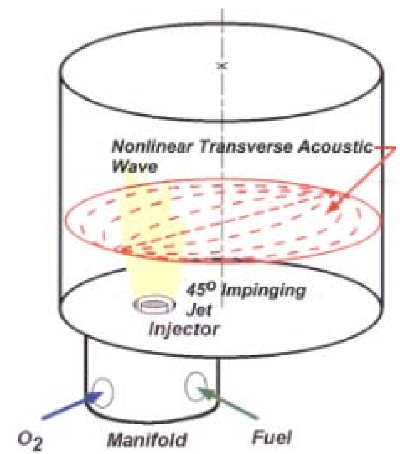
- Effect of the injector length on the combustor stability

Transverse Validation Data



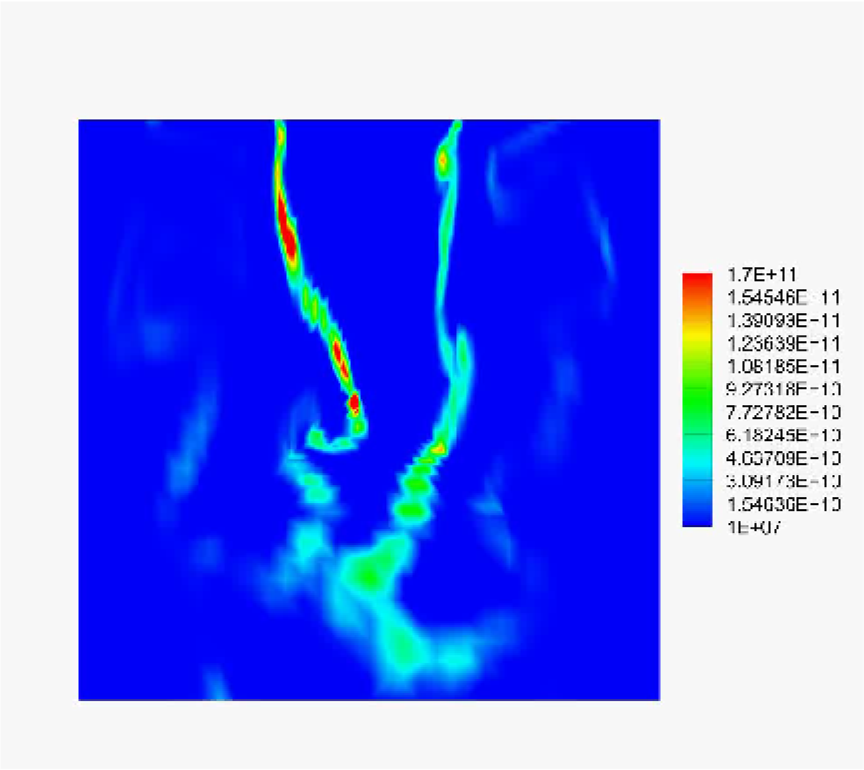


Scaling

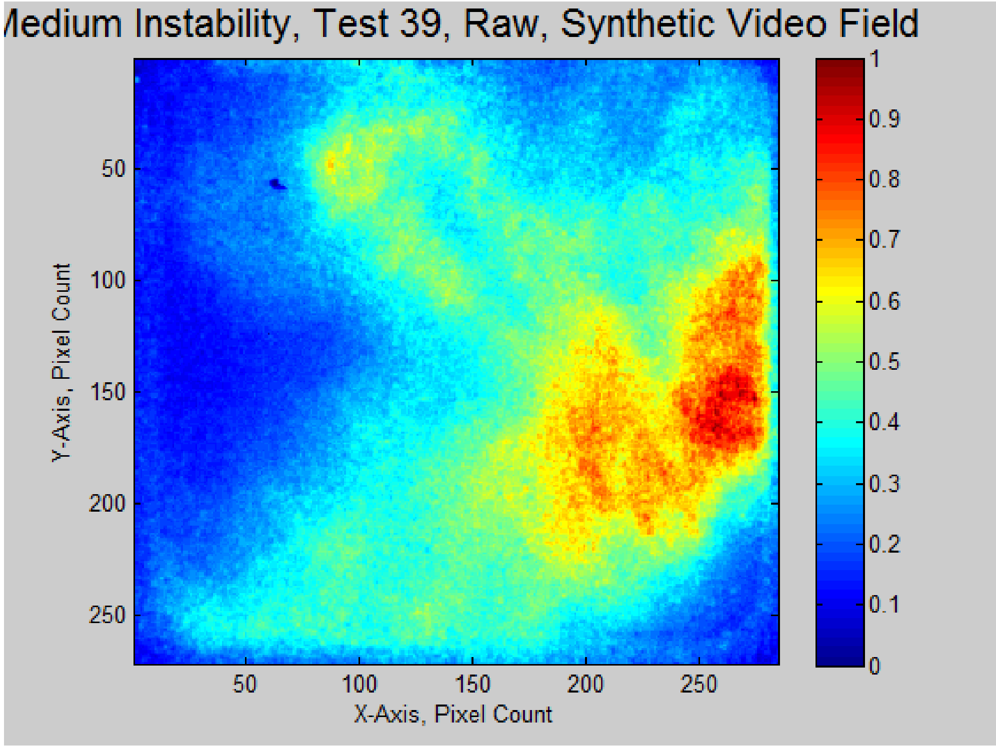


Heat Release

CFD Heat Rate (Watts)



Experiment Video - CH*



Analytical Methods

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

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

GTL

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