Fuel Effects on Combustion

MACCCR Meeting
September 17, 2012

Tim Edwards, AFRL
Aerospace Systems Directorate

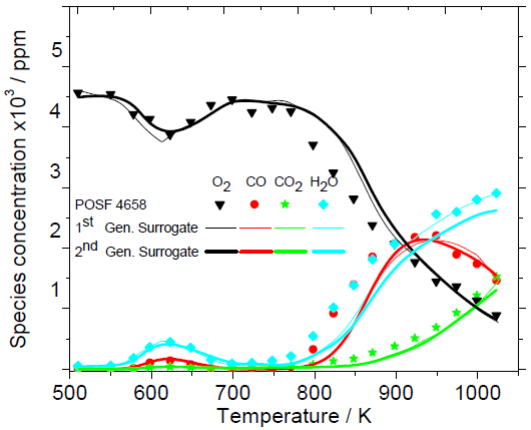
Why Have DOD Labs?

University – Industry Link

Research community

Industry

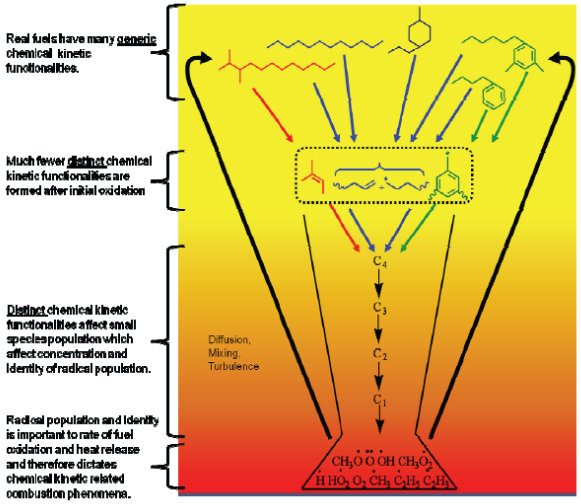
1. Real fuel samples

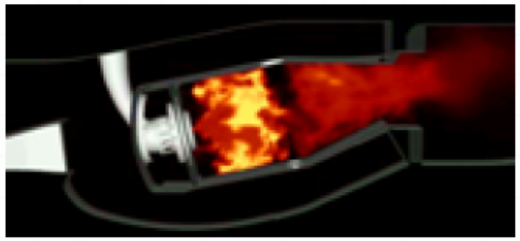


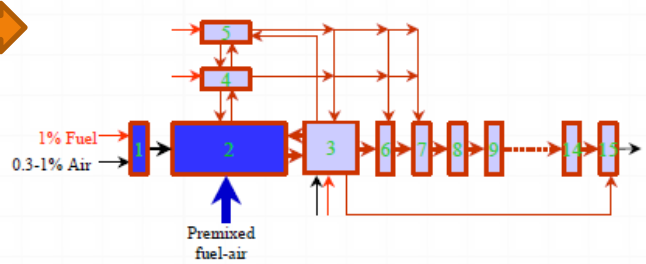
$$\varphi_{LBO} = \left[\frac{f_{pz}}{V_{pz}}\right]\left[\frac{\dot{m}_A}{P_3^{1.3}\exp(T_3/300}\right]\left[\frac{D_0^2}{\lambda_{eff} LCV}\right]$$

Lefebvre [4]

2. Intermediate scale







3. Joint programs!

Alternative Fuels Status

Successes

- SPK approved in 2009, HEFA/HRJ approved in July 2011 in ASTM D7566
- ATJ flight in April 2012 on A-10; joint AF/Navy ATJ RFP released in Aug 2012
- Engine and/or flight tests with other fuels: DSHC, HDCJ, HSK

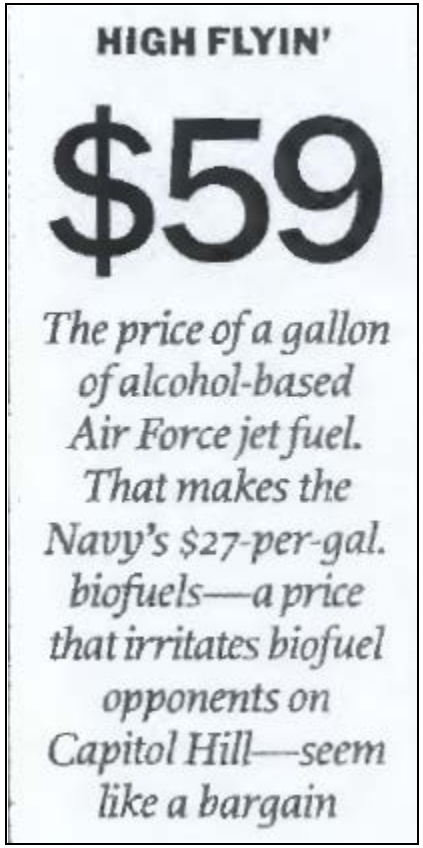
(Wired.com)
May 14, 2012
Republicans Order Navy To Quit Buying Biofuels

How the Navy's Incompetence Sank the 'Green Fleet'
By Noah Shachtman
July 17, 2012

Headwinds

- Cost of fuels becoming an issue – in Congress and in press
- Gov't support of technology development in question

Time, 7/30/12


HIGH FLYIN'

$59

The price of a gallon of alcohol-based Air Force jet fuel. That makes the Navy's $27-per-gal. biofuels—a price that irritates biofuel opponents on Capitol Hill—seem like a bargain

DLA Summary

	Total Gallons	Total Cost	Average Cost per Gallon
Fischer Tropsch	730,000	$2,745,650	$3.76
Hydrotreated Renewable	1,085,450	$41,400,070	$38.14
Alcohol to Jet	11,000	$649,000	$59.00

Operational Facilities

Gevo, Luverne MN, 18 M gal/yr isobutanol

Dynamic Fuels, Geismar LA, 75 M gal/yr

KiOR, Columbus MS, 11 M gal/yr

Amyris, Brazil, 17 M L/yr hydrocarbon

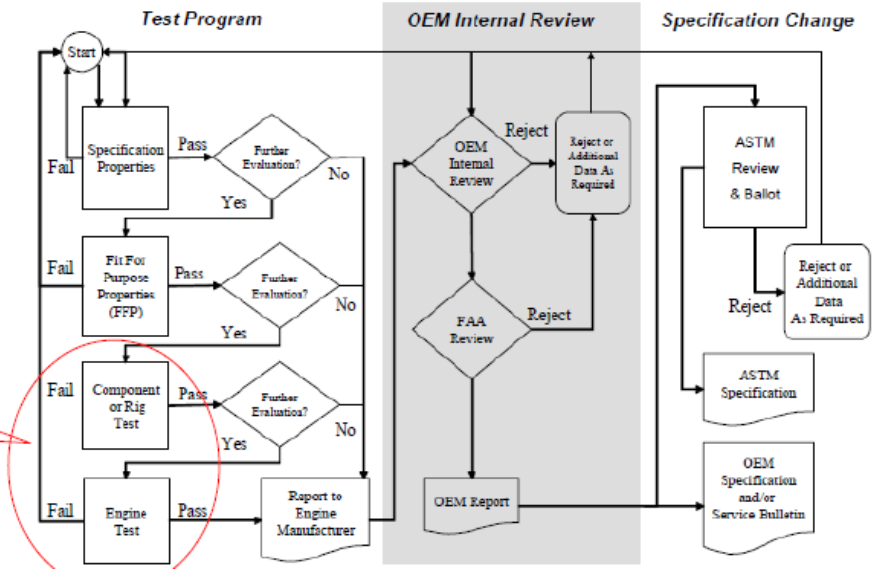
Joint Program #1 – Combustion "Rules and Tools"

Current Certification Process

- Current Certification Process Controlled by ASTM D4054 [5] and MIL-HDBK-510-1 [6]
  - Industry-wide standard
  - Includes fuel specification properties tests, fit-for-purpose properties tests, turbine hot section compatibility tests, combustor performance tests, and full engine tests
- Disadvantages
  - Effective yet expensive, requires large quantities of fuel (estimated at 250K gal), and is very time consuming
    - Evaluation of recent SPK blends took years & millions of $ (ASTM D7566 [2])
  - Required combustor rig and engine testing is listed but the specifics of these tests are not defined
  - Repetitive testing required

Jamey Condevaux, Turbine Engine Technology Symposium, 9/12

Which rigs/engines?



So What?

What is pacing alternative fuels development?

- Alternative aviation fuels
  - F-T fuels from synthesis gas
  - Hydroprocessed fats & oils
  - Alcohol oligomerization
  - Direct fermentation
  - Pyrolysis
  - .....

Very similar to conventional fuels

Potentially very different from conventional fuels

- Past: Fuel was the given; qualified engines and aircraft
- Now: Engine/aircraft are the given; how do we qualify a fuel?
  - Easier when the fuel has properties within experience space
  - Questionable when it doesn't

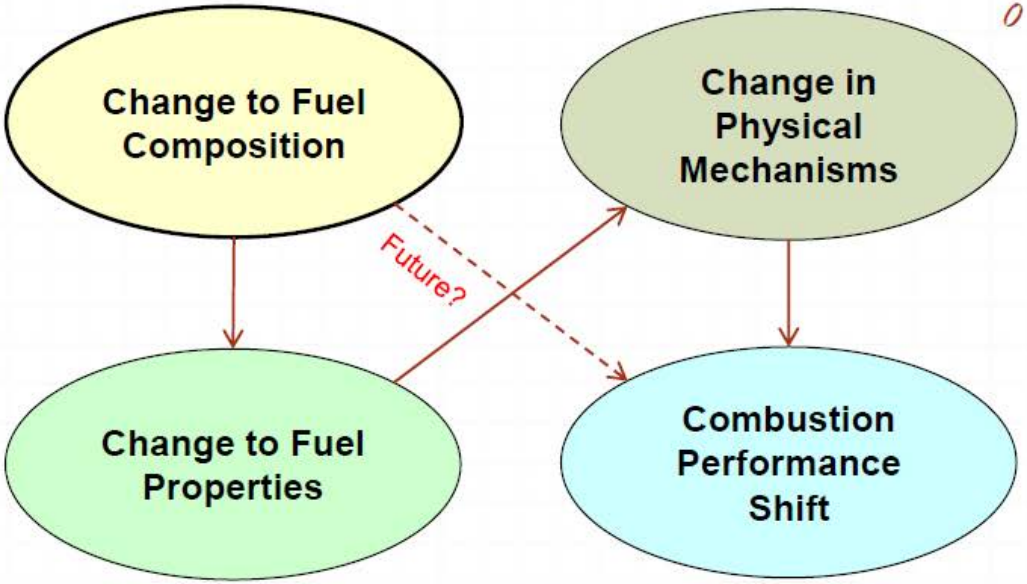
? **How do we qualify fuels outside experience space without sacrificing airworthiness and safety?**

The Key Issue for Alt Fuels….

The Impact of Alt Fuels on Combustion

- Aromatics, cycloparaffins, n- and i-paraffins
- Hydrocarbon chain length

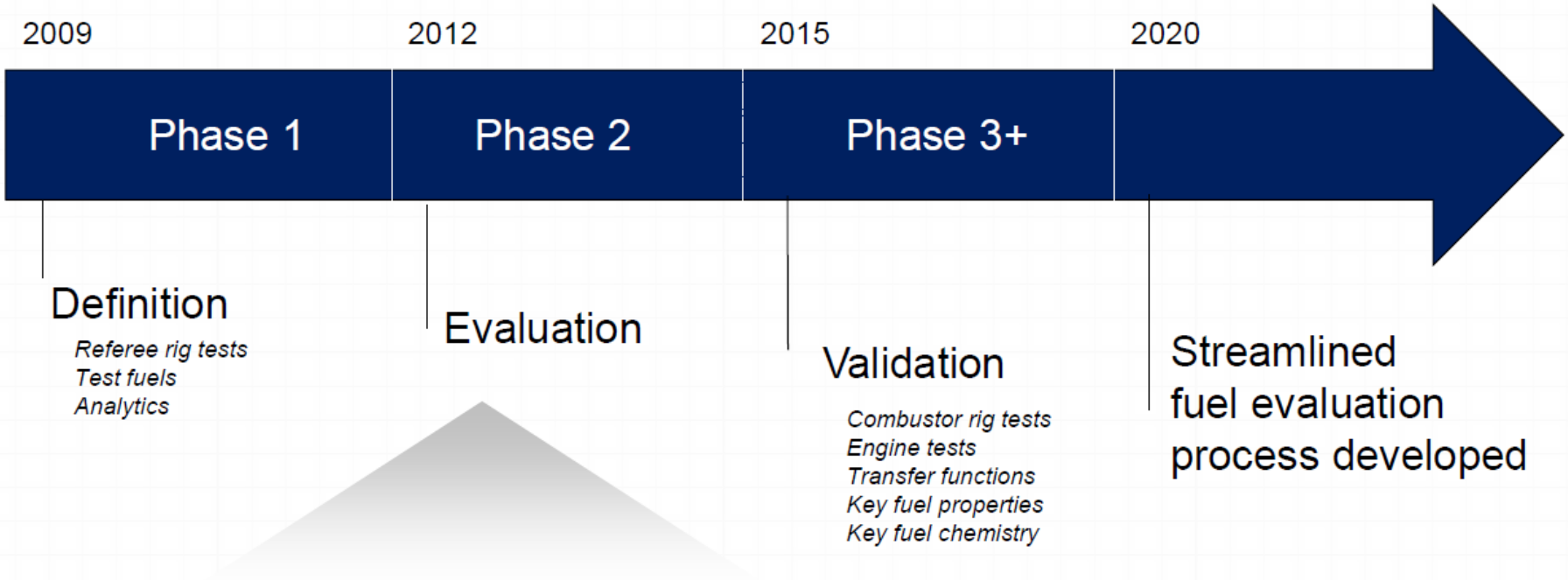
- Density vs T
- Viscosity vs T
- Flash point
- Heat of combustion
- Boiling range
- Vapor pressure
- Surface tension
- Cetane
- …



- Physical mechanisms by which fuels affect combustion:
  - Atomization and Spray Distribution
  - Evaporation
  - Chemical Kinetics
  - …

- Combustion Performance Affected:
  - Lean Blow Out
  - Altitude re-light
  - Combustor Coking
  - Combustor dynamics
  - Emissions / Smoke / PM
  - Pattern Factor
  - Combustor Durability

CRATCAF Vision



- Design, build, and test referee rigs
- Grow models to account for fuel effects

Modeling and Tools Development

- Critical Processes: Atomization, vaporization, fuel-air mixing, chemistry (kinetics), turbulence/chemistry interaction
- Phenomenological models (semi-empirical)
  - Based on physical models of important processes, e.g. atomization, evaporation, mixing, etc…
  - Developed in 70's and 80's; e.g. Lefebvre, Plee, Mellor
  - Successful in correlating fuel effects on wide variety of engines and operating conditions
- CFD models
  - Capture fuel differences and predict effects on combustion issues?
- Need: Better atomization and evaporation sub-models, ignition and LBO transient models, incorporate fuel chemistry
- Hybrid models
  - Combines CFD calculations with reactor network modeling
  - Less computational effort
- Evaluate fuel effects on combustion FOMs in referee rigs
- Basis for transfer functions from referee rigs to full engines

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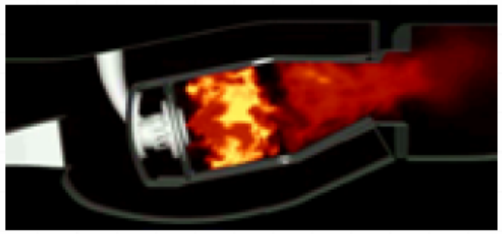
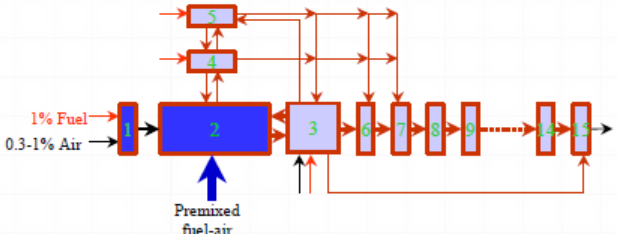
Lefebvre [4]





Reference Fuels

- Category A
  - Define acceptable range of performance of referee rigs
  - Nominal JP-8, “Worst-case” JP-8, “Best-case” JP-8
- Category B
  - Evaluate robustness of rigs and models
  - Alternative fuels already fully evaluated in engines
- Category C
  - Specialty fuels to stress fuel properties anticipated in alternative fuels but not well understood

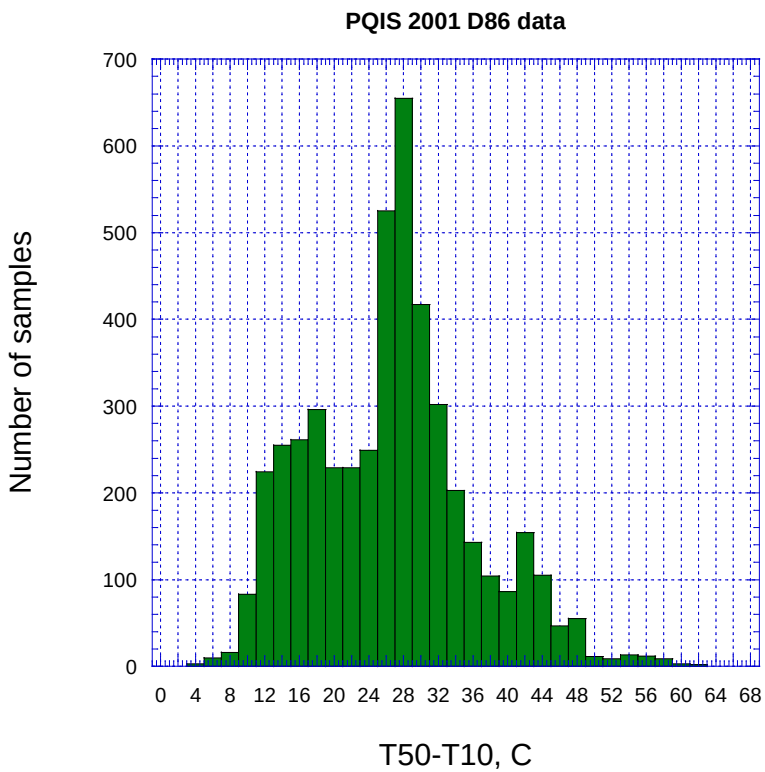
- Narrow boiling range, including single components
- Atypical distribution of hydrocarbon types
- Low/high cetane
- …..

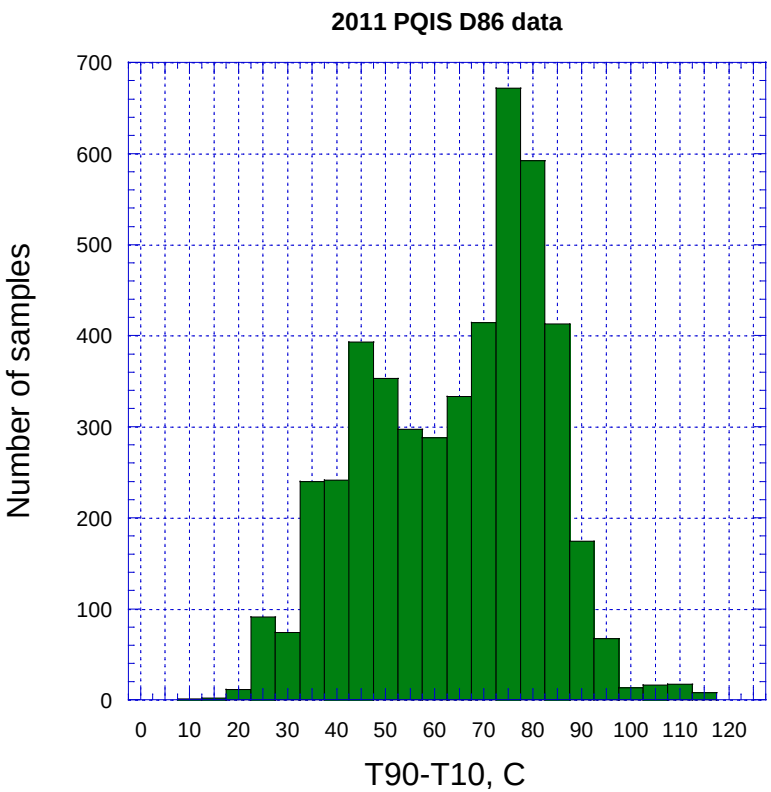
How to Model Reference Fuels?

- **Kinetic model will use surrogate (dodecane/propyl benzene etc.)**
- **Combustor rig and engine will burn "nominal" JP-8 etc.**
- **Disagreements imply:**
  - Kinetic model limitations
  - Surrogate model limitations
- **Ideally would want to run surrogate in combustor rig**
  - $1/mL for some ingredients
- **Solvent surrogates (MURI) offer intermediate step**
  - Model solvent with same surrogate model as JP-8
  - Run solvent surrogate and JP-8 in combustor rig
  - What to match with solvent? DCN, MW, H/C, TSI

Challenge: What is the Experience Base?

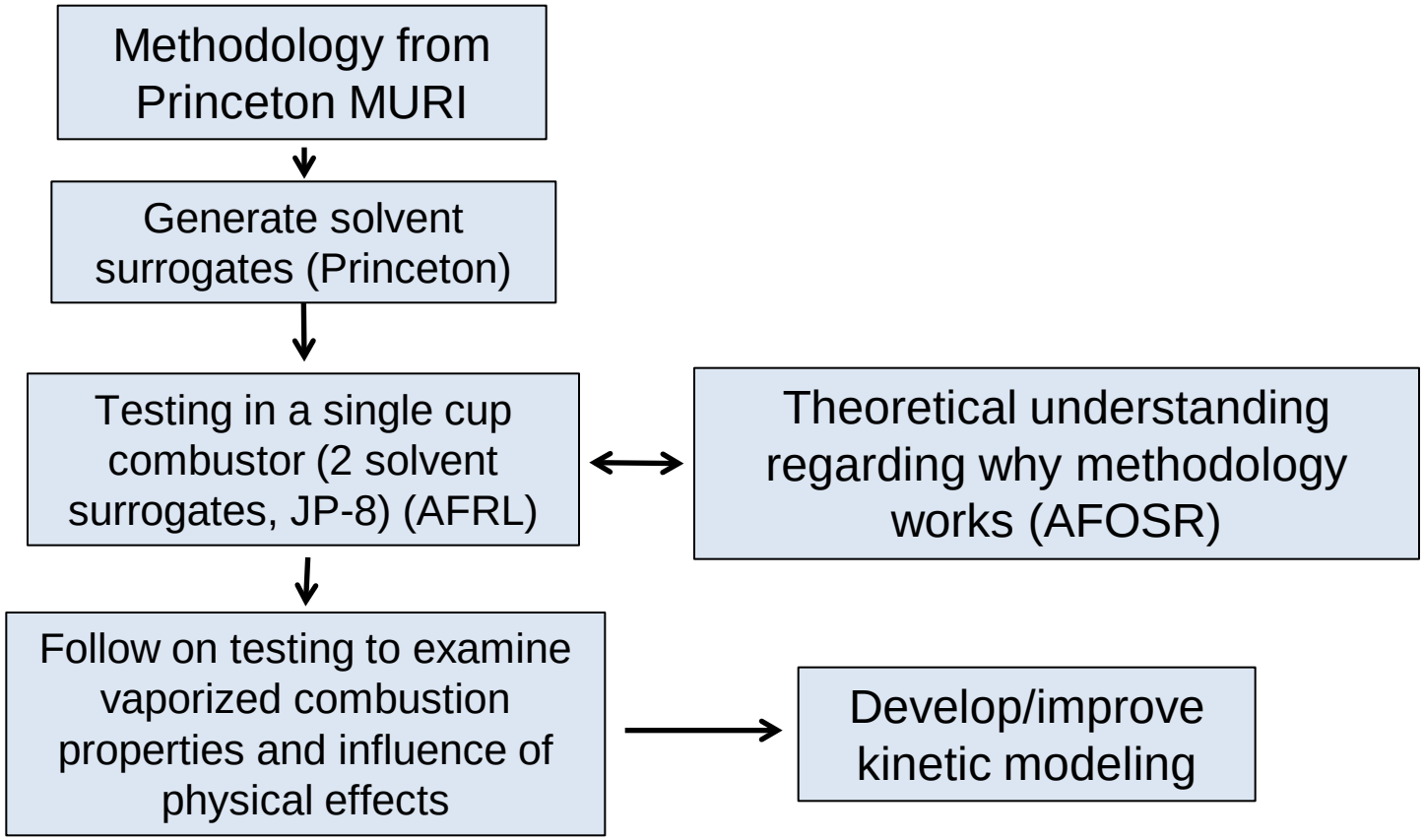
- **All jet fuels are not the same**
- **Alt fuel effects need to be put within context of current experience (assumed to be good!)**





Potential Joint Program #2

- **Pick up MURI methodology and test prior to integration in Rule and Tools program**

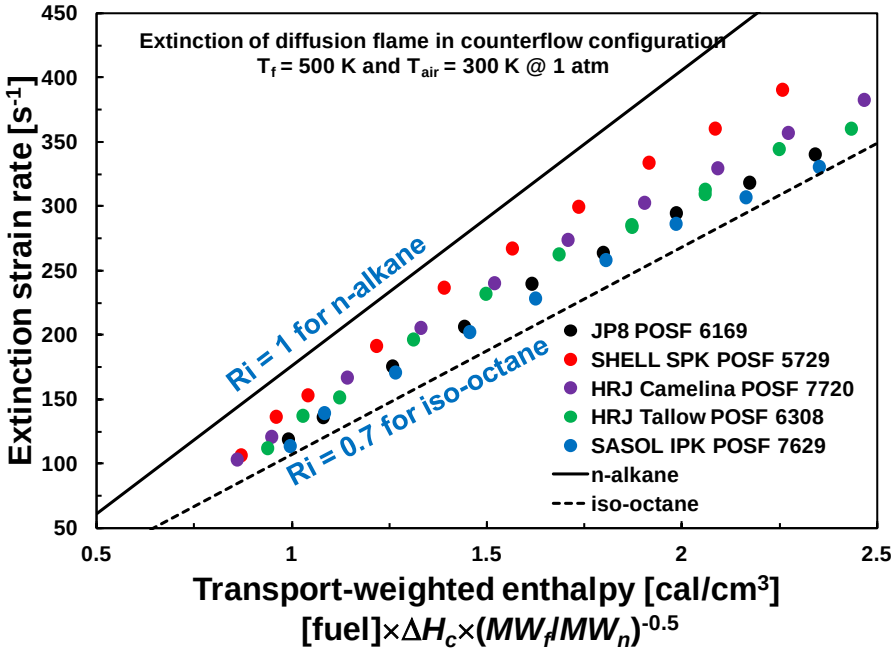


Joint Program #3 – Alt Fuel Effects in Augmentors

- **Funded by Alternative Fuel Certification Office to identify potential augmentor ignition issues**
- **Propulsion Directorate organized fundamental studies at universities to support WPAFB rig analysis**
  - Princeton
  - Stanford
  - CSE
  - ERC
  - Georgia Tech
- **Fuels selected to cover wide range of (anticipated to be relevant) ignition properties – JP-8s, SPK, HRJ, (ATJ), blends**

Example – Princeton Reactivity Study

- **Extinction limits of diffusion flames for pure fuel samples have been completely measured and compared by using TWE**
  - **Heat of combustion, ΔH_c** has been re-estimated based on H/C ratio correlation.
  - Re-evaluation of ΔH_c might be necessary.
- **High temperature reactivity based on Radical index**
  - SPK ≥ HRJ camelina ≥ HRJ Tallow > JP8 ≥ IPK (~iso-octane)
  - Similar order to DCN measurements, IPK must be heavily isomerized.



Fuel	Radical Index	DCN
JP8 POSF 6169	0.78	47.3
SHELL SPK POSF 5729	0.85	58.4
HRJ Camelina POSF 7720	0.82	58.9
HRJ Tallow POSF 6308	0.8	58.1
SASOL IPK POSF 7629	0.76	31.3

Won et al. CNF 159 (2012)

Summary

- **Combustion evaluation of alternative aviation fuels is the “long pole in the tent” at the moment**
- **Key role for MACCCR community is supplying basic research support to this effort**
- **DOD funding picture is looking fairly grim….**