AFRL’s ALREST Physics-Based Combustion Stability Prediction Program

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.
AFRL’s ALREST Physics-Based Combustion Stability Program

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Dr. Doug Talley
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Air Force Research Laboratory

8 November 2012

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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 & 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)?

- 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
Risk Reduction

Approximate analysis
Past experience
Growing CFD

Candidate injector designs ➔ Subscale Testing ➔ Full Scale Design

Bombed testing

Goal is to reach the next plateau

Systematic improvements systematically reduce risk

Desired wave decay following bomb

Risk vs. Capability to model
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
  - NASA CUIP
  - AFRL
  - ALREST

- 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

- **Standing CI**
  - Purdue

- **Longitudinal CI**
  - Data
  - Model
  - Oxidizer Manifold
  - Oxidizer Post
  - Discretely Variable Chamber Length

- **Driven jets**
  - U. Maryland – 2D

**Full Scale (existing and HCB)**

HCB will be heavily instrumented to provide CI data.
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

- Increased Fidelity
- Increased Cost

Experiments
- ALREST-HFM
- Full physics to understand mechanisms and derive response functions

Response Functions
- Near term spinoffs

Materials
- e.g., Hybrid RANS/LES
- e.g., URANS
- e.g., Linear Euler

URANS with response functions and detailed geometries

Analytical Solution
- e.g., Linear Euler

Generalized Instability Model
- e.g., Galerkin Series Expansion

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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-τ 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

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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
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

Steady RANS

URANS

HLES

LES

Virtual Bomb Test

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

Virtual Bomb Test
Approach

Source code will be delivered and maintained by Hypercomp after the contract ends.
## Marriage of PWR PWRflow RANS and Georgia Tech LESLIE3D Codes

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>LESLIE3D</td>
<td>Hybrid HLC/E</td>
<td>Structured; Structured-Unstructured Cartesian</td>
<td>Subgrid Scale K-KL and K-Δ</td>
<td>Variety of Hydrogen and Hydrocarbon Models for Gas Turbines, Ramjets, and LRE's</td>
<td>Mixtures of Calorically Perfect Gases and Mixtures of Peng-Robinson Fluids with Detailed Species Properties</td>
<td>Variety of RANS and LES modeling ranging from flamelets, eddy breakup modeling to LEM (Linear Eddy Modeling)</td>
<td>Detailed Level Set model for drop breakup with interface refinement</td>
<td>Lagrangian Droplet Model with drop breakup and evaporation exercised on gas turbine analyses</td>
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<tr>
<td>PWRflow</td>
<td>Cell-Based Limiting with Rusinov, Roe, and FORCE (large density differences) Riemann solvers</td>
<td>Diagonalized and Preconditioned/Nonpreconditioned Point Implicit, Multigrid and Chunk G-S Global Implicit</td>
<td>Unstructured</td>
<td>Goldberg, Menter, and Spalart-Almaras 1-Equation RANS Models; Anisotropic k-ε Model</td>
<td>1- and 2-step global, quasiglobal, and mechanistic models for a variety of hydrocarbons fuels and hydrogen including RP</td>
<td>Perfect Gas, Equilibrium Air, Mixtures of Calorically Perfect Gases and Mixtures of Redlich-Kwong and Peng-Robinson Fluids</td>
<td>Assumed pdf Model based on k-ε-γ Model in NASA/LaRc Vulcan code</td>
<td>Level Set model for drop breakup employed on some selected problems</td>
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</table>
AHFM Dev’t Team

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- Algorithm Dev’t

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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

ALREST-HFM Phase 1

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>
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<tr>
<td>VR-1.1</td>
<td>3D Uniform Flow in rotated uniform grid</td>
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<tr>
<td>VR-1.2</td>
<td>3D Uniform Flow in rotated non-uniform grid</td>
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<tr>
<td>VR-1.3</td>
<td>Uniform Flow in a 2-domain uniform grid</td>
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<td>VR-2</td>
<td>Simple Scaling Study</td>
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<td>VR-2.1</td>
<td>3D Temporal Mixing Layer (TML) with light load</td>
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<tr>
<td>VR-2.2</td>
<td>3D TML with normal load</td>
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<tr>
<td>VR-3</td>
<td>Wave Propagation Accuracy</td>
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<tr>
<td>VR-3.1</td>
<td>Quasi 1D Gaussian pressure pulse traveling in a duct of variable area</td>
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<tr>
<td>VR-3.2</td>
<td>Above with temperature variation</td>
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<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>
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<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>
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<tr>
<td>VR-5.2</td>
<td>Above with turbulent inflow</td>
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<tr>
<td>VR-5.3</td>
<td>Above with Calorically (CPG) vs Thermally (TPG) perfect gas models</td>
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<tr>
<td>VR-6</td>
<td>Convection Test Cases</td>
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<tr>
<td>VR-6.1</td>
<td>1D Tests of wave speed with jump in species concentration</td>
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<tr>
<td>VR-6.2</td>
<td>1D Shock tube problem with limiters and artificial dissipation</td>
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<td>VR-6.3</td>
<td>1D Gaussian pulse with different flux formulae</td>
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<td>VR-6.4</td>
<td>2D convected vortex</td>
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<td>VR-6.5</td>
<td>1D Gaussian entropy wave</td>
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<tr>
<td>VR-7</td>
<td>Temporal Mixing Layer</td>
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<tr>
<td>VR-7.1</td>
<td>3D, 1 species Euler CPG mixing layer model</td>
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<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>
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<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>
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</tbody>
</table>

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

- Hydrogen Stable Single Element (PSU)
- Supercritical Non-reacting (AFRL)
- Stable Single Element Methane (Singla)
- Unstable Longitudinal Methane Single Element (Purdue)
- Transverse single elem. hydrocarbon (Purdue, UAH)
- Transverse few elem. Hydrocarbon (Purdue, Orbitec, GA Tech)
- "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)

Purdue longitudinal validation case

7 element scalability study
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-α1 (LESLIE3D-GA)
Computer System & No. of Cores
Grid Size:
Other Special Characteristics:
• Mixture of Calorically Perfect Gases
• xx Methane – Oxygen Kinetics
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
- \( P_0 = 1.55 \text{ Mpa} > P_{\text{exp}} = 1.4 \text{ MPa} \)

36.85 cm
Parametric study with Axi-LES

- Effect of the injector length on the combustor stability
  - L<9cm and L>16cm: strong reduction of acoustics
  - L>9cm and L<16cm: unstable combustor
- Good prediction of the stability domain:
- 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.
Heat Release

CFD Heat Rate (Watts)  Experiment Video - CH*

[Image of a graph showing medium instability, test 39, raw, synthetic video field with X-axis, pixel count, and Y-axis, pixel count axes.]
CAD drawing of engine and manifolds

Fuel

Chamber

LOX
Five Element Sector Mesh
Analytical Methods

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

\[
\frac{dR_m}{dt} = \alpha_m R_m; \quad \alpha_m = \left\{ \begin{array}{l}
\frac{1}{2E_m} \int \int_{S_{inj}} M_{inj} \left( A_{inj}^{(r)} + 1 \right) \psi_m^2 dS - \frac{1}{2E_m} \int \int_{S_N} M_{inj} \left( A_N^{(r)} + 1 \right) \psi_m^2 dS \\
\text{Pressure Coupling}
\end{array} \right.
\]

\[
\frac{1}{2E_m} \int \int_{S_{inj}} M_{inj} \left( B_{inj}^{(r)} \right) \psi_m^2 dS - \frac{1}{2E_m} \int \int_{S_{inj}} \left( \frac{\delta}{2\gamma M_{inj}} \right)^2 \left( \nabla \psi_m \cdot \nabla \psi_m \right) dS
\]

\text{Nozzle Damping}

\[
\frac{1}{2\gamma P_0 E_m} \int \int_{V} \rho_0 \mathbf{u}_0 \cdot \left( \mathbf{u}_1 \times \omega_1 \right) dV - \frac{1}{2\gamma P_0 E_m} \int \int_{V} \rho_1 \mathbf{u}_1 \cdot \left( \mathbf{u}_0 \times \omega_0 \right) dV
\]

\text{Viscous Damping at Injection Surfaces}

\[
\frac{1}{2\gamma P_0 E_m} \int \int_{V} \left( \frac{\mathcal{H}_1}{T_1} - \frac{\mathcal{H}_0}{T_0} \right) dV
\]

\text{Vortex Shedding Effects; Flow-Turning Damping}

\[
\frac{1}{2\gamma P_0 E_m} \int \int_{V} \left( \frac{\mathcal{H}_1}{T_1} + \frac{\mathcal{H}_0}{T_0} \right) dV + \left\{ \text{Viscous Losses; Energy Dissipation} \right\}
\]

\[
+ \left\{ \text{Heat Transfer; Particle Damping and Other Two-Phase Flow Effects} \right\}
\]

\text{Distributed Combustion; Heat Release}
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