AFRL’s ALREST Physics-Based Combustion Stability Program

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Distribution A: Approved for Public Release; Distribution Unlimited
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
Facilities

Bench-level Labs

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

Altitude Facilities

- From micro-newtons to 50,000 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 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 increase in delivered payload
What is a Combustion Instability (CI)?

- 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.

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

– JANNAF Stability Panel Draft

Damaged F-1 engine injector faceplate caused by combustion instability
Risk Reduction

Approximate analysis

Past experience

Growing CFD

Candidate injector designs

Subscale Testing

Full Scale Design

Systematic improvements systematically reduce risk

Goal is to reach the next plateau

Desired wave decay following bomb

Risk

Capability to model

τ
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

Experiments

Spinning CI

Longitudinal CI

Standing CI

Driven jets

GA Tech

Purdue

Standing CI

U. Maryland – 2D

Acoustics

HCB will be heavily instrumented to provide CI data

Full Scale (existing and HCB)

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**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
- **Yang (PA State)**
  - AFOSR, AFRL, MDA
- **Bellan (JPL)**
  - AFOSR
- **Kassoy (U. Colo.)**
  - AFOSR
- **Priem consultants**
  - ALREST
- **Menon (GA Tech)**
  - ALREST, AFOSR
- **Munipalli (HyPerComp)**
  - ALREST
- **Sirignano, Sideris (UC Irvine)**
  - AFOSR
- **Lynch (PWR)**
  - ALREST

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**Increased Fidelity**

- ~Full physics to understand mechanisms and derive response functions
- URANS with response functions and detailed geometries
- Analytical Solution
- Generalized Instability Model
- e.g., Linear Euler
- e.g., Galerkin Series Expansion
- e.g., URANS

**Increased Cost**

- e.g., Hybrid RANS/LES
- Experiments
- ALREST-HFM
- Near term spinoffs

**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

- Admittance Models
  - N-\(\tau\) combustion response from historical database
  - Cavity admittance
  - Injector admittance

- Combustion Distribution and Speed of Sound
  - Heritage combustion tools (CICM/SDER)
  - Equilibrium chemistry

- Combustion Time Lag
  - Heritage combustion analysis tools (CICM/SDER)
  - Equilibrium chemistry

- 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

10PD-130-043
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

Industry standard CI tools

Acoustic Mode
- Linear Stability Analysis Tools
  (e.g. FDORC, ROCCID or proprietary code)
- Solve for Relative Stability of Combustor
  - Range of frequencies
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  - Open or closed loop

Chug Mode
- SP-194 Chug Mode Models
  (Chug_tf or proprietary code)
- Solve for Relative Stability of Combustor
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  - Normalized pressure drop
Combustion Stability Design Tools

Future vision

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

- Current SOA Capability with 2000 cores
- Capability at Program End in 2015 (2,000 cores+GPUs)
- Capability at Program End (20,000 cores+GPUs)

Increasing Fidelity

Extent of Domain (Geometric Complexity)

Fidelity

- LES
- HLES
- URANS
- Steady RANS

Single Element
- Multi-Element
- Many element
- Sector (Baf-2-Baf)
- Full Featured Combustor

Virtual Bomb Test

ALREST-HFM 1.0
High fidelity CFD replaces current industry standard tools
Source code will be delivered and maintained by Hypercomp after the contract ends.
Four Stages of Development

- Point of Departure: LESLIE3D-NJ
- Software Requirements Specification (SRS)
- AHFM Alpha 1 (LESLIE3D-GA)
- AHFM Alpha 2 (LESLIE3D-CT)
- AHFM Alpha 3
- AHFM Beta
- AHFM 1.0
- ALREST Phase 2

We are here
ALREST Verification Suite

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Description of Test Case used for Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR-1</td>
<td>Uniform Flows (Run with all available schemes)</td>
</tr>
<tr>
<td>VR-1.1</td>
<td>3D Uniform Flow in rotated uniform grid</td>
</tr>
<tr>
<td>VR-1.2</td>
<td>3D Uniform Flow in rotated non-uniform grid</td>
</tr>
<tr>
<td>VR-1.3</td>
<td>Uniform Flow in a 2-domain uniform grid</td>
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<tr>
<td>VR-2</td>
<td>Simple Scaling Study</td>
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<tr>
<td>VR-2.1</td>
<td>3D Temporal Mixing Layer (TML) with light load</td>
</tr>
<tr>
<td>VR-2.2</td>
<td>3D TML with normal load</td>
</tr>
<tr>
<td>VR-3</td>
<td>Wave Propagation Accuracy</td>
</tr>
<tr>
<td>VR-3.1</td>
<td>Quasi 1D Gaussian pressure pulse traveling in a duct of variable area</td>
</tr>
<tr>
<td>VR-3.2</td>
<td>Above with temperature variation</td>
</tr>
<tr>
<td>VR-4</td>
<td>Flame Test Cases</td>
</tr>
<tr>
<td>VR-4.1</td>
<td>Laminar premixed methane/air flame (phi=1, p=1 to 60 atm, 4-step, 8-species, initial solution from GRI)</td>
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<tr>
<td>VR-4.2</td>
<td>Laminar premixed H2/Air flame (phi=0.7)</td>
</tr>
<tr>
<td>VR-5</td>
<td>Boundary Condition Test Cases</td>
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<tr>
<td>VR-5.1</td>
<td>Pressure reflection from inflow, non-reflecting exit at outflow</td>
</tr>
<tr>
<td>VR-5.2</td>
<td>Above with turbulent inflow</td>
</tr>
<tr>
<td>VR-5.3</td>
<td>Above with Calorically (CPG) vs Thermally (TPG) perfect gas models</td>
</tr>
<tr>
<td>VR-6</td>
<td>Convection Test Cases</td>
</tr>
<tr>
<td>VR-6.1</td>
<td>1D Tests of wave speed with jump in species concentration</td>
</tr>
<tr>
<td>VR-6.2</td>
<td>1D Shock tube problem with limiters and artificial dissipation</td>
</tr>
<tr>
<td>VR-6.3</td>
<td>1D Gaussian pulse with different flux formulae</td>
</tr>
<tr>
<td>VR-6.4</td>
<td>2D convected vortex</td>
</tr>
<tr>
<td>VR-6.5</td>
<td>1D Gaussian entropy wave</td>
</tr>
<tr>
<td>VR-7</td>
<td>Temporal Mixing Layer</td>
</tr>
<tr>
<td>VR-7.1</td>
<td>3D, 1 species Euler CPG mixing layer model</td>
</tr>
<tr>
<td>VR-7.2</td>
<td>2D, 2 species CPG model</td>
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<tr>
<td>VR-7.3</td>
<td>Shock Wave Test Cases</td>
</tr>
<tr>
<td>VR-7.4</td>
<td>1D Sod shock tube test case</td>
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<tr>
<td>VR-7.5</td>
<td>2D Oblique shock Mach 5, 25 deg wedge</td>
</tr>
<tr>
<td>VR-7.6</td>
<td>2D Richtmyer-Meshkov Instability</td>
</tr>
</tbody>
</table>

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

1. Hydrogen Stable Single Element (PSU)
2. Supercritical Non-reacting (AFRL)
3. Stable Single Element Methane (Singla)
4. Unstable Longitudinal Methane Single Element (Purdue)
5. Transverse single elem. hydrocarbon (Purdue, UAH)
6. Transverse few elem. Hydrocarbon (Purdue, Orbitec, GA Tech)
7. “Final Exam”
   - 82-Element Methane Stable & Unstable (Jensen)
   - Engine Chamber Conditions with RP/LOX (HCB)
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
Pressure Signal

- 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

\[ P_0 = 1.55 \text{ MPa} > P_{\text{exp}} = 1.4 \text{ MPa} \]
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

- Effect of the injector length on the combustor stability
Transverse Validation Data

Oxidizer Manifold

Study Element

Fuel Injectors

Optical Access

Converging Nozzle

Exhaust

Ox Posts

Driving Element

11 High Freq Pressure Por

Scaling

Nonlinear Transverse Acoustic Wave

$45^\circ$ Impinging Jet Injector

$O_2$ Manifold Fuel
Heat Release

CFD Heat Rate (Watts)  Experiment Video - CH*

Medium Instability, Test 39, Raw, Synthetic Video Field
Analytical Methods

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

\[
\frac{dR_m}{dt} = \alpha_m R_m; \quad \alpha_m = \left\{ \begin{array}{l}
\frac{1}{2E_m} \int \int_{S_{inj}} M_{inj}(A_{inj}^{(r)} + 1) \psi_m^2 dS - \frac{1}{2E_m} \int \int_{S_N} M_{inj}(A_N^{(r)} + 1) \psi_m^2 dS \\
\frac{1}{2E_m} \int \int_{S_{m||}} M_{inj}(B_{inj}^{(r)}) \psi_m^2 dS - \frac{1}{2E_m} \int \int_{S_{m||}} \left( \frac{\delta}{2\gamma M_{inj}} \right) (\nabla \psi_m \cdot \nabla \psi_m) dS \\
- \frac{1}{2\gamma P_0 E_m} \int \int \int_{V} \rho_0 u_0 \cdot (u_1 \times \omega_1) dV + \frac{1}{2\gamma P_0 E_m} \int \int \int_{V} \rho_1 u_1 \cdot (u_0 \times \omega_0) dV \\
+ \frac{1}{2\gamma P_0 E_m} \int \int \int_{V} \left( \frac{H_1 T_1 - H_0 T_0^2}{T_0} \right) dV + \left( \text{Viscous Losses; Energy Dissipation} \right) \\
+ \left( \text{Heat Transfer} \right) \\
+ \left( \text{Particle Damping and Other Two-Phase Flow Effects} \right) \\
\end{array} \right.
\]
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