**ALREST High Fidelity Modeling Program Approach**

**ABSTRACT**

The U.S. Air Force Research Laboratory (AFRL) is working with Pratt & Whitney Rocketdyne (PWR) to develop improved computational tools to predict better combustion stability of hydrocarbon-fueled liquid rocket engines. The Advanced Liquid Rocket Engine Stability Technology – High Fidelity Model (ALREST-HFM) code will be designed to improve the prediction of combustion instability using Computational Fluid Dynamics (CFD). Pratt & Whitney Rocketdyne has assembled a team that includes Professor Suresh Menon and coworkers at the Georgia Institute of Technology who have developed the LESLIE3D for supercritical hydrocarbon combustion; HyPerComp, Inc., a small business located in Westlake Village, CA, that specializes in the research and development of computational tools for fluid mechanics and combustion; and United Technologies Research Center (UTRC) in East Hartford, CT, who have extensive experience with hydrocarbon combustion and fluid properties. Pratt & Whitney Rocketdyne will lead the code development and provide its expertise in hydrocarbon-fueled rocket engines.
Abstract: The U.S. Air Force Research Laboratory is working with Pratt & Whitney Rocketdyne (PWR) to develop improved computational tools to predict better combustion stability of hydrocarbon-fueled liquid rocket engines. The Advanced Liquid Rocket Engine Stability Technology – High Fidelity Model (ALREST-HFM) code will be designed to improve the prediction of combustion instability using Computational Fluid Dynamics (CFD). Pratt & Whitney Rocketdyne has assembled a team that includes Professor Suresh Menon and coworkers at the Georgia Institute of Technology who have developed the LESLIE3D for supercritical hydrocarbon combustion; HyPerComp, Inc., a small business located in Westlake Village, CA., that specializes in the research and development of computational tools for fluid mechanics and combustion; and United Technologies Research Center (UTRC) in East Hartford, CT who have extensive experience with hydrocarbon combustion and fluid properties. Pratt & Whitney Rocketdyne will lead the code development and provide its expertise in hydrocarbon-fueled rocket engines.
ALREST High Fidelity Modeling Program Approach

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Importance of Combustion Instability as Issue in LRE Development

- PWR Apollo-Era F-1 Engine Required Over 2000 Full Engine Tests to Attain Stable Design
- Several Billion Dollars in Current Terms

Damage to Rocket Chamber from Combustion Instability
Genesis of ALREST-HFM Program

• Potential Attractiveness Of Liquid Hydrocarbon Engines For Boost Applications
• Propensity Of Hydrocarbon Engines For Combustion Instability
• Air Force Initiated Hydrocarbon Boost Demo Program To Develop Technology For Next Hydrocarbon-fueled Boost Rocket Engine
• ALREST-HFM To Create Tools Which Can Provide Nonlinear, Chamber-level Stability Predictions For Hydrocarbon-fueled Engines To Help Industry In The LRE Design/Development Process
Cost Structure of Previous LRE Development Programs

- Eliminate Failure Modes: 73%
- Design: 2%
- Certification: 15%
- Engineering Support: 10%
Rationale for Importance of Use of High Fidelity Analysis Tools

(a) Effect of reducing technical uncertainty

Before TUF reduc.

After TUF reduc.

CRW_{u-u}  \quad TUF_{u-u}
Current State for Combustion Instability Prediction in Rocket Engine Development in Industry

Current State (Start of Phase 1)

- Admittance Models
- Combustion Distribution and Speed of Sound
- Combustion Time Lag

Acoustic Mode
- Linear Stability Analysis Tools
- Solve for Relative Stability of Combustor

Chug Mode
- SP-194 Chug Mode Models
- Solve for Relative Stability of Combustor
Future State for Combustion Instability Prediction in Rocket Engine Development in Industry

Future State (End of Phase 1)

ALREST-HFM 1.0
Provides High-Fidelity Inputs to Industry Stability Tools

- Linear Stability Analysis Tools
- SP-194 Chug Mode Models

Acoustic Mode
Solve for Relative Stability of Combustor

Chug Mode
Solve for Relative Stability of Combustor

10PD-130-045
Future Vision

ALREST-HFM x.x
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

Fidelity
- LES
- HLES
- URANS
- Steady RANS

Extent of Domain (Geometric Complexity)
- Single Element
- Multi-Element
- Many element
- Sector (Baf-2-Baf)
- Full Featured Combustor

Virtual Bomb Test

High fidelity CFD replaces current industry standard tools
ALREST-HFM Development Plan and Team
## Marriage of PWR PWRflow RANS and Georgia Tech LESLIE3D Codes

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<td><strong>LES3D</strong></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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<td><strong>PWRflow</strong></td>
<td>Cell-Based Limiting with Rusanov, 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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Quasiglobal Modeling Provides Cost Effective Solution to Tip Flame Stability Prediction

- Finite-Rate Propane Kinetics
- 11-Species Quasiglobal Modeling Approach
- 41-Species, 163-Reaction Mechanistic Model
Postprocessing Key Element of ALREST-HFM Tool

- Presupplied Functions and User Defined Functions
  - Rayleigh integral
  - Frequency Domain Quantities
  - Response Functions
  - Nozzle and Manifold admittances

- Open Loop LOX Post Response Function
  - Unsteady PWRflow Supercritical Full Navier-Stokes CFD Analyses
  - 82-element Jensen LOX-Hydrocarbon Stability Tests
  - Experience with Upstream BC Issues
Combine Demonstrated Capabilities of PWRflow and LESLIE3D

- **LESLIE3D**
  - Successful at predicting flame dynamics for gas turbines, scramjets and rocket injectors
- **PWRflow**
  - Designed for steady and unsteady RANS
  - Successful in predicting $\eta_{c^*}$ and wall heat transfer in single and multiple injector chambers
PreContract PWRflow Examples
Cross Section of LOX Stream for 3-Element PWRflow Analysis of PSU Test

- Penn State 3-element Lox-hydrogen Test
- Approximately 900,000 Gridpoints
- Peng-Robinson Supercritical Fluid Equation Of State
- Mechanistic Finite-rate Combustion
Wall Heat Transfer Comparison for PWRFlow Simulation of 3-Element Chamber
28-Element 40k-Calorimeter CFD Analysis Showing LOX Streams through z Contours

- 9,000,000 Gridpoint Computation with Fully Unstructured Grid
- Global Hydrogen–Oxygen Finite-rate Combustion
- Peng-Robinson Equation of State for Supercritical Fluids
H$_2$O Forms in Shear-Layer Between LOX and H$_2$
Comparison to Wall Heat Transfer for 40k Calorimeter Analysis

- Unstructured Grid Opened Up Too Quickly Downstream
- Mixing Rate Overpredicted in Near Field
- Wall Heat Transfer Underpredicted
- Grid Resolution Needs to Be Finer Near Throat to Capture Peak Heating

![Graph showing comparison between subscale data and CFD results.](attachment:graph.png)
Validation Plan Includes 82-element Jensen LOX-Hydrocarbon Stability Tests

- “Final Exam” Validation through Hydrocarbon Boost Preburner and Main Injector data
- Midterm Exam through 82-element Jensen LOX-Hydrocarbon Stability Tests
  - Stability and Instability in Same Rig
  - Investigators at PWR
  - Methane Equal or Worse Case than RP
Summary

- Collaborators Bring Previous Technology into Program
  - PWR: Rocket Stability and RANS CFD Modeling
  - UTRC: Combustion Modeling
  - Georgia Tech: LES Combustion Modeling
  - HyPerComp: CFD Software Development
- SRR Completed on Program
- Validation Plan Defined
- Departure Code Being Distributed to Team Members
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