EAR 99 – Non-Proprietary

National Jet Fuels Combustion Program

Initial Results of Alternative Fuel Effects on Combustor Performance: *Lean Blowout and Ignition*

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CAAFI SOAP Jet Webinar

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What is the NJFCP?

Mission:

… to help streamline the fuel approval process…

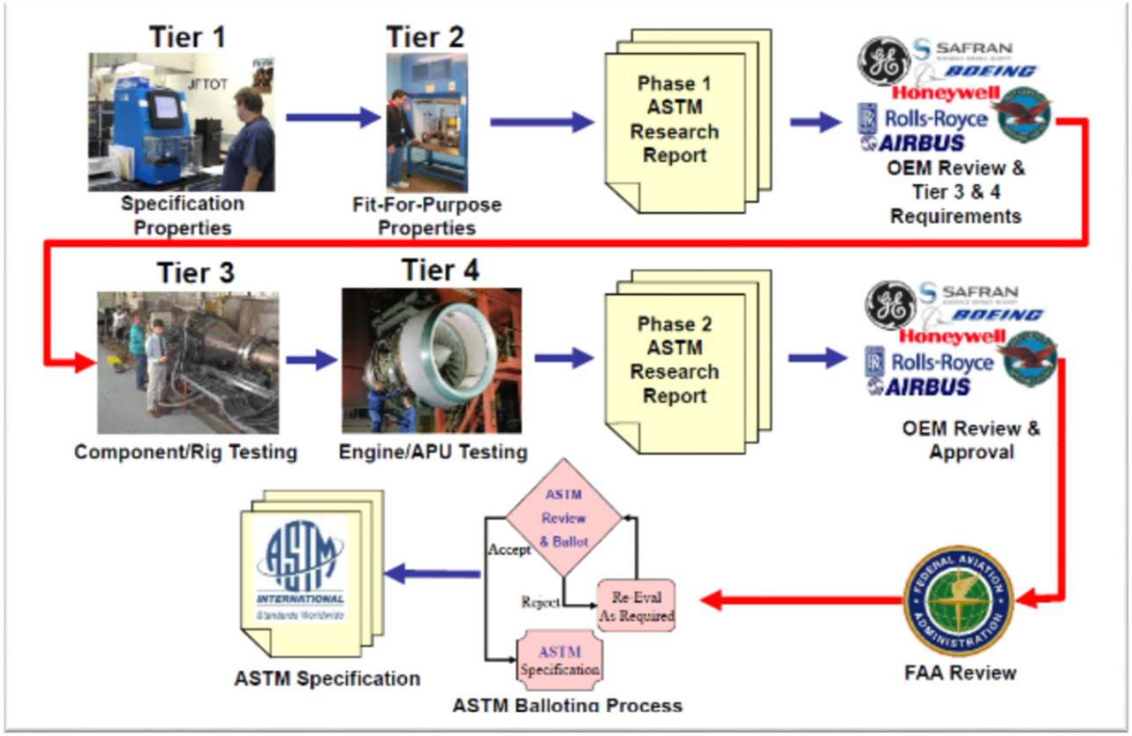
Who:

- 30+ institutions
  - 12 universities
  - 8 gov't agencies
  - 5 OEMs
  - 5+ other research institutes

Funding:

- FAA
- AFRL/AFOSR
- NASA
- DLA
- Air Transport Canada
- European Agencies

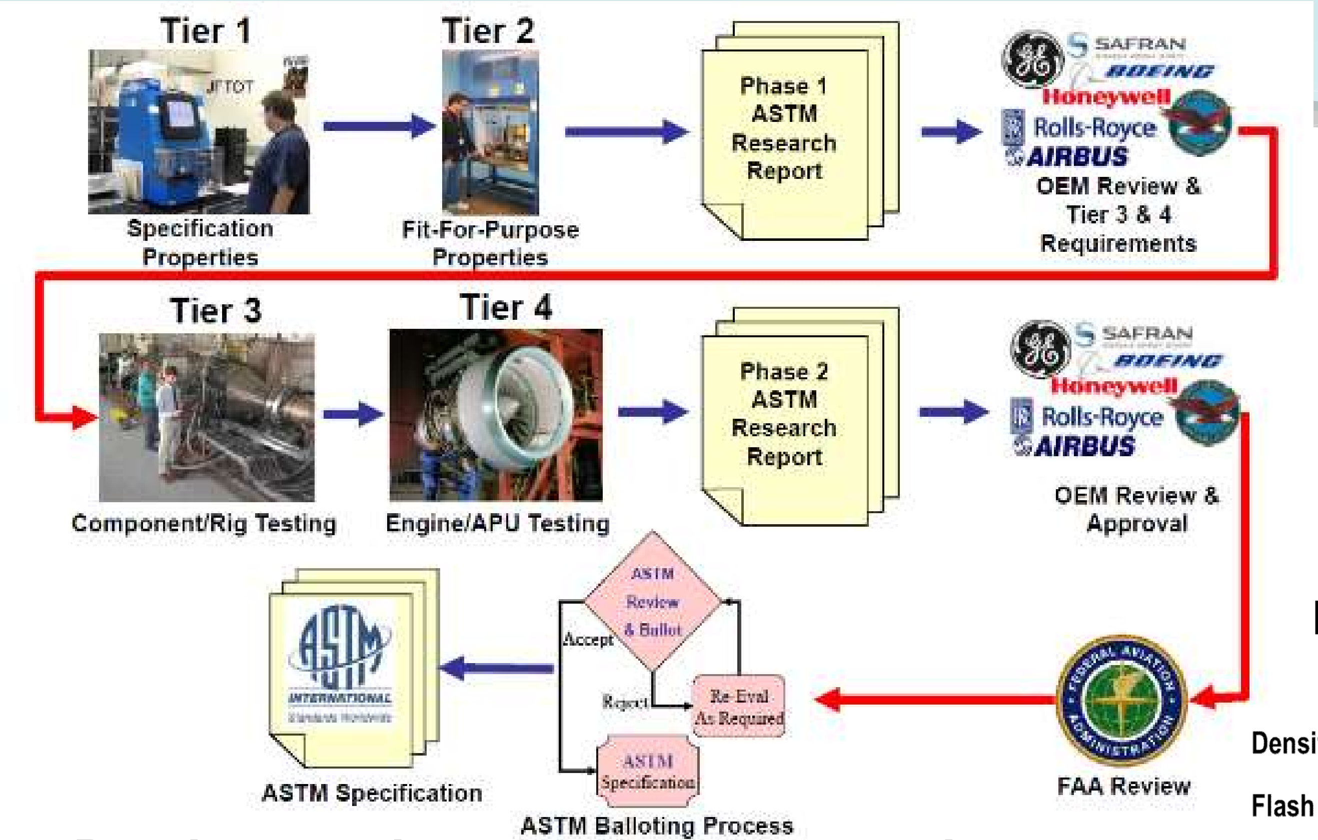
EXISTING ASTM FUEL APPROVAL PROCESS



When:

- Grew out previous AFRL "Rules and Tools" program
- Started in Dec. 2014, entering 4th year

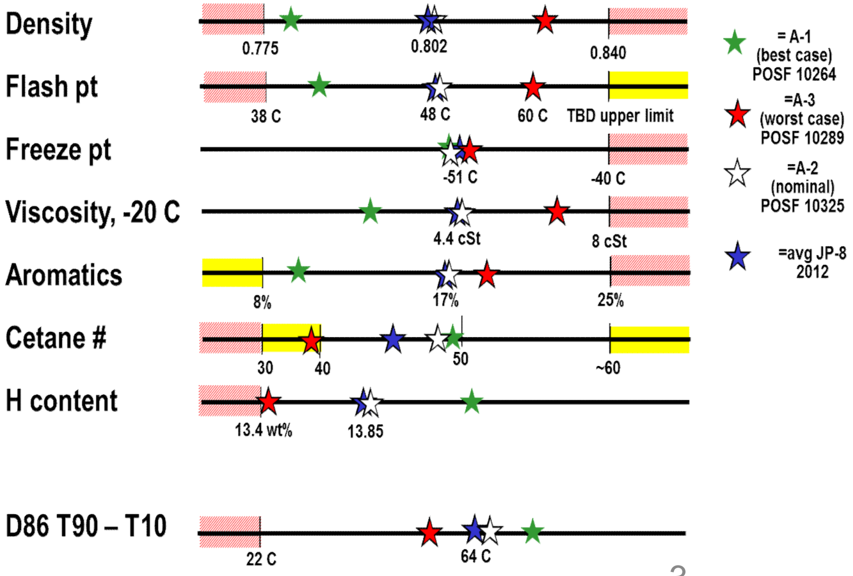
NJFCP's mission to help *Streamline the Current ASTM Fuel Approval Process*



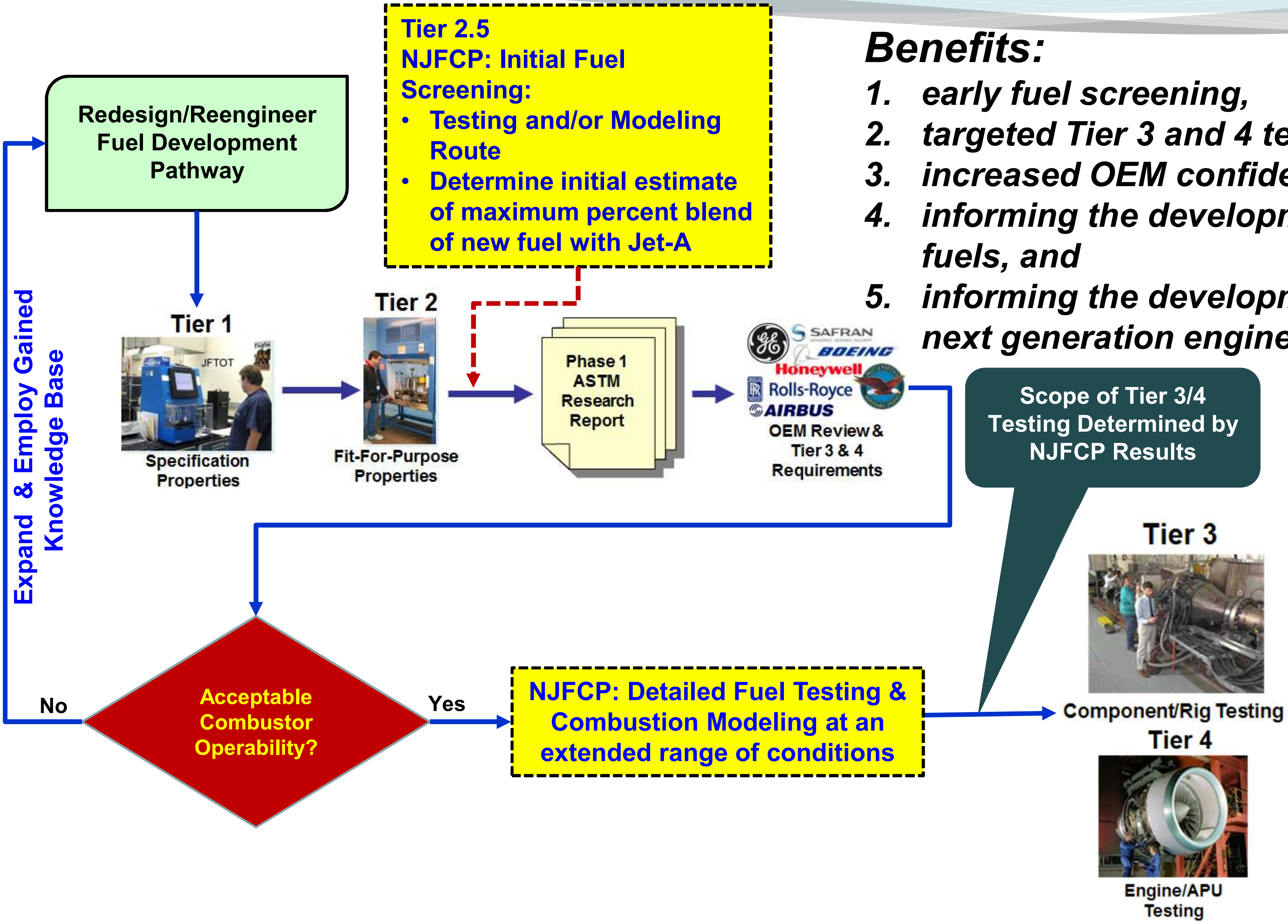
Tier 3/4 testing is critical for evaluating FOMs. Testing costs increase significantly as fuels transition from Tier 1/2 to Tier 3/4 testing performed by the OEMs

- **Previous and near-term approvals have approved *blends* of alternative with conventional at 50% or less to be within the bound of conventional fuel properties.**
- **Long-term approvals could be *fully synthetic* fuels with very different chemical composition and would demand extensive testing and resources**

Properties of interest for jet fuel performance



Improved OEM Screening of Fuels with NJFCP Integration



Redesign/Reengineer Fuel Development Pathway

Tier 2.5
NJFCP: Initial Fuel Screening:

- **Testing and/or Modeling Route**
- **Determine initial estimate of maximum percent blend of new fuel with Jet-A**

Tier 1

Specification Properties

Tier 2

Fit-For-Purpose Properties

Phase 1 ASTM Research Report

OEM Review & Tier 3 & 4 Requirements

Scope of Tier 3/4 Testing Determined by NJFCP Results

Tier 3

Component/Rig Testing

Tier 4

Engine/APU Testing

Expand & Employ Gained Knowledge Base

No

Acceptable Combustor Operability?

Yes

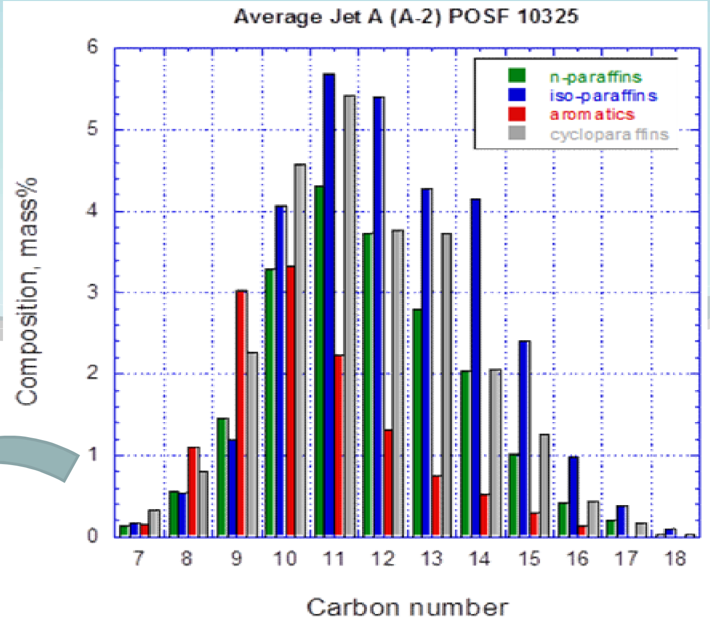
NJFCP: Detailed Fuel Testing & Combustion Modeling at an extended range of conditions

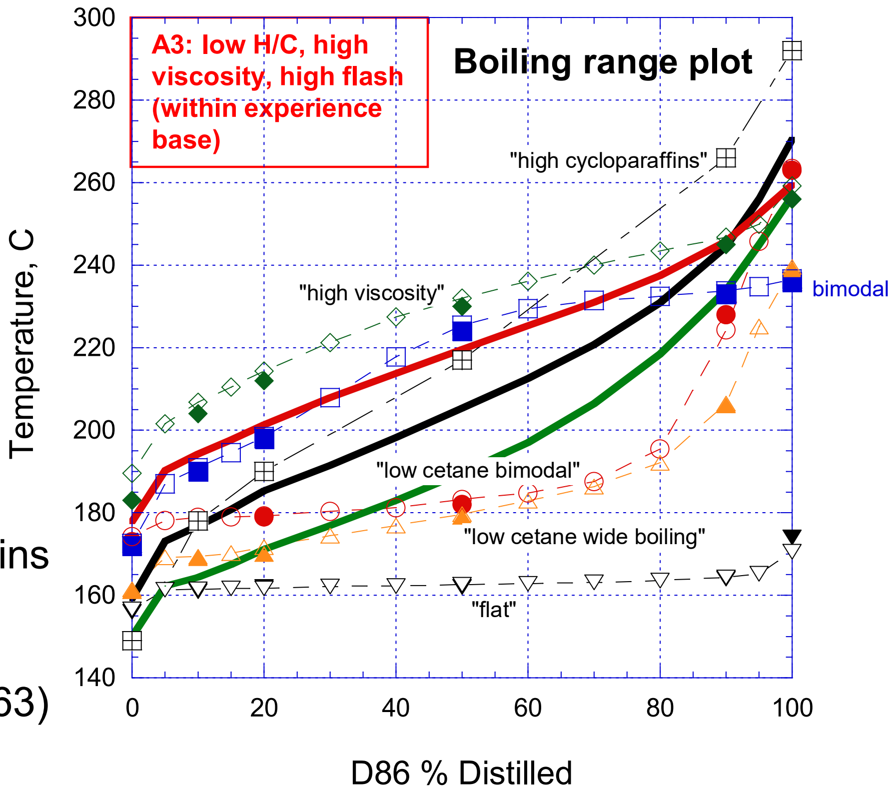
Benefits:

1. ***early fuel screening,***
2. ***targeted Tier 3 and 4 tests,***
3. ***increased OEM confidence,***
4. ***informing the development of alt. fuels, and***
5. ***informing the development of next generation engines.***

Fuel Candidates and Screening

- Reference Fuels Required to Characterize Rig and Engine Fuel Response
- Category A: Three Conventional (Petroleum) Fuels
  - “Best” case (A-1)
  - “Average” (A-2)
  - “Worst” case (A-3)
- Category C: Nine “Test Fluids” With Unusual Properties
  - **C-1: low cetane, narrow boiling (downselected)**
  - C-2: bimodal boiling, aromatic front end
  - C-3: high viscosity
  - C-4: low cetane, wide boiling
  - **C-5: narrow boiling, full fuel (downselected)**
  - **C-6 and C-6a: high cycloparaffins**
  - C-7 – blended fuel with maximum achievable cycloparaffins (~62 vol%)
  - C-8 – blended fuel with maximum aromatics (25 vol%)
  - C-9 – modified alternative fuel that has maximum DCN (63)


Average Jet A (A-2) POSF 10325


Boiling range plot

A3: low H/C, high viscosity, high flash (within experience base)

C-1 and C-5 were selected for detailed study in Year 1.

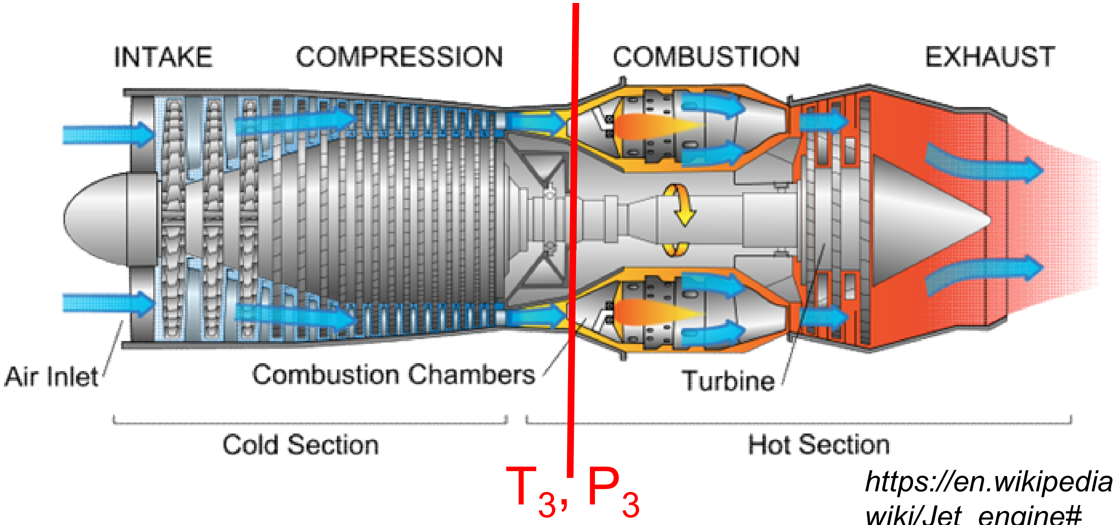
C-6 and C-6a not available

Key Certification Requirements: Fuel Figure of Merit (FOM) Behavior

Fuel property effects are evaluated at relevant conditions to estimate alternative fuel behavior on Figure of Merit (FOM) performance.

- Lean Blowout
- Cold Start Ignition
- Altitude Relight

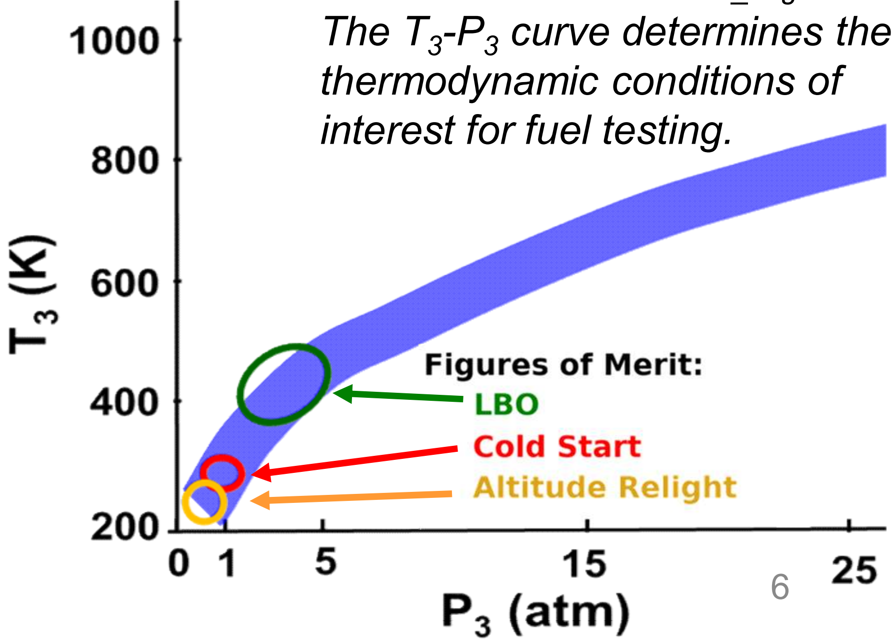
Gas Turbine Engine Schematic



https://en.wikipedia.org/wiki/Jet_engine#

NJFCP Topic Areas for FOM Evaluation:

1. **Lean Blowout (LBO)**
2. **Ignition**
3. Chemical Kinetics
4. Spray
5. Computational Fluid Dynamics (CFD) Modeling
6. Common Format Routine (CFR)



The T_3-P_3 curve determines the thermodynamic conditions of interest for fuel testing.

Current NJFCP Structure with Working Groups

- **LBO**:
  - AFRL/UDRI – Referee Rig
  - AFRL/UDRI – Well-Stirred Reactor
  - Ga. Tech. – High Sheer Rig
  - Univ. of Sheffield – Tay Combustor
  - Univ. of Cambridge – Bluff-body Stabilized Swirl Combustor
  - Honeywell – Auxiliary Power Unit (APU)
  - Oregon State – Turbulent Flame Speed
  - OEMs
- **CFD (OEM Working Group lead)**:
  - Stanford – Modeling Referee Rig
  - Ga. Tech. – Modeling Referee Rig
  - UTRC – Modeling Referee Rig and Ga. Tech. High Sheer Rig
  - Argonne – Referee Rig LBO
  - Univ of Michigan – Forced Ignition
  - OEMs
- **Kinetics**:
  - Stanford – Shock Tube ignition delays and species profiles
  - Stanford – HyChem kinetic modeling
  - UConn – Chemistry reduction
  - OEMs
- **Ignition (OEM Working Group lead)**:
  - AFRL/UDRI – Referee Rig
  - Ga. Tech. – Forced Ignition Rig
  - ARL/UIUC – Altitude testing of Referee Rig Swirler/nozzle
  - NRC Canada – Altitude testing of Microturbo TRS-18
  - Honeywell – APU
  - Univ. of Cambridge – Bluff-body Partially Prevaporized flow rig
  - University of Michigan – Forced ignition modeling
  - OEMs
- **Common Format Routine, CFR (OEM Working Group lead):**
  - UDRI
  - Stanford – Flamelet Models
  - Ga. Tech – LESLIE Code
  - OEMs
- **Sprays (OEM Working Group lead)**:
  - Purdue – Rules and Tools Rig with Referee Rig Swirler and nozzle
  - NRC Canada – Referee Rig Nozzle
  - Honeywell – Altitude Spray Rig
  - OEMs

Executive Summary

Lean Blowout (key certification criteria):

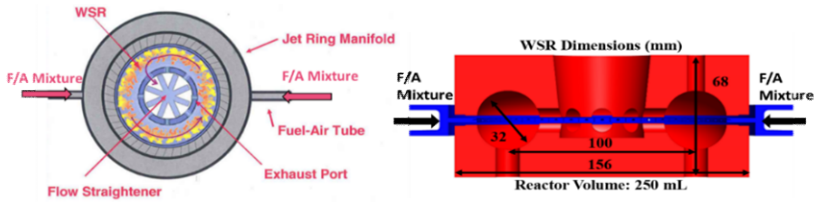
- For most rigs, Lean Blowout (LBO) was found to correlate with DCN (new result relative to prior studies)
  - OEMs have identified this as a major NJFCP benefit
  - Evidence obtained explaining link of autoignition to LBO
- Fuels with low vapor pressure and high viscosities are observed to exhibit deleterious LBO behaviour.
- CFD Teams are iterating towards predicting Lean Blowout trends for selected NJFCP fuels.
- CFD combustion model developed into OEM common format routine (CFR) for alternative jet fuel evaluation in OEM hardware.
- Progress achieved connecting fundamental shock tube results to test rig Lean Blowout results.

Ignition (key certification criteria):

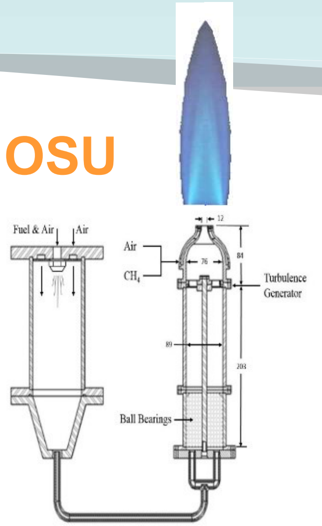
- Initial fuel screening at relevant conditions suggests that high initial distillation temperatures and properties associated with poor spray atomization lead to deleterious performance.
- Initial NJFCP results are consistent with prior experimental studies

LBO Rigs

AFRL/UDRI

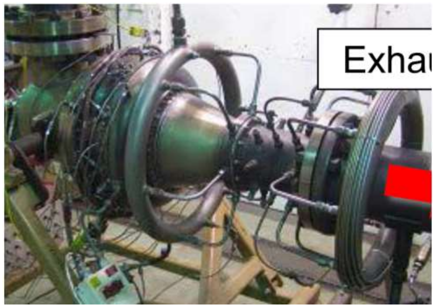


OSU



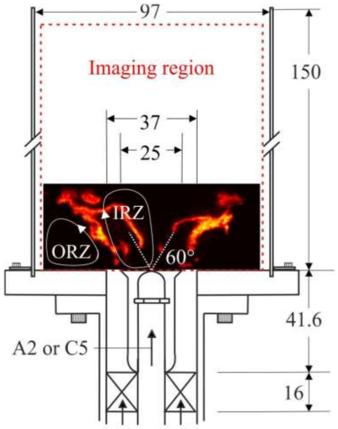
NASA

Honeywell



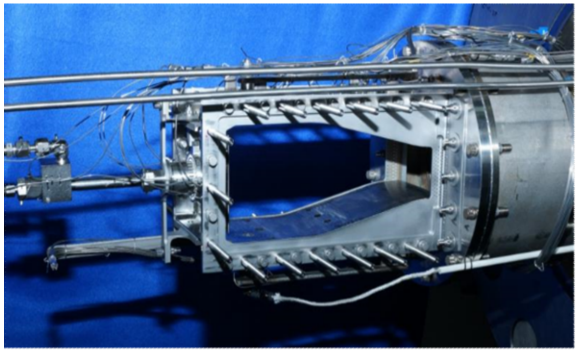
More fundamental

More "Product-like"

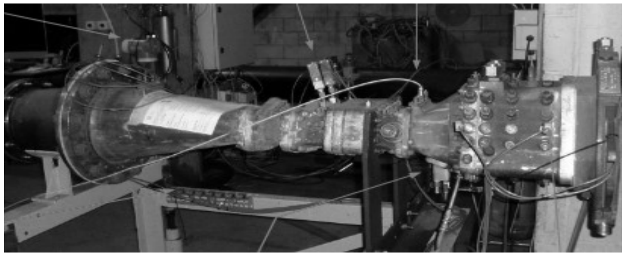


Univ. of Cambridge

Georgia Tech

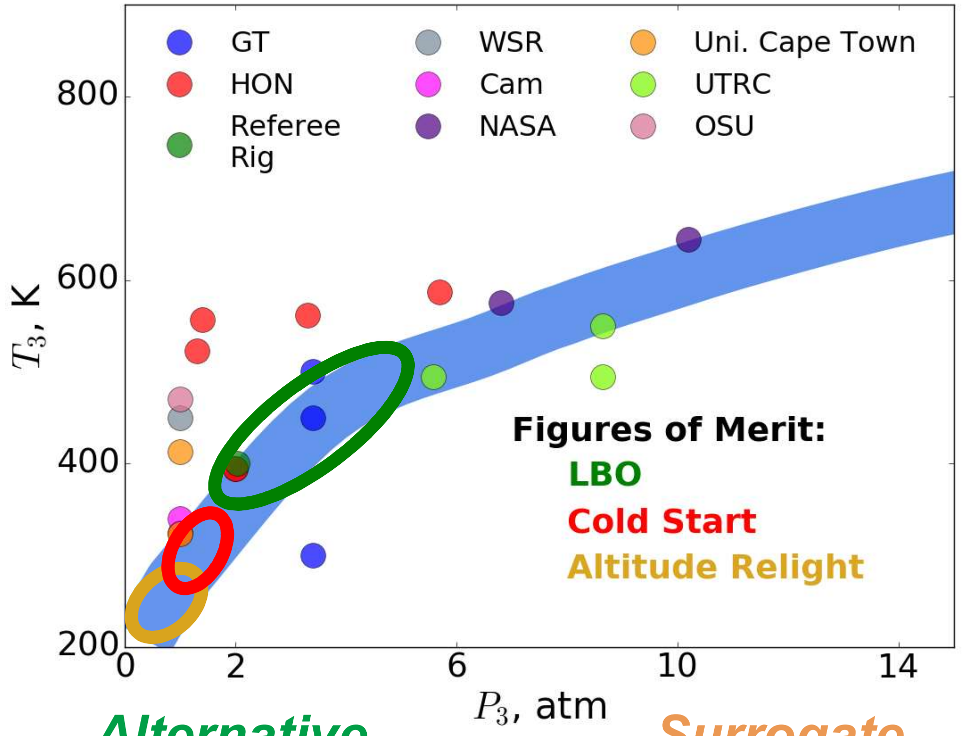


AFRL/UDRI Referee Rig



Univ. Sheffield

LBO: Rig Conditions and Fuels Tested

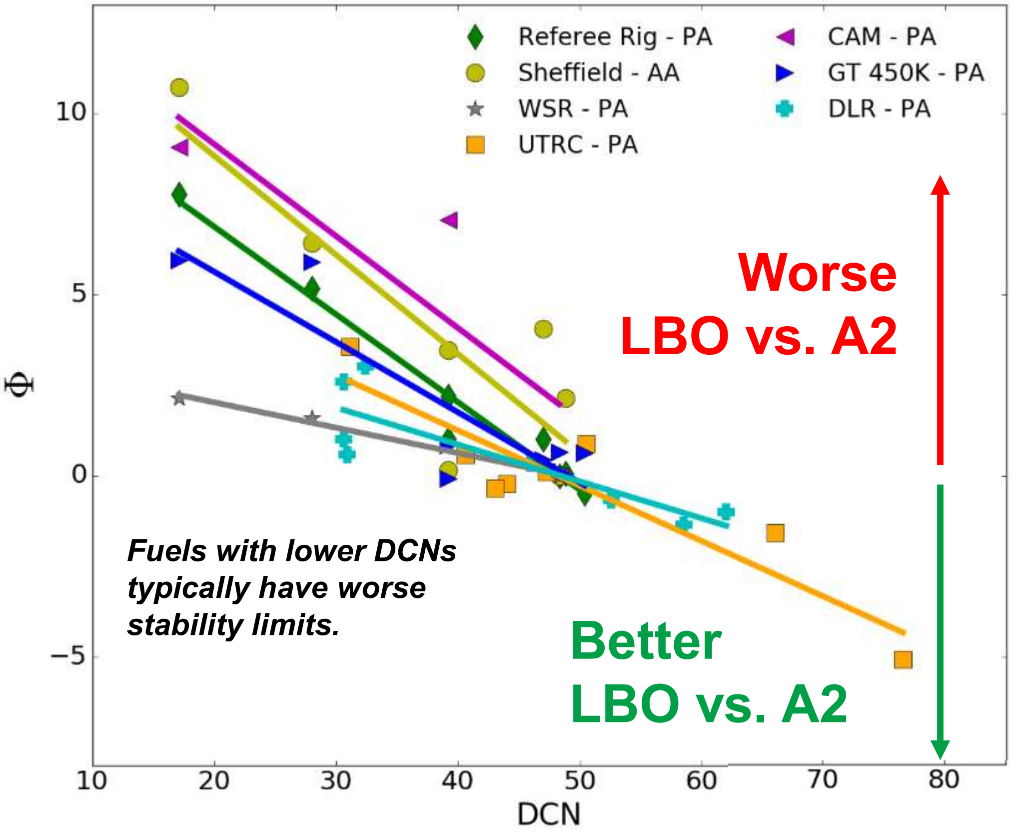


The blue shaded region is the typical flight envelop. Only LBO points are plotted.

	Conventional Fuels				*Alternative Fuels*							*Surrogate Fuels*		
	A-1	**A-2**	**A-3**	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-7**	**C-8**	**C-9**	**S-1**	**S-2**	**nC12**
GT	x	x	x	x	x	X	X	x	x	x	x	x	x	x
Honeywell	x	x	x	x	x			x						
Referee Rig	x	x	x	x	x	X	X	x	x	x	x	x	x	x
WSR		x	x	x			X	x						x
NASA		x		x		X								
Sheffield	x	x	x	x		X	x	x						
Oregon State		x		x				x						
Cambridge		x		x				x						
Univ. Cape Town/ Sasol (via DLR Ger.)	Crude-derived Jet A-1,Jet A-1 + 50% n-dodecane, FSJF (certification), FSJF (commercial), FSJF (commercial) + 1.5% HCPP, Experimental GTL kerosene, Synthetic paraffinic kerosene (SPK), Heavy naphtha refinery stream													

LBO Results

9 of 10 rigs that examine LBO limits show first order DCN dependence.



Worse LBO vs. A2

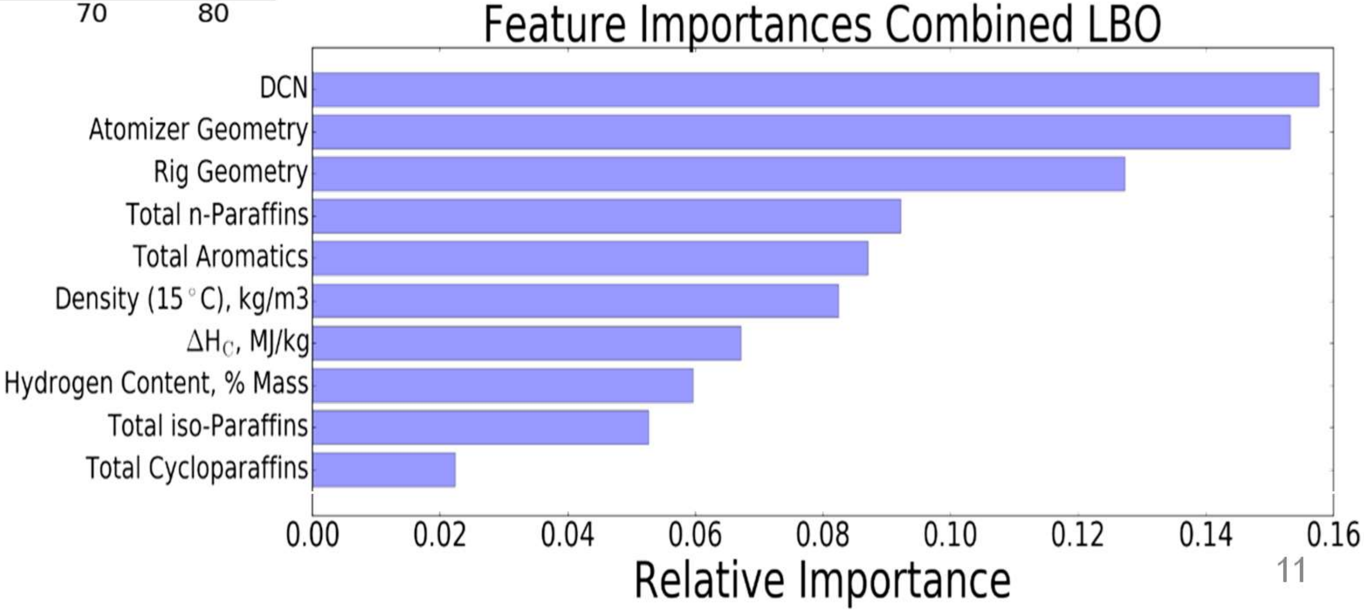
Better LBO vs. A2

Fuels with lower DCNs typically have worse stability limits.

LBO is the lower equivalence ratio stability limit. Equivalence ratios lower than this do not sustain a stable flame.

$$\phi = \frac{F/A}{F/A|_{stoic}}$$

Random Forest Regression Analysis show that the derived cetane number, DCN, of a fuel is the best predictor of the stability limit of a fuel.

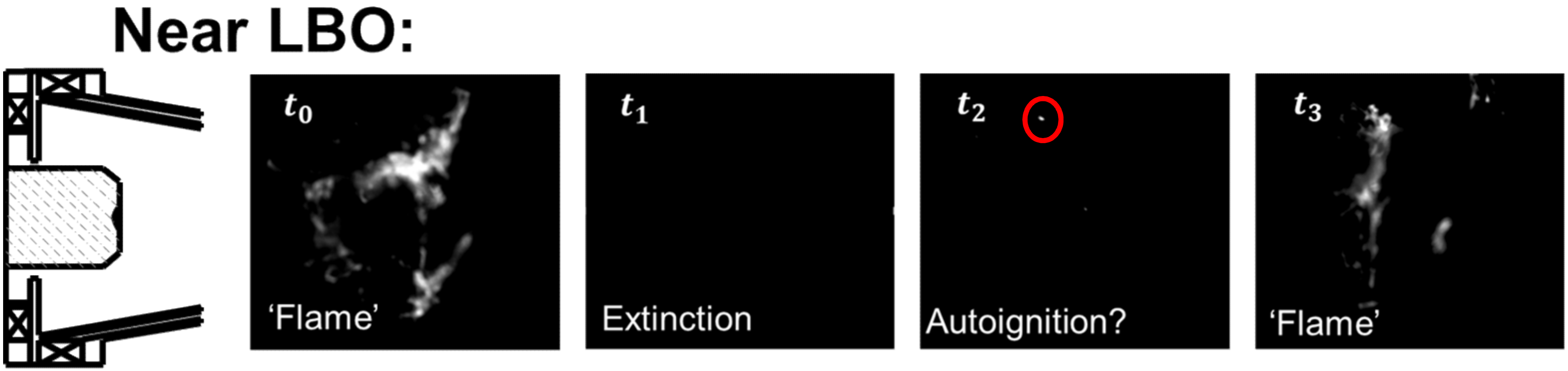


High Speed Videos Near LBO

Supports autoignition as key to LBO limits

Chemiluminescence videos in the GT LBO Rig

- Light colored areas indicate reactions, and dark regions imply no reactivity.
- Flow rates for fuel and air are constant for each screen capture.



Extinction appears to occur followed by autoignition, which corroborates the strong DCN correlation.

Chemiluminescence imaging: short pass filter at 665 nm cutoff

Chtev, I., Rock, N., Ek, H., Smith, T., Emerson, B., Nobel, D. R., Seitzman, J., Lieuwen, T., Mayhew, E., Lee, T., Jiang, N., and Roy, S., "Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels," *55th AIAA Aerospace Sciences Meeting*, Grapevine, TX: American Institute of Aeronautics and Astronautics, 2017.

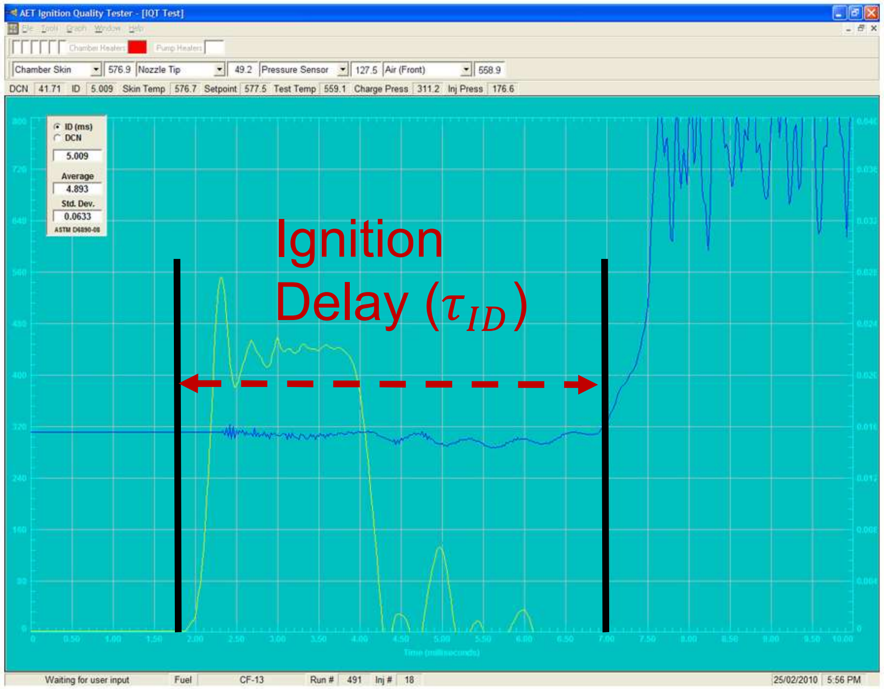
What is the DCN?

The CETANE NUMBER is *the propensity of a fuel to autoignite…*

… nominally it is the inverse of the OCTANE NUMBER, which is *the inhibition of a fuel to autoignite.*

Related Cetane Tests:

- Cetane Number (CN)
  - ASTM D613
- Derived Cetane Number (**DCN**)
  - ASTM D6890
  - Others as well


AET Ignition Quality Tester - [IQT Test]

Chamber Skin 576.9 Nozzle Tip 49.2 Pressure Sensor 127.5 Air (Front) 558.9

DCN 41.71 ID 5.009 Skin Temp 576.7 Setpoint 577.5 Test Temp 559.1 Charge Press 311.2 Inj Press 176.6

● ID (ms)
○ DCN
5.009
Average
4.893
Std. Dev.
0.0633
ASTM D6890-08

Waiting for user input Fuel CF-13 Run # 491 Inj # 18 25/02/2010 5:56 PM

Ignition Delay (τ_{ID})

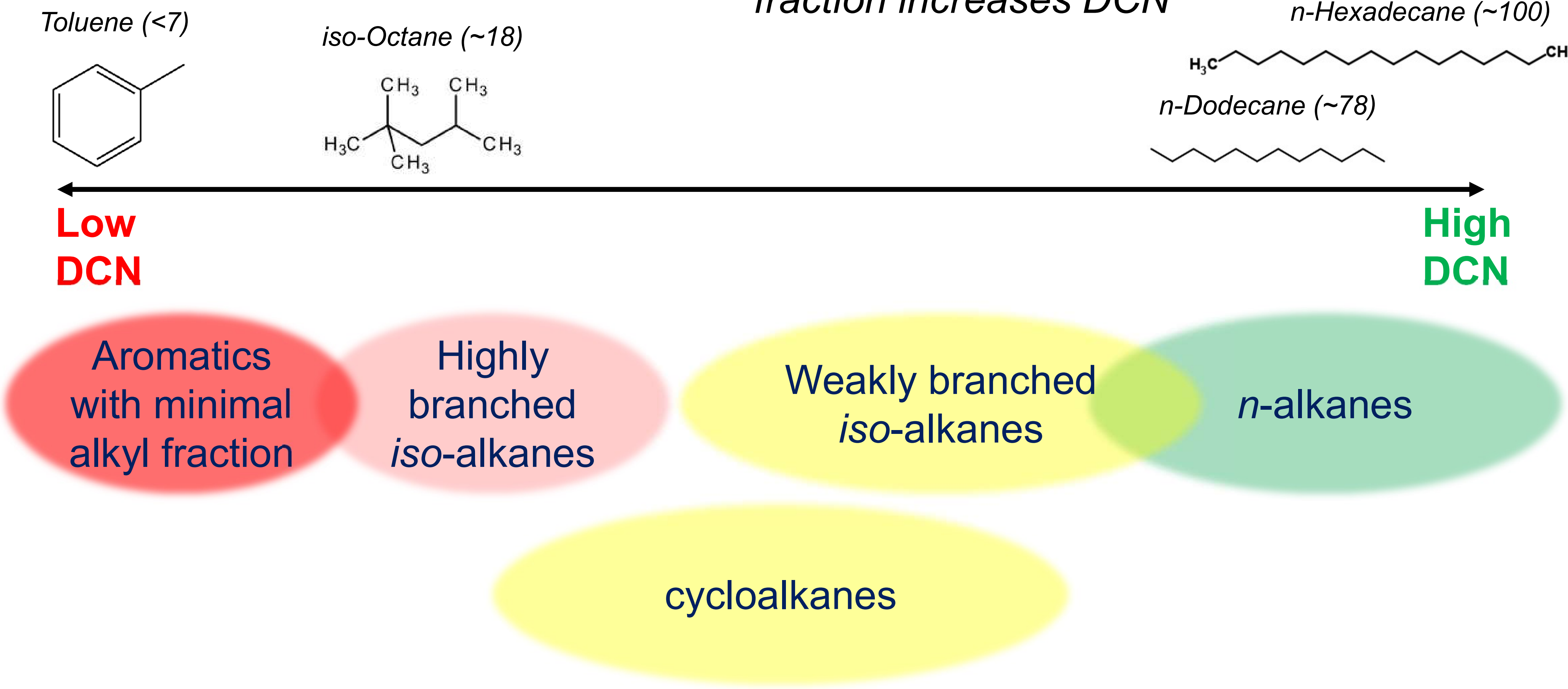
Ignition Quality Tester (IQT™) from AET

$$\mathrm{DCN} = f(\tau_{ID})$$

Applying DCN to AJF Blends

Molecular structure effects the DCN of a fuel

Increasing n-alkane (-CH_2-) fraction increases DCN



LBO CFD

Fuel dependent LBO is still to be demonstrated, but consistent spray and boundary conditions have been developed.

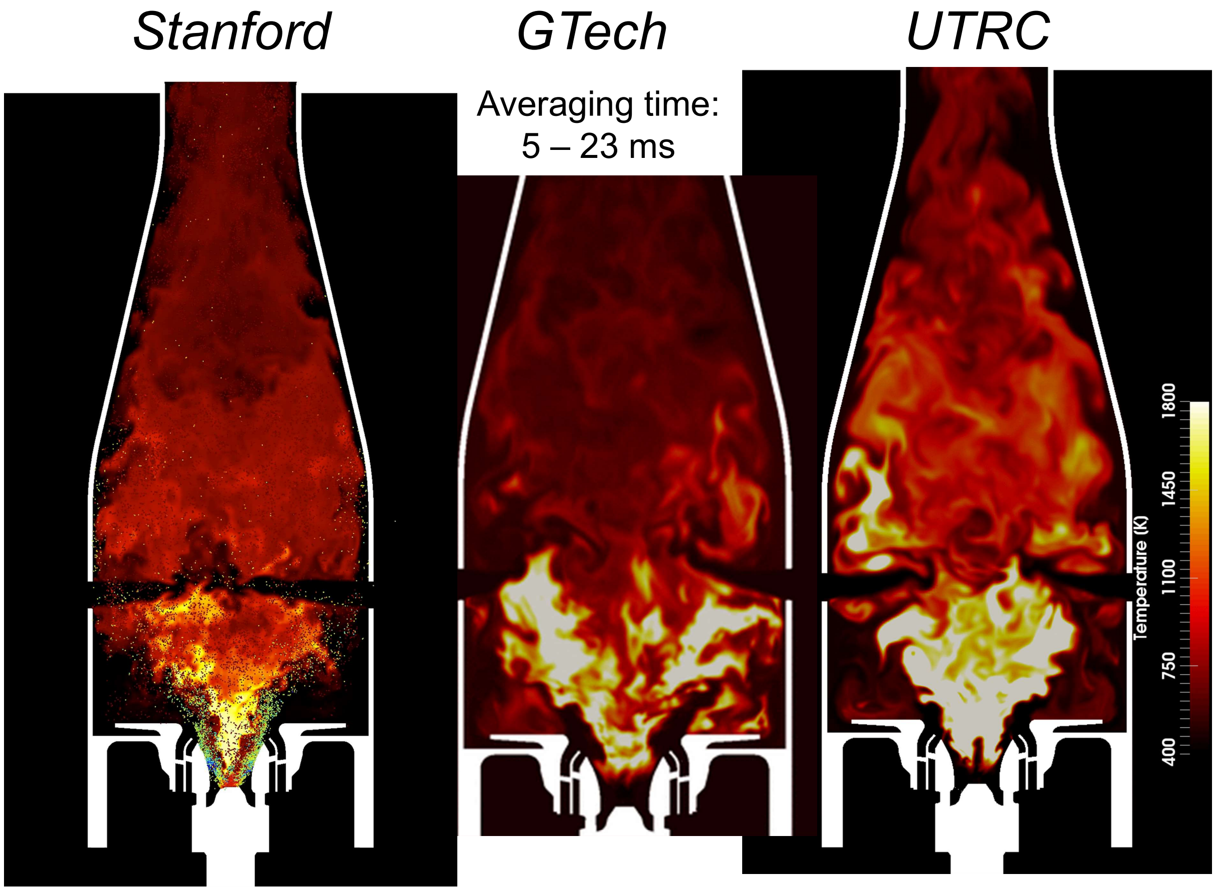
Near LBO simulations:

- Flame stabilization at near LBO condition demonstrated to be strongly dependent on spray injection and evaporation by the 3 teams which use different turbulent combustion and chemical modeling approaches.

Approach to LBO simulations status

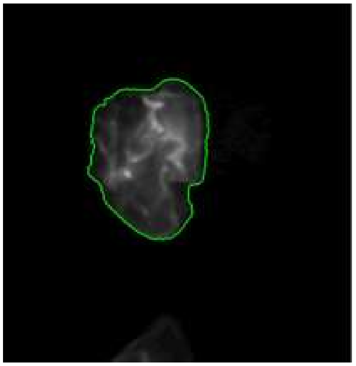
- A consistent approach has been established for each of the CFD teams with LBO predictions forthcoming.

Instantaneous or movie of temperature contour plots for C1

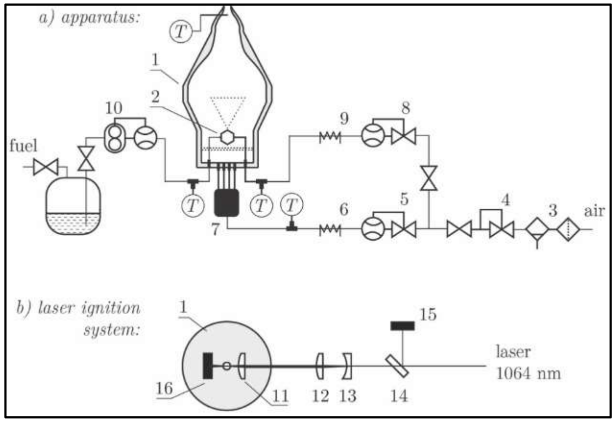


Escalpez,L., M, P.C., Xu, R., Stouffer, S.D. Lee, T., Wang, H., Imhe, M., Combustion and Flame (2017).
S. Yang, R. Ranjan, V. Yang, W. Sun, S. Menon, 10th US National Combustion Meeting, Maryland, April 23-26, 2017.
V. Sankaran, UTRC, 2017.

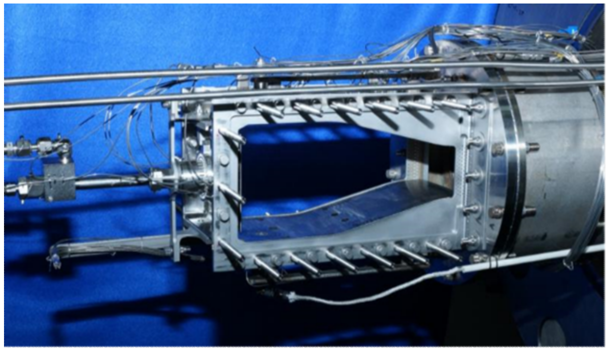
Ignition Rigs



Prevaporized Georgia Tech



Univ. of Cambridge

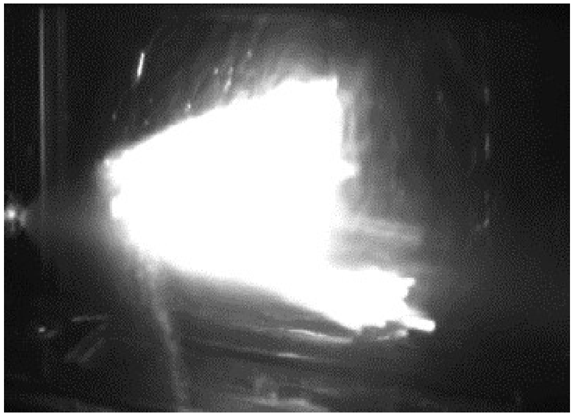


Referee Rig

NRC

More fundamental

More 'Product-like'



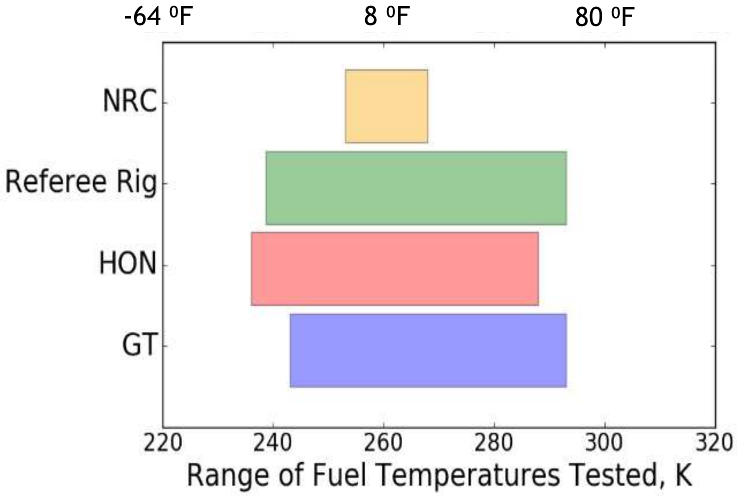
Spray Georgia Tech

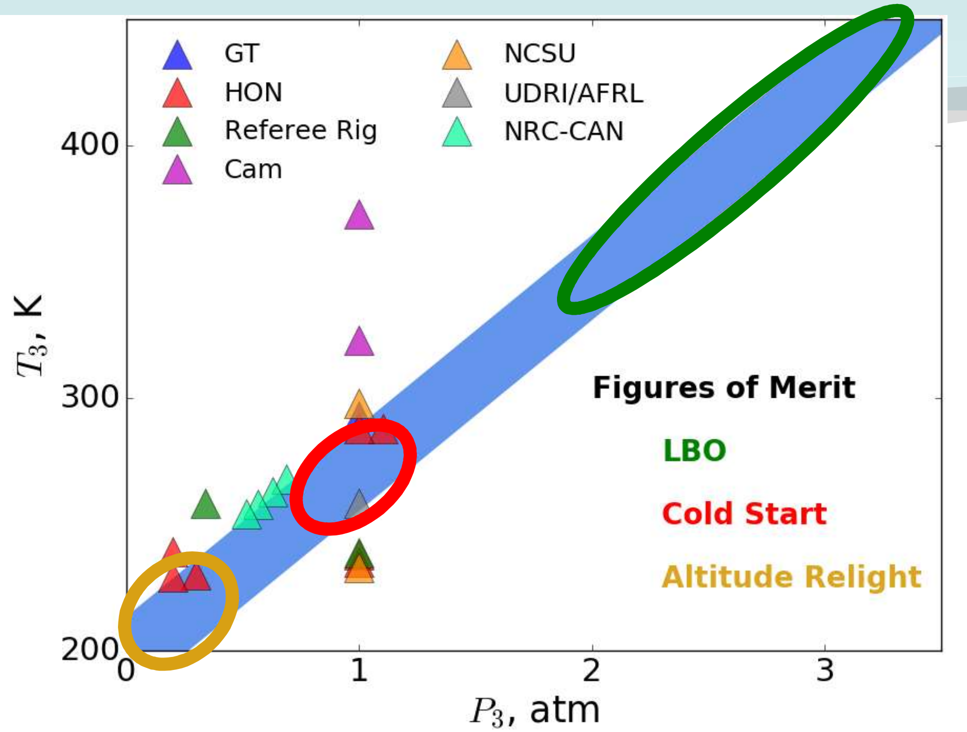
ARL

Honeywell

Ignition: Fuels and Test Conditions

Cold Fuel Temperature Capabilities Developed





	Conventional Fuels			*Alternative Fuels*						
	A-2	**A-1**	**A-3**	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-7**	**C-8**
NRC-CAN	X			X		X		X		
Honeywell	X	X	X	X	X			X		
Cambridge	X			X						
GT – PV	X	X	X	X	X	X	X	X		
Referee Rig	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	
GT – Spray	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
ARL	**X**	**X**	**X**	**X**		**X**				

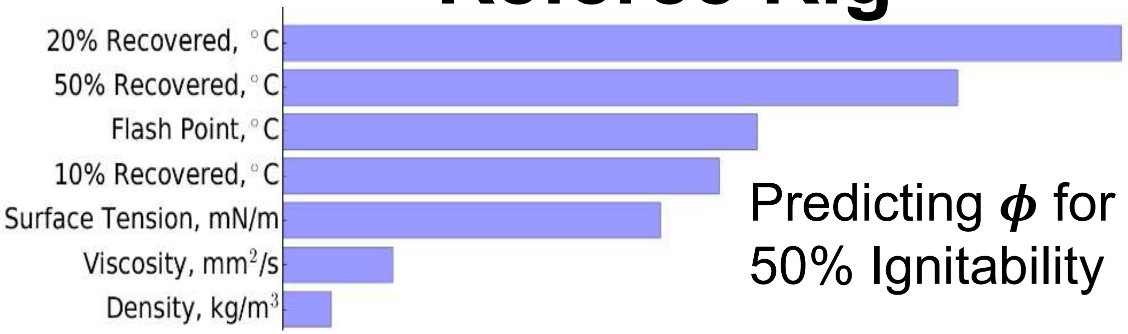
The blue shaded region is the typical flight envelop. Only ignition points are plotted.

Ignition Results

Distillation and physical properties are confirmed to determine ignitability, consistent with historical data.

- **Cold air and fuel at sub-atmospheric conditions have been developed.**
- **Preliminary results suggest distillation and physical properties dominate the ignitability of a fuel.**
- **Modeling efforts for a prevaporized experiment are underway.**

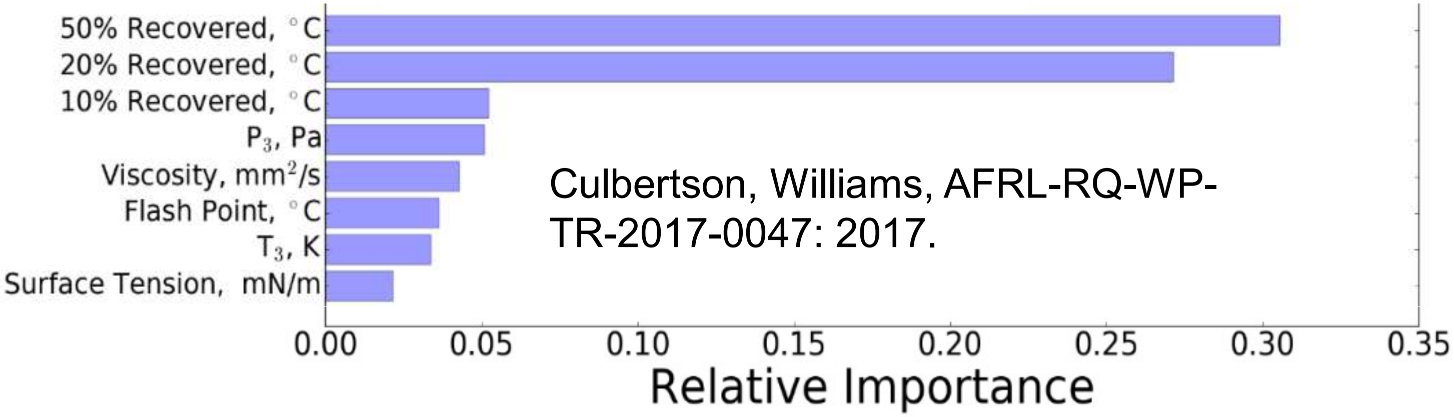
Referee Rig



Predicting ϕ for 50% Ignitability

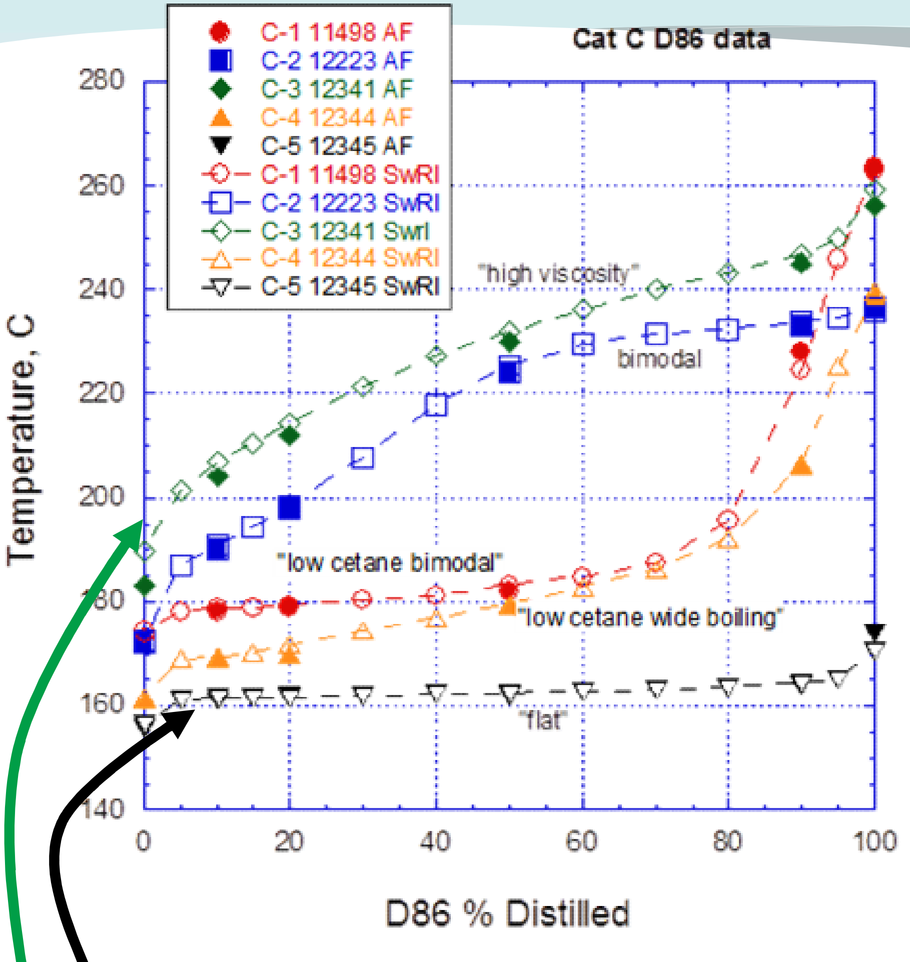
T. H. Hendershott, S. Stouffer, J. R. Monfort, J. Diemer, K. Busby, E. Corporan, P. Wrzesinski, A. W. Caswell. "Ignition of Conventional and Alternative Fuel at Low Temperatures in a Single-Cup Swirl-Stabilized Combustor", 2018 AIAA SciTech Forum, (AIAA 2018-1422)

Honeywell APU



Culbertson, Williams, AFRL-RQ-WP-TR-2017-0047: 2017.

Applying Ignitability Correlations to AJF Blends



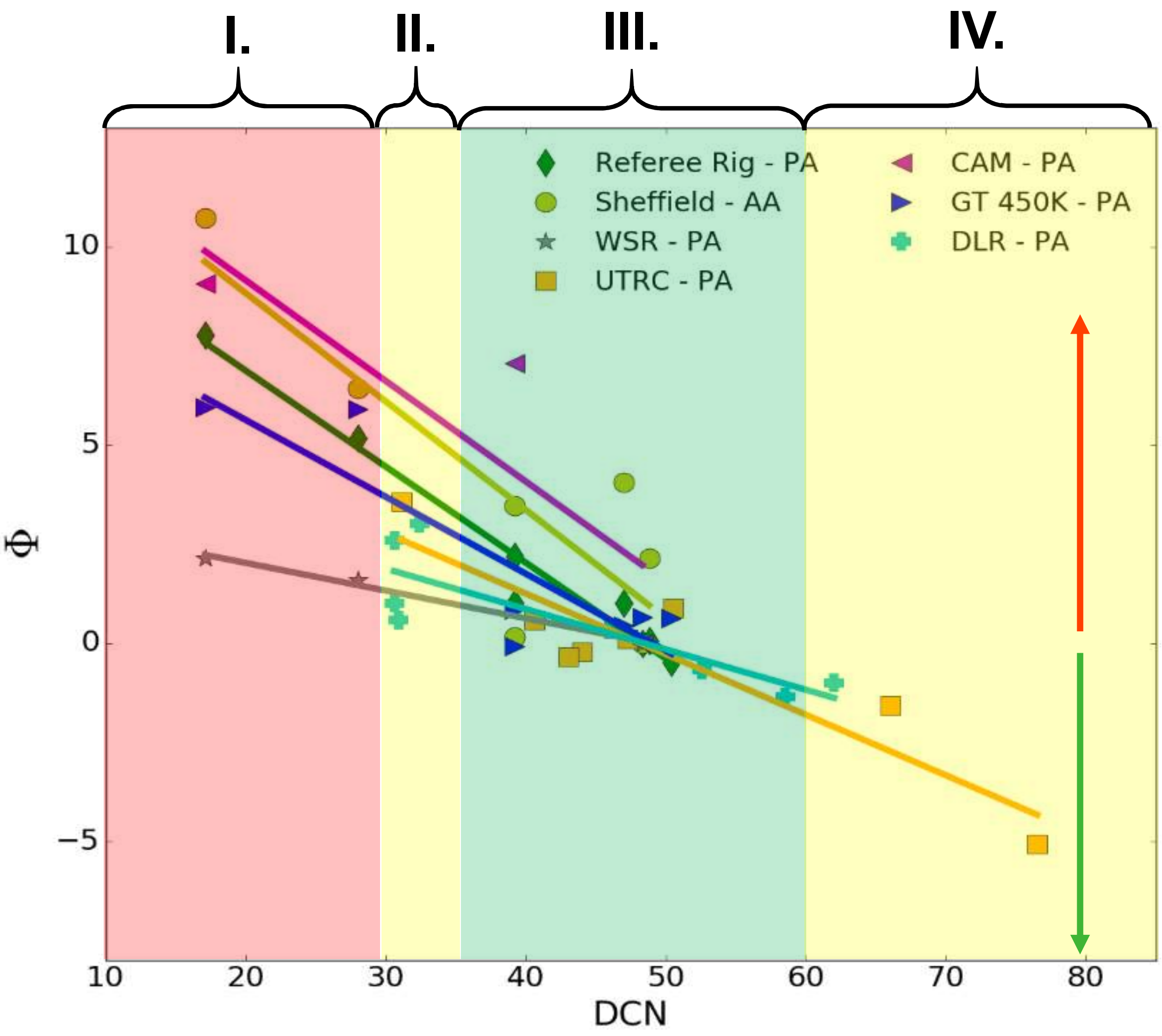
Boiling point, viscosity, and surface tension all correlate with worse ignition behavior.

These properties largely scale with the molecular weight of the components.

C5 is the easiest to ignite. C3 is the most difficult fuel to ignite.

C3 is the 'heaviest' and most difficult to ignite, while C5 is the 'lightest' and easiest to ignite.

LBO Summary



I. **DCN<30**
   - Worse than typical conventional fuels

II. **30<DCN<35**
   - Envelop of historical experience

III. **35<DCN<60**
   - Region of typical conventional fuels

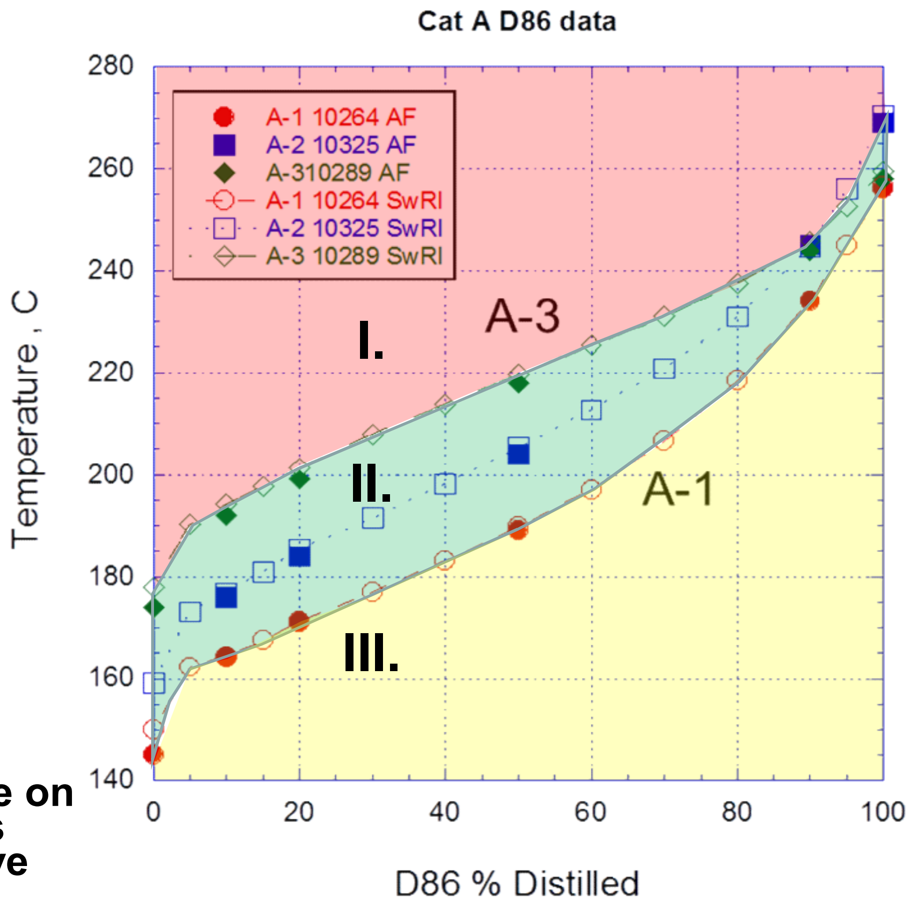
IV. **DCN>60**
   - Upper bound of experience envelop
   - This level of reactivity could be cause pre-ignition for heavily premixed high pressure engines.

Ignition Summary

I. ‘Heavier’ than conventional
  - Region associated with ***worse*** ignition

II. Conventional fuel bound
  - Region associated with ***similar*** ignition

III. ‘Lighter’ than conventional
  - Region associated with ***better*** ignition, but flash point may be too low.



NOTE ON LBO:

- The only rig that did not show first order dependence on LBO, the Honeywell Rig, would also benefit from this distillation curve restriction. A lower distillation curve would also be associated with lower viscosity and surface tension which are associated with the LBO character of the Honeywell rig.
- Deleterious behavior was observed for surrogates with high concentrations of hexadecane. Limiting the heavy fraction of a fuel would additionally increase the stability limit.

Next Steps

- LBO
  - Geometry variations with additional diagnostics and analysis
  - LBO CDF predictions for multiple fuels and groups is forthcoming
- Ignition
  - Conclude initial screening at lower temperatures with sub-atmospheric tests.
  - Low temperature and pressure spray tests are forthcoming to illuminate the effects of low temperature on sprays

Acknowledgements and External Communications

- Principal Investigators:
  - Professors Ronald Hanson, C. T. Bowman, Hai Wang, and Matthias Ihme (Stanford University),
  - Prof. Tiangfeng Lu (University of Connecticut),
  - Professors Timothy Lieuwen, Jerry Seitzmann, Suresh Menon and Dr. Ben Emerson (Georgia Institute of Technology),
  - Professors Robert Lucht and Jay Gore (Purdue University),
  - Professor David Blunck (Oregon State University),
  - Prof. Tonghun Lee (University of Illinois, Urbana-Champagne),
  - Dr. Scott Stouffer (University of Dayton Research Institute),
  - Prof. E. Mastorakas (Cambridge University),
  - Prof. Bhupendra Khandelwal (University of Sheffield),
  - Professors Sang Hee Won and Fred Dryer (University of South Carolina),
  - Dr. Vaidya Sankaranan (UTRC),
  - Drs. W. Chishty, P. Canteenwala, and A. Corber (National Research Center of Canada),
  - Dr. Patrick LeClerc (DLR) and
  - their students, post-doctoral candidates and research staff members.

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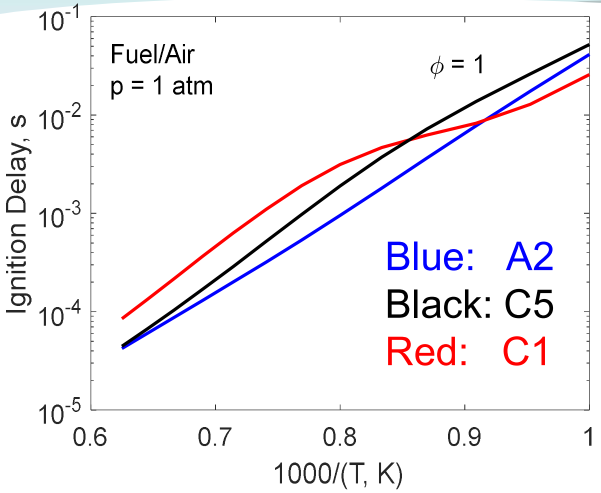
- **Conference Proceedings/ Presentations: 103**
- **Peer Reviewed Journal Publications: 15**
- **Book: 1 (in preparation)**

Supplemental Material

Kinetics

Chemical kinetic model development (kinetics Fuel X) and reduction procedures have been developed.

Kinetic Model Development



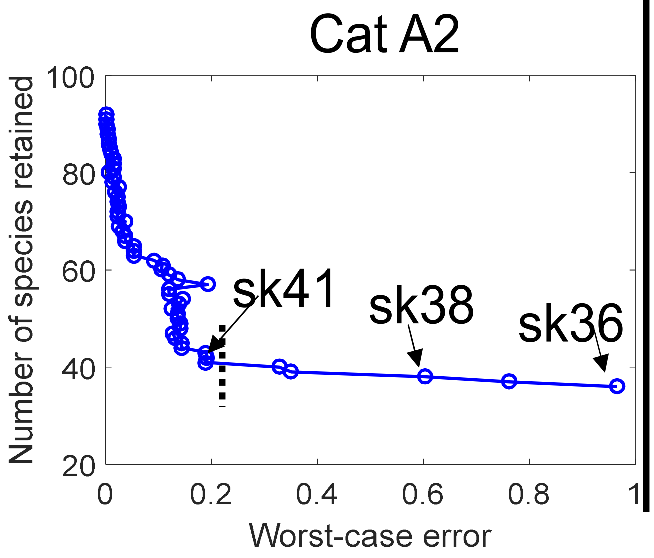
A chemical kinetic development procedure (kinetics Fuel X) has been developed to generate chemistry for novel alternative fuels.

Xu, R., Wang, K., Banerjee, S., Shao, J., Parise, T., Zhu, Y., Wang, S., Movaghar, A., Lee, D. J., Zhao, R., Han, X., Gao, Y., Lu, T., Brezinsky, K., Egolfopoulos, F. N., Davidson, D. F., Hanson, R. K., and Bowman, C. T., "A Physics-based approach to modeling real-fuel combustion chemistry - II. Reaction kinetic models of jet and rocket fuels,"

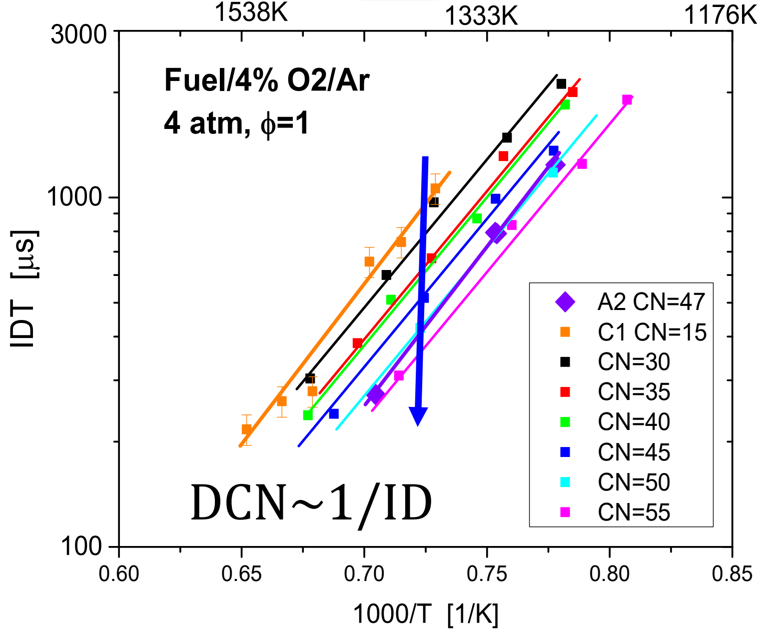
Kinetic Model Reduction

Model reduction limits are ~40 species for 'best' (A-2) to 'worst' (C-1) chemistries.

Gao, Y., Lu, T, "Reduced HyChem Models for Jet Fuel Combustion'" 10th U.S. National Combustion Meeting," College Park, Maryland, 2017.



IDT for Synthetic Fuels with Varying DCN



DCN trends well with high temperature ignition delay measurements.

Shengkai Wang, Thomas Parise, David F. Davidson, Ronald K. Hanson, "A New Diagnostic for Hydrocarbon Fuels using 3.41-μm Diode Laser Absorption," 10th US National Combustion Meeting, College Park, Maryland, April 23-26, 2017.

Sprays

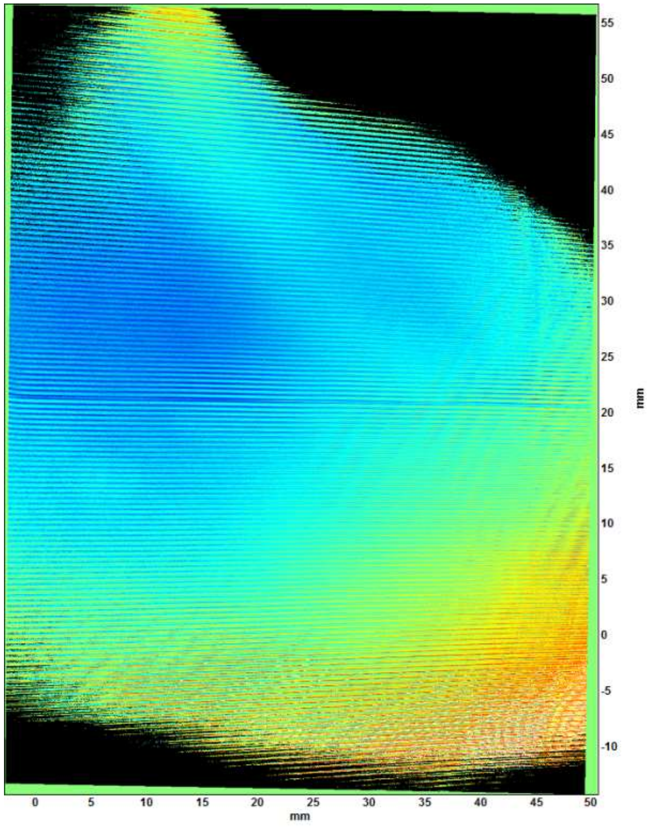
Fuel dependent spray effects near LBO conditions are small, and a generic modeling (Spray Fuel X) approach has been developed.

NRC-Canada Sample Results

Ratio-metric Imaging

Uncalibrated LIF/Mie Images

ΔP/P = 4%



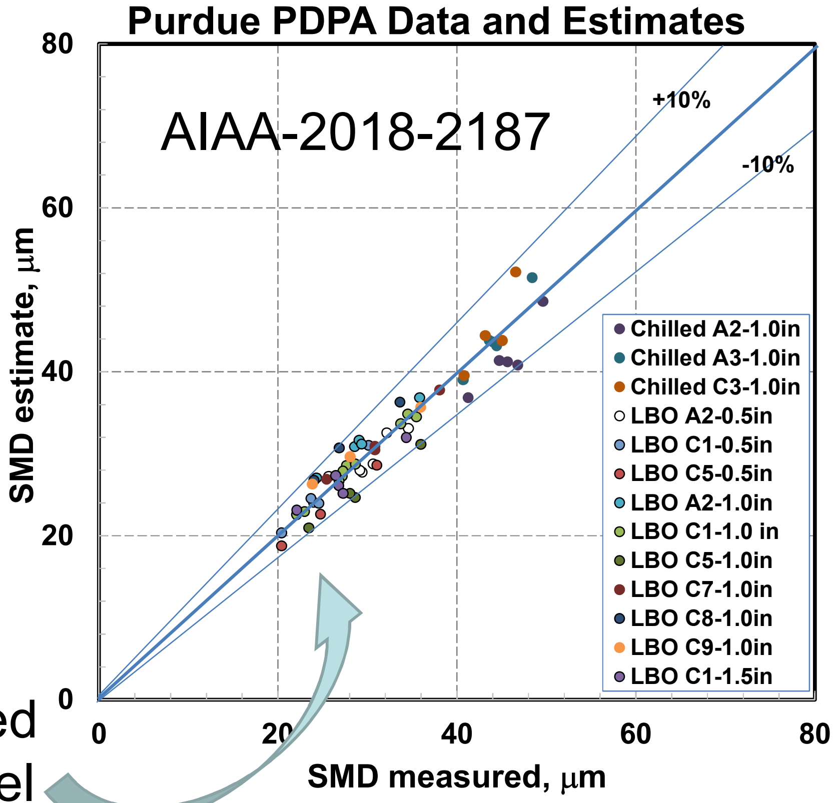
- LIF/Mie system to get SMD for 2-D spray profiles.
- Development of sub-ambient temperature tests.

Corber, A., Rizk, N., and Chishty, W. A., "Experimental and Analytical Characterization of Alternative Aviation Fuel Sprays Under Realistic Operating Conditions," *ASME Turbo Expo 2018, submitted*.

- Spray Fuel X has been developed and is being refined to predict novel fuel spray character.

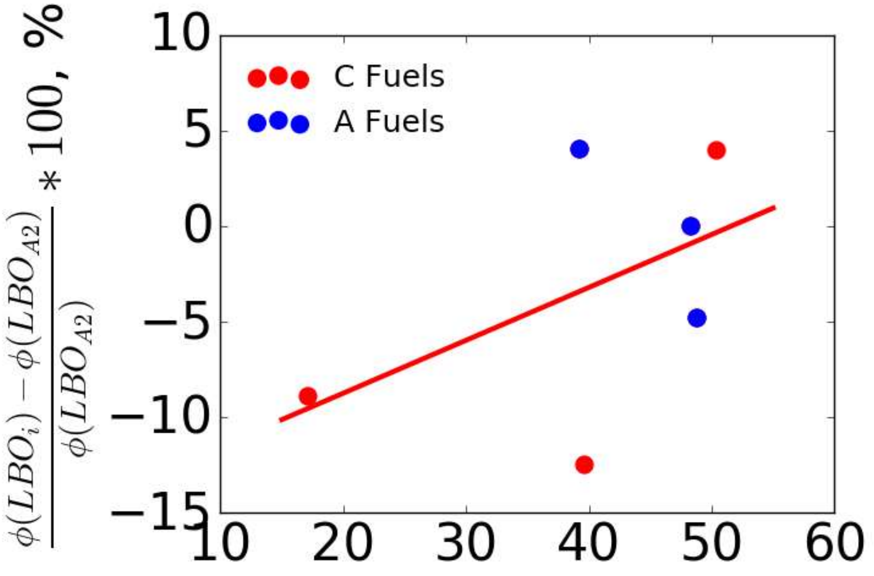
Bokhart, A. J., Shin, D., Rodrigues, N., Sojka, P., Gore, J., and Lucht, R. P., "Spray Characteristics at Lean Blowout and Cold Start Conditions using Phase Doppler Anemometry," 56th AIAA Aerospace Sciences, 2018.

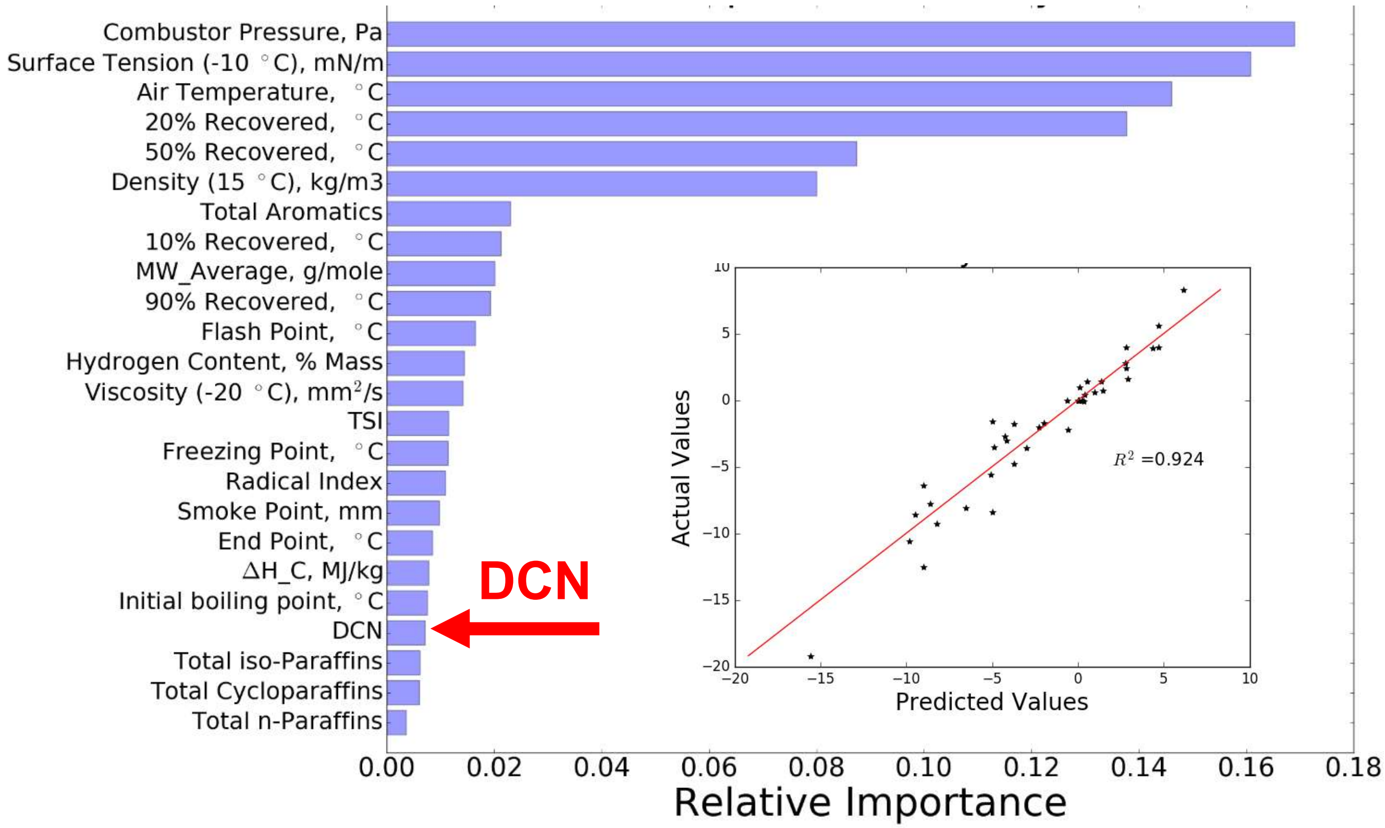
All PDPA Test Points



HON Rig Shows No Significant Dependence on DCN

The ‘worst’ behaving category C fuel, C-1, behaved the ‘best’ at NJFCP LBO conditions.





DCN

Thermo and physical properties dominate the HON regression.