Rules and Tools for Alternative Fuels

Combustion Rules and Tools for Alternative Fuels

Highlights of Phase 1 and R&D Needs

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Outline

In 8/2009, AFRL and DESC funded the 5 GT engine OEMs to collaboratively develop a plan to understand fuel effects on combustor performance and to facilitate fuel certification processes.

This presentation summarizes the outcome of that program

- **Introduction**
- **Program Objectives and Status**
- **Program Overview**
- **Observed fuel effects**
- **Brief Description of Rigs**
- **Modeling Review**
- **Fundamental R&D Needs**

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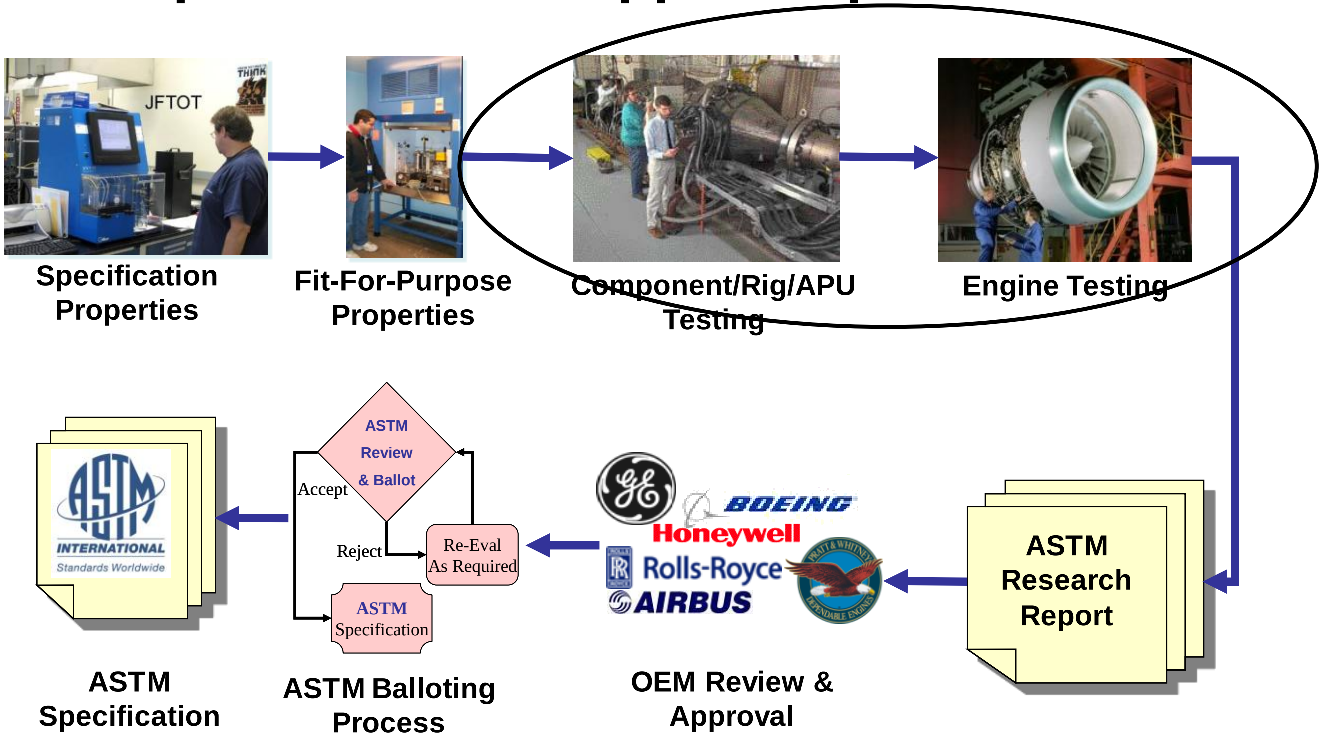
Introduction (1)

- **USAF needs to reduce its dependency on foreign oil sources**
  - **AF Policy Memo 10-2…50% of AF domestic aviation fuel requirement by 2016 via an alternative fuel blend…alternative component derived from *domestic sources***
- **Fuel needs to be from renewable or green energy sources (Waxman and Davis)**
  - **The domestic sourced fuel must show equal to or less lifecycle GHG than conventional fuels produced from petroleum**
- **Desire speedier/more efficient fuel approval process**
  - **Understand impact of new fuels on engine performance and operability**
  - **Cost effective screening of alternative fuels (in terms of time, fuel quantities, engine tests)**
- **Commercial aviation faces the same pressures and opportunities**

Understand the impact of fuel properties on combustion and engine performance critical for widespread use of alternative fuels in aviation

Introduction (2)

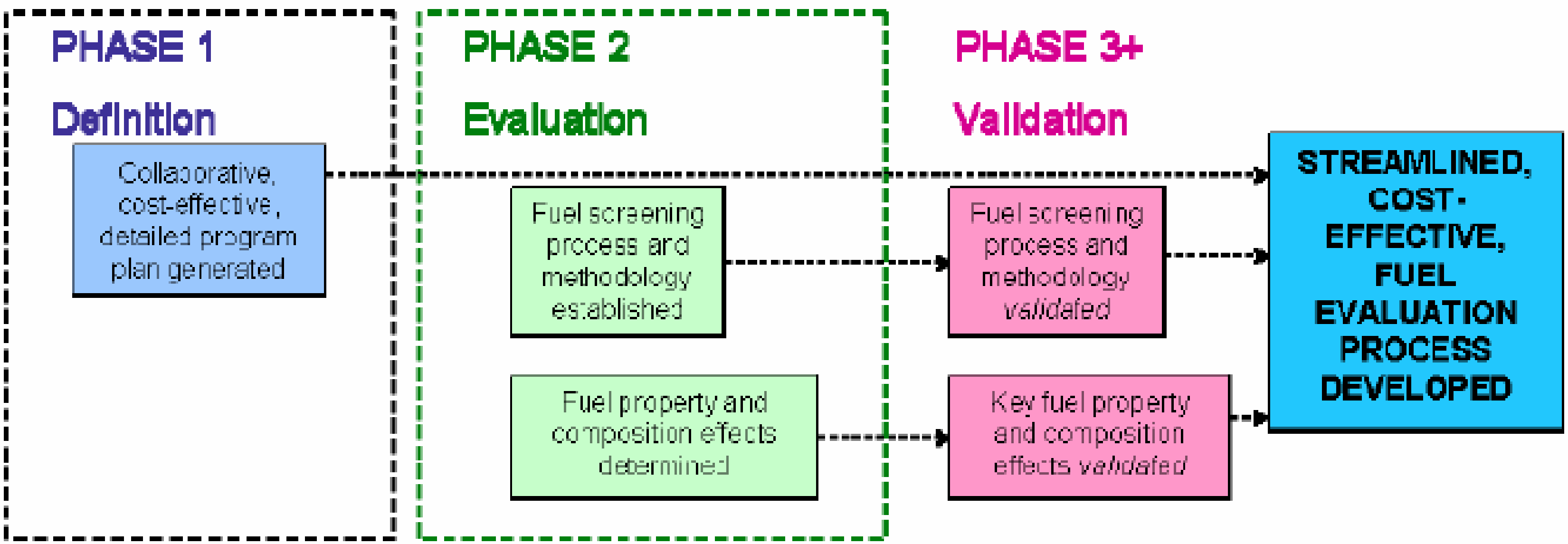
- Expensive portion of fuel approval process is not well defined



- Multiple/duplicative combustor rig and engine tests performed at various OEMs, including flight tests, but criteria requiring tests and interpretations appear excessive
- Can a streamlined, well-validated process be identified?

Rules and Tools Program Goals and Plan

- **Develop fundamental understanding of how fuel properties impact combustion**
  - **Establish a non-proprietary group including industry, government and academia**
  - **Identify combustion parameters, referee combustion rigs and modeling-simulation tools to ascertain the impact of fuel on combustion**
  - **Program divided into three phases**
    - **1: Review current evaluation methods, develop conceptual definition of test rigs and detailed program plan**
    - **2: Establishing a test protocol to screen combustion characteristics of fuels**
    - **3: Develop comprehensive evaluation methodology including validated models and tests to ascertain fuel's combustion characteristics**



Phase 1 - Program Accomplishments

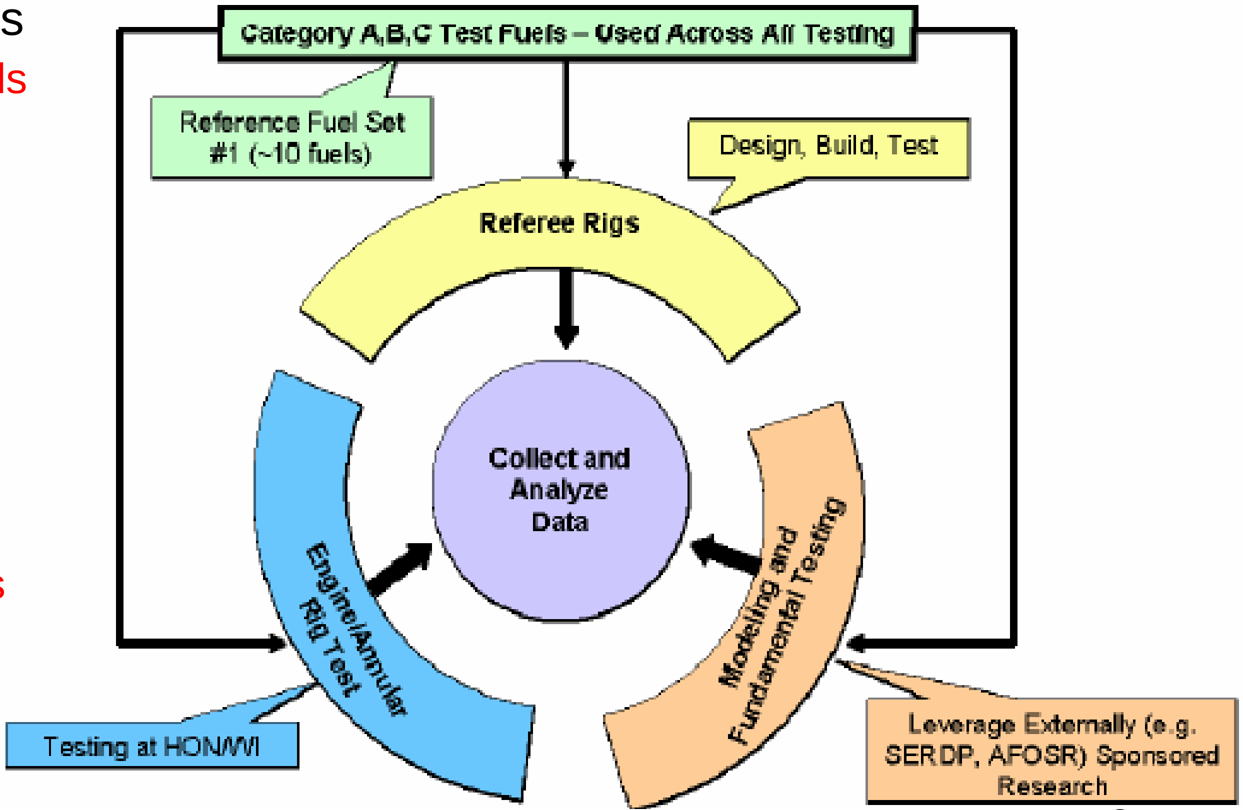
- **Established an integrated working arrangement between all five OEM's**
- **Created reference databases**
  - **Recent OEM fuels testing**
  - **Who's who in fuels**
  - **Test sites and capabilities**
- **Reviewed current fuel evaluation process to identify deficiencies & needs**
- **Developed a methodology/process for fuel evaluation**
  - **Identified and prioritized Combustion Figures of Merit (FOM's)**
  - **Defined a set of non-proprietary 'referee' combustion test articles**
  - **Identified and categorized test fuels to benchmark perfomance in the test articles**
  - **Identified near term modeling tools to support the proposed methodology**
  - **Identified fundamental research needs for longer-term computational modeling and combustion testing for model validation**
- **Developed a multiphase program approach to mature the methodology and provided a first-level of detail of the requirements and program plan for the next phase of the program**

Honeywell
Rolls-Royce
Williams International

Proposed Phase 2 Program

Goal: demonstrate a new evaluation methodology based on generic rig tests, analytical tools and limited engine tests to assess combustion risks associated with alternative fuels.

- Define and procure three categories of reference test fuels
  - See presentation by Tim Edwards
- Design, fabrication, installation and benchmark testing of test articles
  - Covers large and small engines, augmentors and APUs
- Execute and facilitate modeling and fundamental testing activities
  - Including fuels with range of physical and chemical properties
- Develop a Phase 3 plan that would validate the rigs and models developed in Phase 2 with operational engine tests

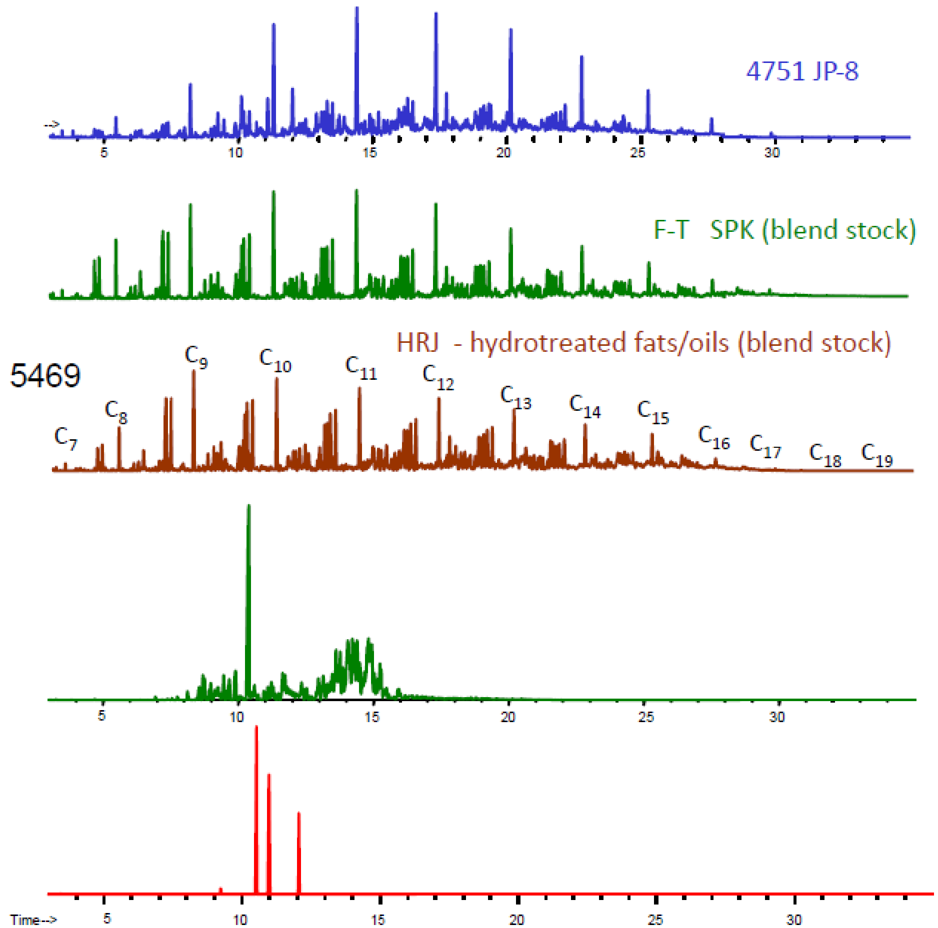


Phase 2 Proposal (White Paper)

- Design and fabrication of referee rigs
- Facility preparation and installation of rigs/engines
- Fuel selection and property tests
- Rig/Engine testing
- Fundamental combustion tests
- Modeling activities

Current Alternative Fuels Environment

- **Fuel requirements are multi-faceted - and may evolve**
- **Minimizing life cycle GHG emissions drives new fuel stocks which look different from JP-8**
  - Fully synthetic fuels are emerging w/ cycloparaffins, synthetic aromatics
  - Future fuel stocks may look radically different (flat distillation curve, unusual isomers)
  - How to quickly assess a fuel which does not look like Jet-A / JP-8 drop-in?



Reference: "Alternative Fuels Strategy and Results", Harrison. CAAFI Overview, September 2009 [2]

Observations from Alternative Fuel Tests in 1970's and 1980's

- Increased hydrogen content led to decreased smoke emissions
- Low power CO and THC emissions dependent on the fuel physical properties or atomization quality
- NOx emissions increased with lower hydrogen content
- Liner temps increased with lower hydrogen content
- Multi-ring aromatics and naphthalene affected smoke emissions
- Fuel nozzle life correlated with breakpoint temperature
- Starting & relight affected by volatility and viscosity
- Little effect of fuel properties on pattern factor or profile

Recent Alternative Fuels Testing

- Recent evaluations mostly limited to FT and HRJ SPK blends
  - CTL and GTL F-T SPKs from several producers (military)
  - Multiple feedstock for HRJ SPKs (commercial)
- Most tests for rich swirl-cup type combustors
  - Some testing on reverse-flow annular combustors and slinger type combustion systems
- Wide range of atomizers evaluated (pressure-type, airblast, hybrid, slinger)
- Range of engine and flight tests
- Figures of Merit evaluated:

Flight Tests
Performance (thrust/power)
Acceleration/deceleration
Restarts (windmill, starter-assisted)
Simulated missed approach
Suction feed test
APU starts

Engine Tests (mostly ground)
Performance
Starts (starter-assist, spool-down)
Acceleration/deceleration for transient operability
Gaseous, particulate, smoke emissions
Acoustics/dynamics/screech/rumble
Augmented/non-augmented performance
Lean blowout margin checks
Endurance test cycles

Indications from Recent Alternative Fuel Tests

- Mixed impact on ignition and lean blowout (LBO) characteristics
- Inconclusive impact on gaseous emissions
- Significant reduction in smoke emissions (lower aromatics)
- No impact on combustor exit temperatures
- Effect on durability not evaluated

Specific Trends Observed

- FT and Bio-SPK/HRJ fuels showed no significant impact on ignition and LBO within operational range
- Bio-Jet showed overall positive impact on ignition and LBO
- JP-900 and DCL fuels and FAME blends (both with high density and viscosity) had mixed impact
  - DCL fuel showed a positive impact on ignition and LBO, contrary to expectations based on physical properties (high viscosity, low volatility), may be due to chemical composition (cyclo-paraffins)
  - FAME fuel blends (down to 20% FAME) showed significant negative impact in ignition and LBO during both component and system level testing
- Bio-SPK1 (high relative viscosity) showed an overall negative impact on LBO
- Some FT SPK blends had low density

Combustion Characteristics

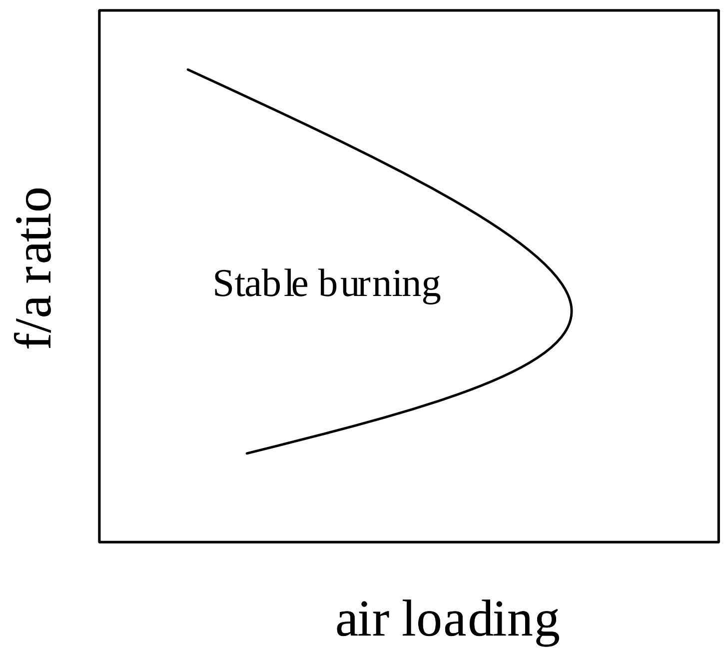
Consensus opinion of OEMs:

- Key properties: the most critical (operationally) and the most likely phenomena to be affected by fuel property variation.
  - Lean Blow Out (LBO)
  - Ignition and relight

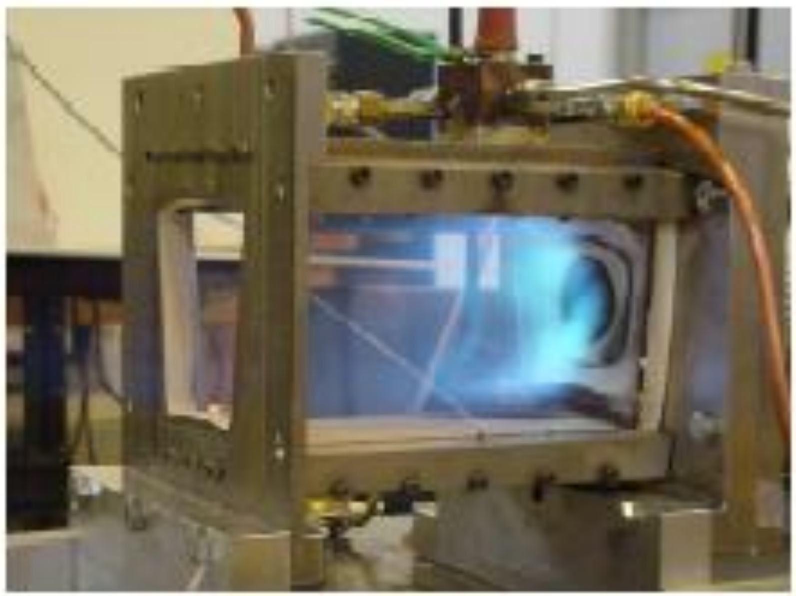
- Other properties to monitor: either are of secondary importance or have little impact on safety/operation
  - e.g., emissions, etc.

Lean Blow Out

- Measurements of lean blow out (LBO) fuel-air ratio (FAR) in combustion systems provide information on stability limits of the combustor.
- Combustor LBO is typically problematical near center of the flight envelope during minimum power decent of throttle chops where combustor FAR reaches a minimum



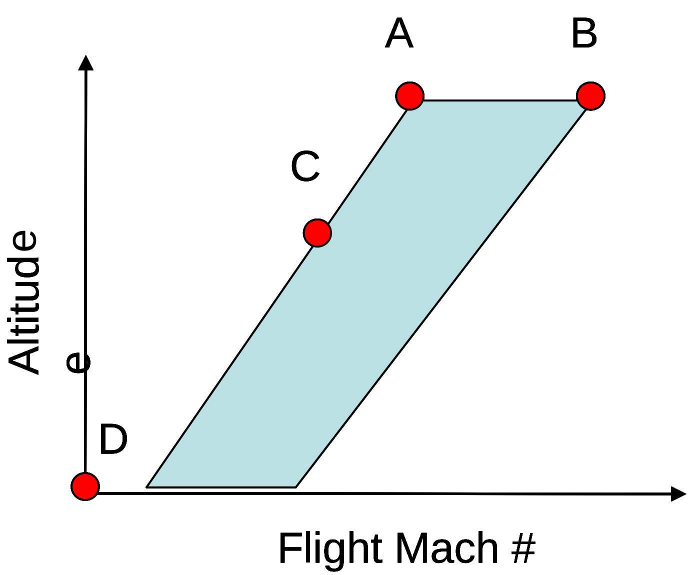
Typical Stability Loop for a Combustion System

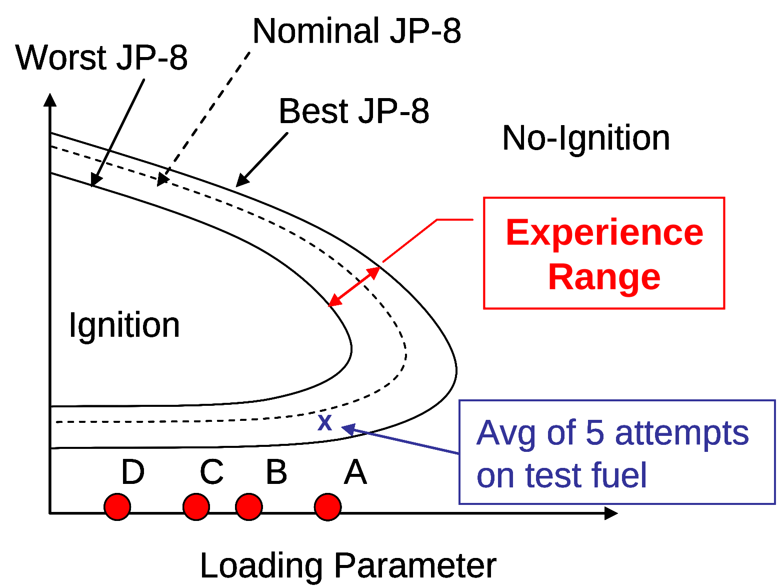


Single-Cup Combustor Rig

Ignition and Relight

- Ignition behavior is typically important for high altitude relight performance (safety issue) and ground starting at cold conditions (reliability issue)
- Figure on left represents areas with the engine operating envelop where ignition / relight are of interest, while the right figure illustrates a typical ignition loop where successful ignition occurs inside the loop
- Correspondence between two is made by appropriate selection of a dependent variable that incorporates most of the relevant differences between points A, B, C and D

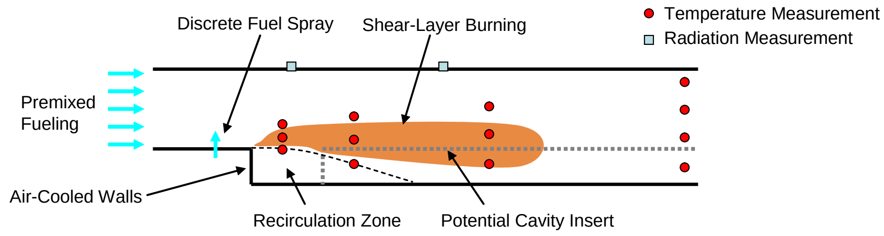




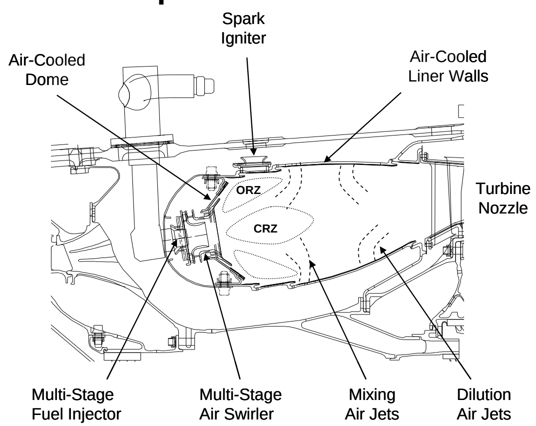
Proposed Test Facilities (6)

Spray rig for initial screening

'2-D' Bluff-body stabilized rig



Swirl-cup stabilized burner

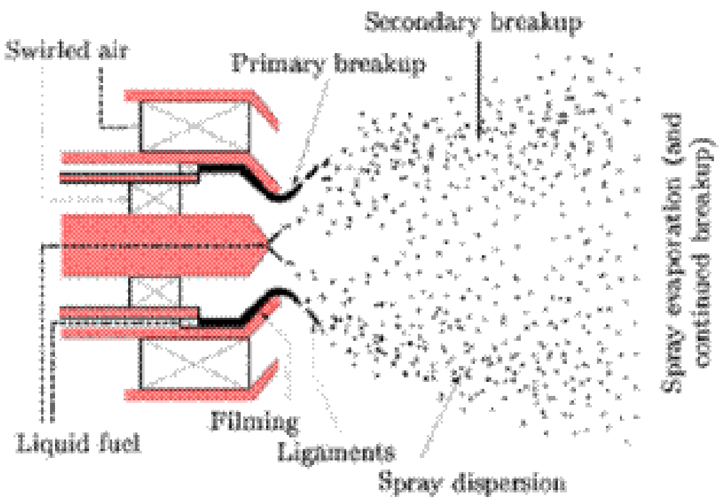


Annular rigs and engines utilizing tangentially-stabilized flames

Modeling to Interpret Rig Results

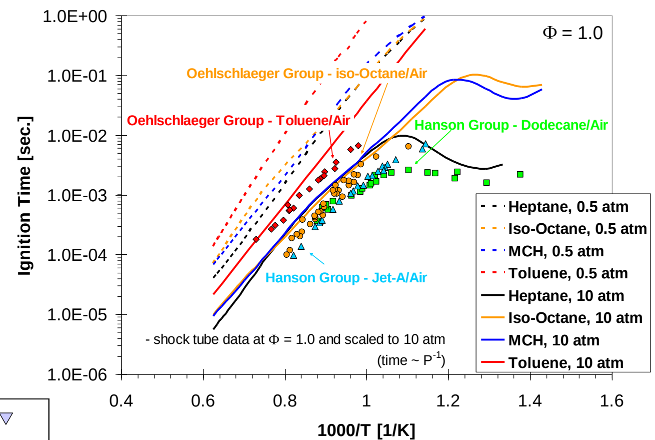
Fuel impacts critical processes:

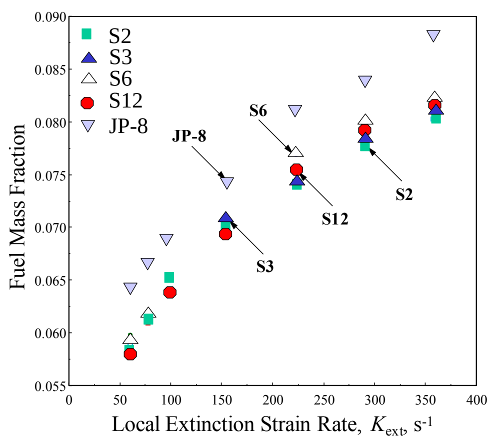
Physical properties: Spray/Vaporization



Fuel Chemistry: Kinetics

Ignition





Flame extinction

Fundamental Test Requirements

Two Categories Identified to Provide Data for Modeling Development

<u>Sub/Super-Atmospheric Spray Measurements</u>

- Spray chamber with optical windows
- Variable Pressure
- Variable Temperature
- Aerodynamic control at windows (fouling, icing, etc.)
- Temperature matching between fuel and air
- Test matrix: 3 fuel injectors, 4 pressure/airflow, 4 temperatures, 5 fuels (including baseline)
- Benchmark testing with MIL-C-7024 calibrating fluid
- Traversing system for PDPA droplet measurements, shadowgraphs, LIF, Mie scattering, PIV

<u>Combustion Characteristics</u>

- Opposed jet-flame burner for extinction strain-rate
- Flame-speed measurements
- Heated shock tube for ignition delay measurements

Fuels (~10):
See presentation by Tim Edwards

Modeling - Strategy

Need underlying physics, validation, and multiple tools, with ***focus on fuel-type effects***

Models for:

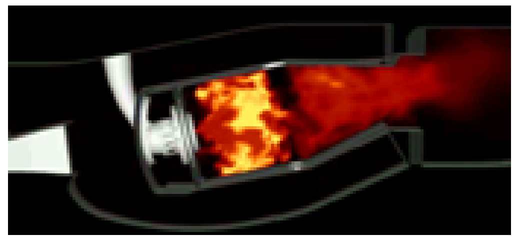
- Spray
- Kinetics
- Altitude Relight
- Lean Blow Off
- Emissions
- Combustion Dynamics

Model Classification:

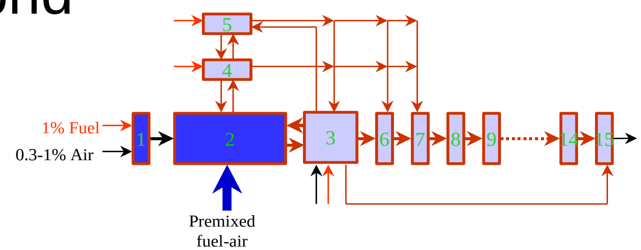
Phenomenological

$$q_{LBO} = \frac{A` \cdot f_{pz} \cdot m_A}{V_c \cdot P_3^{1.3} \cdot \exp(T_3/300)} \cdot \frac{D_r^2}{\lambda_r \cdot LCV_r} \cdot \left[\frac{D \text{ at } T_F}{D \text{ at } 277.5K}\right]^2$$

CFD

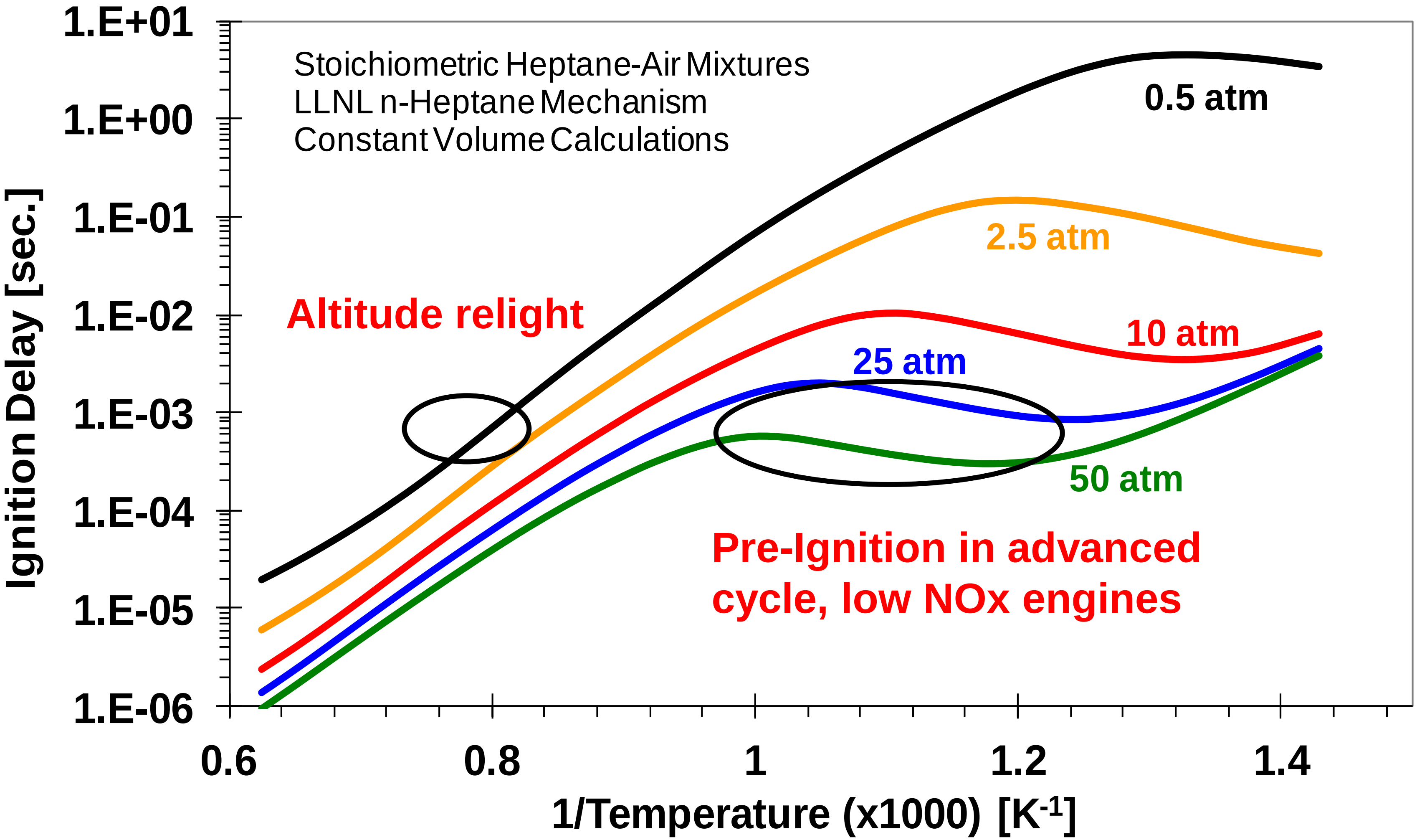


Hybrid



Goal: create validated tool sets that can explain observed fuel effects and, eventually, to predict fuel impact on combustor performance

Example of Needs: Focused Areas for Ignition



Needs from Community to Support Phase 2

Spray modeling
- Practical atomization models
  - Primary/secondary break-up
- Vaporization
  - Dependent on distillation curve
  - Multicomponent

Kinetic characterization of a set of fuels (~10)
- Flame speeds
- Auto-ignition
- Extinction strain rates (pm and non-pm)
- Surrogate definition with kinetics
- Model reduction

Hybrid Modeling
- Demo existing SOA
- Advance capabilities
- Combustion dynamics w/fuel effects

LES/CFD Modeling
- Practical ignition/LBO models
- Incorporation of kinetics/spray models

Closely coupled working/teaming agreements and working relationships will be required

Critical R&D Needs

- Understanding of T5/T10/T50/T90 impact on ignition and blow-off
- Fuel effects on combustion dynamics
- Validation of phenomenological models for post-1990 engines
- Selection of surrogates – for broad range of properties
- Validated chemical kinetics models
- Efficient fuel-dependent sub-models for CFD
- Validated spray models
- Better understanding of aromatic effects
- Fuel-dependent thermal stability models

Summary

- **Comprehensive Phase 2 program plan developed**
- **Expected duration is 3-4 years**
- **Major tasks are: combustor testing, modeling and fundamental testing for screening process development**
- **Close coordination amongst OEMs, universities/small businesses and government agencies will be required**
- **Steering committees will be created to guide Phase 2 work**

Acknowledgements

Project would not have happened without:

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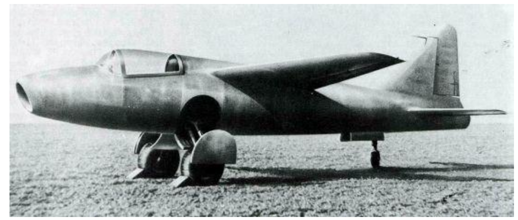
Universal Technology Corporation: Clifford Moses and James Klein

AFRL & DESC for program funding

QUESTIONS?

Jet Fuel History



- Von Ohain (Germany) first turbojet flight on 08/27/39 with Heinkel HE 178 using Aviation Gasoline
- Whittle (England) engine flight on 05/15/41 with Gloster Meteor using Kerosene
- DERD 2482 published in England in 1947 was the first jet fuel specification developed
- JP-1, JP-2, & JP-3 unsuccessful in balancing volatility/freeze point (FP) with availability/cost
- 2 types emerged for US Military in early 50's:
  - JP-4 (MIL-F-5624A, USAF adoption in 1951): wide-cut Naphtha/Kerosene
  - JP-5 (MIL-F-5624B, US NAVY adoption in 1953): high flash point Kerosene
- Commercial adopted DERD 2494 in England (Jet A-1 per ASTM D1655) with –50C FP, and Jet A was specified in US by ASTM D1655 with –40C FP. Jet A-1 FP changed to –47C in late 70's to improve availability/cost
- Several other specialty fuels developed second half of 20th century:
  - JP-6 (MIL-F-25656): low volatility Kerosene developed for XB-70 in 1956
  - JP-7 (MIL-T-38219): low-volatility/high thermal stability, high energy, low sulfur and aromatics Kerosene developed for SR-71 in 1970
  - JP-TS (MIL-T-25524): high thermal stability, low FP non-Kerosene fuel developed for U2 in 1956
- Kerosene-type JP-8 (MIL-DTL-83133) for USAF was developed to primarily improve safety

Reference Fuel Set

- **Category A** reference fuels are motivated by need to characterize fuel effects that are currently acceptable to the fleet within context of property distributions
  - Worst case JP-8 will set the boundary
  - Best case JP-8 will enable validation of proposed screening methodology
  - Nominal JP-8 will further add to our understanding of fuel property effects
- **Category B** reference fuels will provide an opportunity to using fuels in rigs that have recently failed and passed engine-level evaluations
  - Recommendations include FAME (failed) and Sasol fully synthetic fuel (passed)
- **Category C** fuels will provide final check on defined process by testing whether or not it will identify combustion effects due to property variation that is not currently covered by fuel specifications, and to provide data necessary to extend models into these domains

Transitions Costly and Time Consuming

- Changes to baseline jet fuel or certification of new fuels/additive
  - JP-4 to JP-8 (Drastic Change)
    - **Long timeframe (~20 years)**
    - **Very costly…difficult to place an exact $ amount**
    - Many challenges…root cause of leaks never truly determined…aromatics question not answered
  - JP-8+100 (Relatively small change)
    - **Long timeframe (~10 years)**
    - **Costly…estimated at $50M spent by DoD**
    - Cleaning/lack of fouling on aircraft…reduced particulate emissions
    - Challenges: Not being able to take advantage of the increased heat sink, filter disarming
  - 50% FT derived synthetic fuels, ASTM D7566 (Relatively small change)
    - **Relatively less time, but very costly**
    - Only slightly different than Jet-A/JP-8 fuel…"drop-in"
      - Lower specific gravity, lower viscosity and little to no aromatic content
    - Engine manufacturers and industry testing laboratories have evaluated the physical and chemical properties of the synthetic fuel
    - US military has spent 4+ years progressively testing the fuel with its inventory of engines and airframes
    - **Approval of 50:50 HRJ blends expected late 2011**

Technology Gaps and Missing Correlations

- Experimental ignition delay data on both current turbine fuel as well as potential fuels
- Surrogate fuel development and validation
- Type and minimum aromatic content
- Evaluation of minimum density
- More pure and high polycyclic containing materials need to be tested to explore the relationship to soot formation
- Determine what chemical and/or physical property(ies) go with autoignition behavior, fuel reaction rate, and laminar flame speed
- More development of fuel thermal stability prediction from chemical composition
- Determine what chemical and/or physical property(ies) correlate between injector orifice behavior and fuel pressure