EAR 99 – Non-Proprietary

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National Jet Fuels Combustion Program

Status Update

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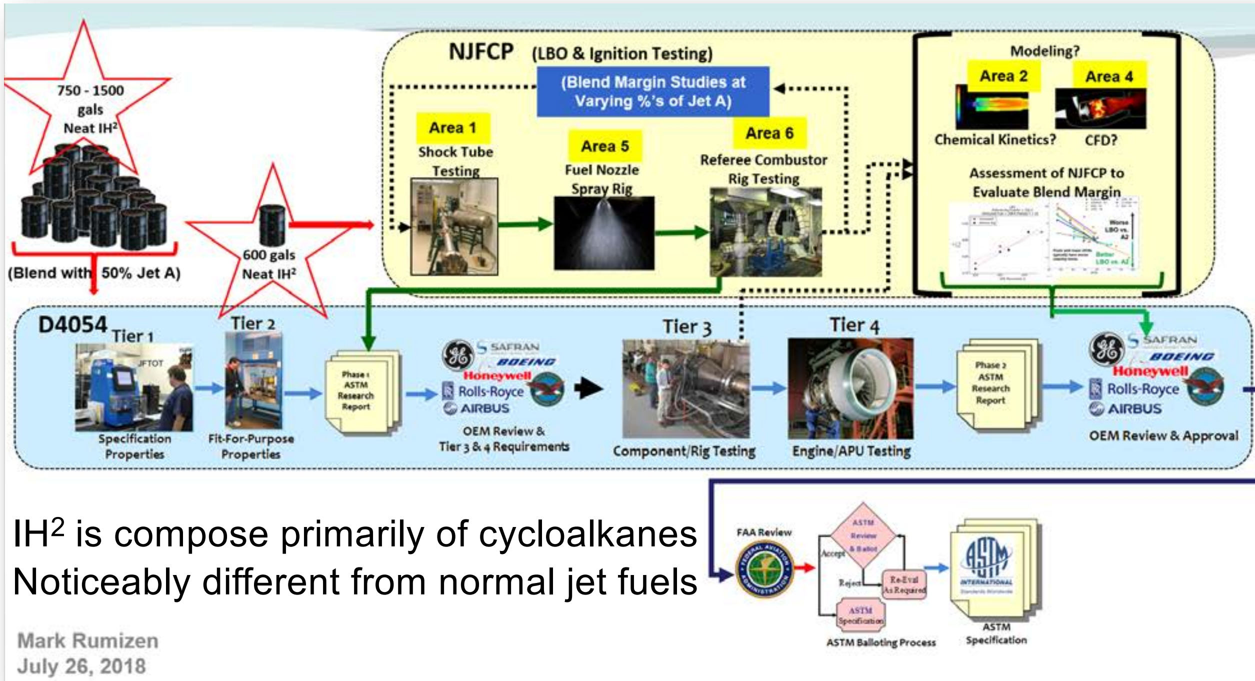
FAA Program Manager

ASCENT Spring MEETING
April 10, 2019
Atlanta, GA

IH^2 Integrated NJFCP-D4054 Testing

A Focus of Year 5 NJFCP – IH^2 testing



IH^2 is compose primarily of cycloalkanes
Noticeably different from normal jet fuels

Some activities delayed until IH^2 deliveries

NJFCP: Program Budget and Contributors

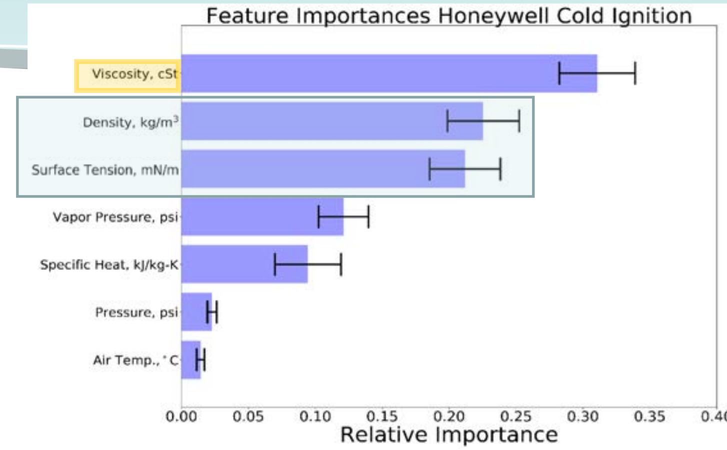
Agency	$K Year-1	Year-2	Year-3	Year-4	Year-5
FAA	2500	1353	2000	950	845
NASA	-	1103	1315	1,300	560
AFRL*	1971	1650	1000	1,000	500
DLA Energy	750	500	500	500	0
NavAir	200	200	400	200	200
ARL				650	tbd
Grand Total	**5421**	**5191**	**5215**	**4600**	

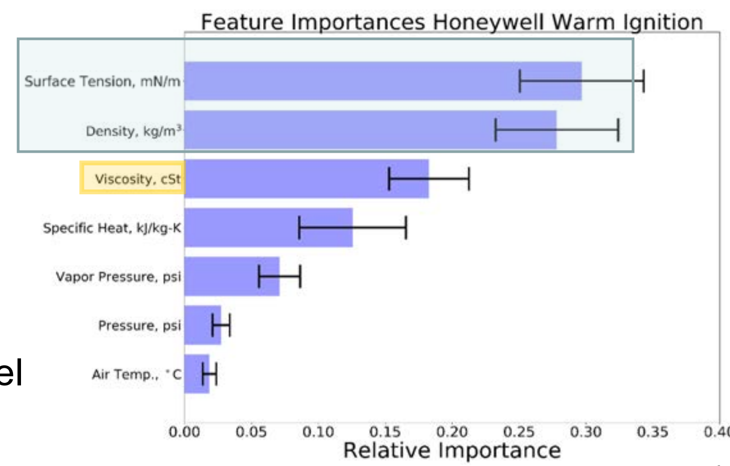
** AFRL spends additional funds (that are not included here) to procure/distribute fuels and develop/maintain rig.*

Additional Synergies:

- **DOE** (in-house activities at National Labs, $12 million announced in jet fuel programs, & possible planned activities)
- **AFOSR** (in-house activities)
- **NASA** (in-house activities)
- **NIST** (in-house activities)
- **NRC Canada** (in-house activities)
- **DLR** (In-house activities, JetScreen Program)
- **Univ. Sheffield** (in-house activities, JetScreen Program)
- **Cambridge Univ.** (in-house activities)
- **Univ. South Carolina** (Supported by AFRL)
- **Univ. of Toronto** (in-house activities)
- **Univ. of Dublin** (in-house activities)

Ignition:
Variance is captured with four properties; the relative importance is TBD





Major Results:

1. All rigs show similar trends
2. Viscosity, surface tension, density, and volatility are *potentially* all important.
   - Collectively more than 96% of variance is captured with these properties.
   - Only one 'odd' fuel (C5) and condition (alt. relight) are identified to date. It remains unexplained.
3. The relative importance of these properties is not currently definitive and may not be universal.

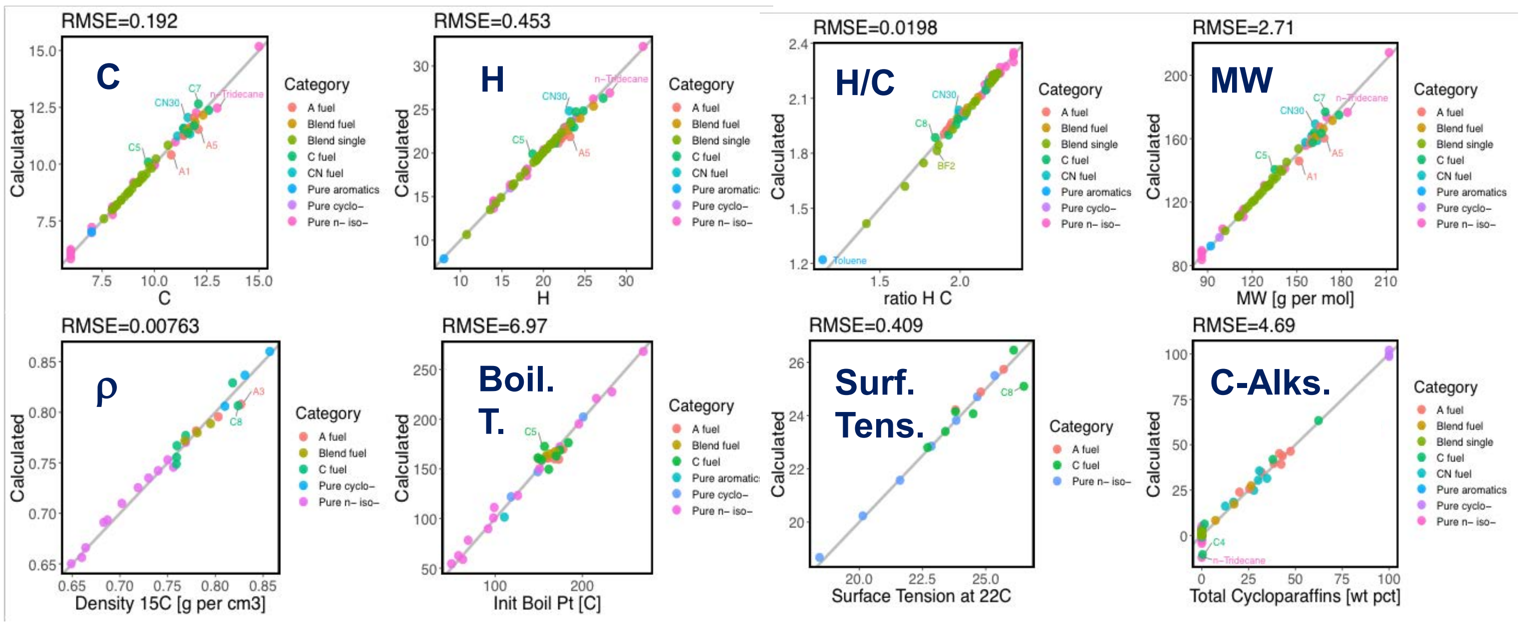
Implications:

1. Add maximum flash point.

2. Add maximum surface tension.

} to fuel spec

Kinetics Group: IR signatures can provide good fits to key fuel properties

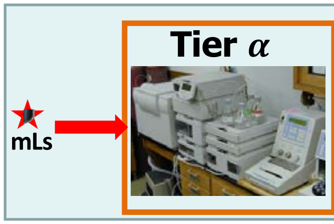


Good fits also obtained for DCN, Heat of combustion, that correlate with LBO
Fits all obtained from IR spectra of unreacted fuel near to 3.3 microns.

Results support early fuel assessment, with small amounts (ml) of fuel

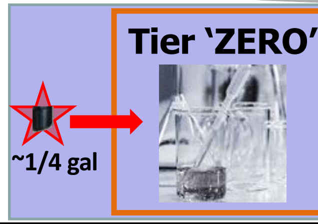
Tiered Screening/Approval

Pre-Screening



Property Predictions & Blend Estimations

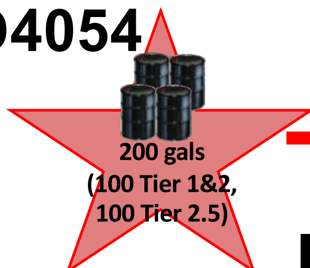
- GCxGC,
- IR absorption, and/or
- NMR

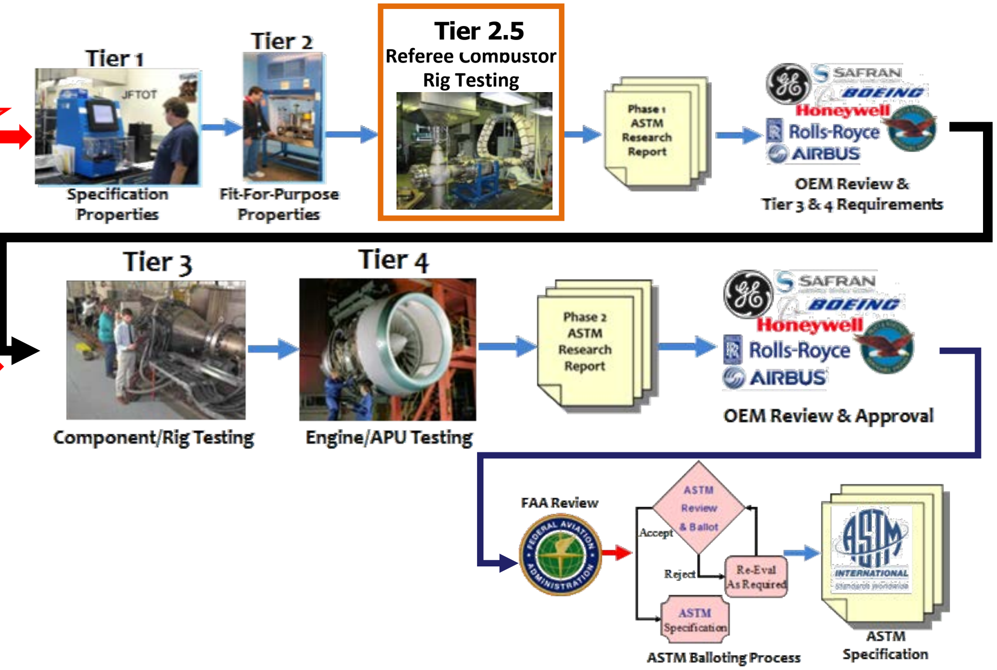


Critical Properties & Blend Limits

- DCN
- Density
- Distillation Curve
- Viscosity
- Surface Tension

ASTM D4054





Tier	$\mathcal{O}$(gal)
α	$\sim 10^{-4}$
'ZERO'	$\sim 10^{-1}$
1 & 2	$\sim 10^{2}$
2.5	$\sim 10^{2}$
3 & 4	$\sim 10^{3}$

Overall NJFCP Accomplishments
Spring 2019

Previously Completed, Recently Completed, and Expected

- Developed CFD models to predict fuel-dependent LBO limit trends
- Consistent fuel dependencies of Referee Rig with OEM facilities
- Method developed for time scale coupling for LBO limit interpretation
- Additional analysis of ignition results
- Demonstration of IR-property correlations, including LBO
- Refine pre-screening and screening process
- Definition of HyChem model for C-4 fuel
- Demonstration of screening method for IH^2 Fuel
- Explain variations in CFD modeling predictions for LBO limits
- Complete draft of book for American Institute of Aeronautics and Astronautics (AIAA)

National Jet Fuels Combustion Program

Project 029(A) National Jet Fuels Combustion Program
Area #5: Atomization Test and Models

Robert P. Lucht, Jay P. Gore, Paul E. Sojka, Scott E. Meyer, Andrew Bokhart, Dongyun Shin, and V. Raju Hasti
Purdue University, West Lafayette, IN

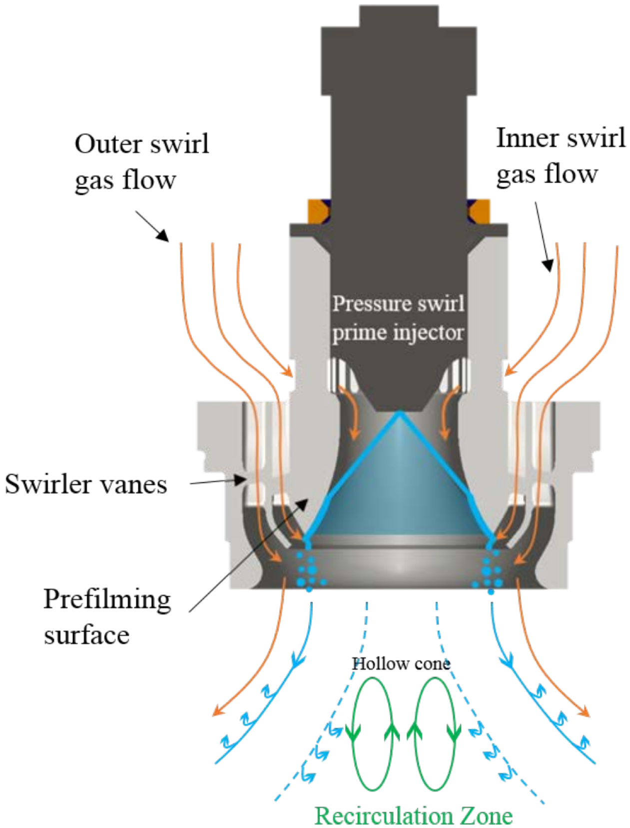
Nader Rizk, Indianapolis, IN

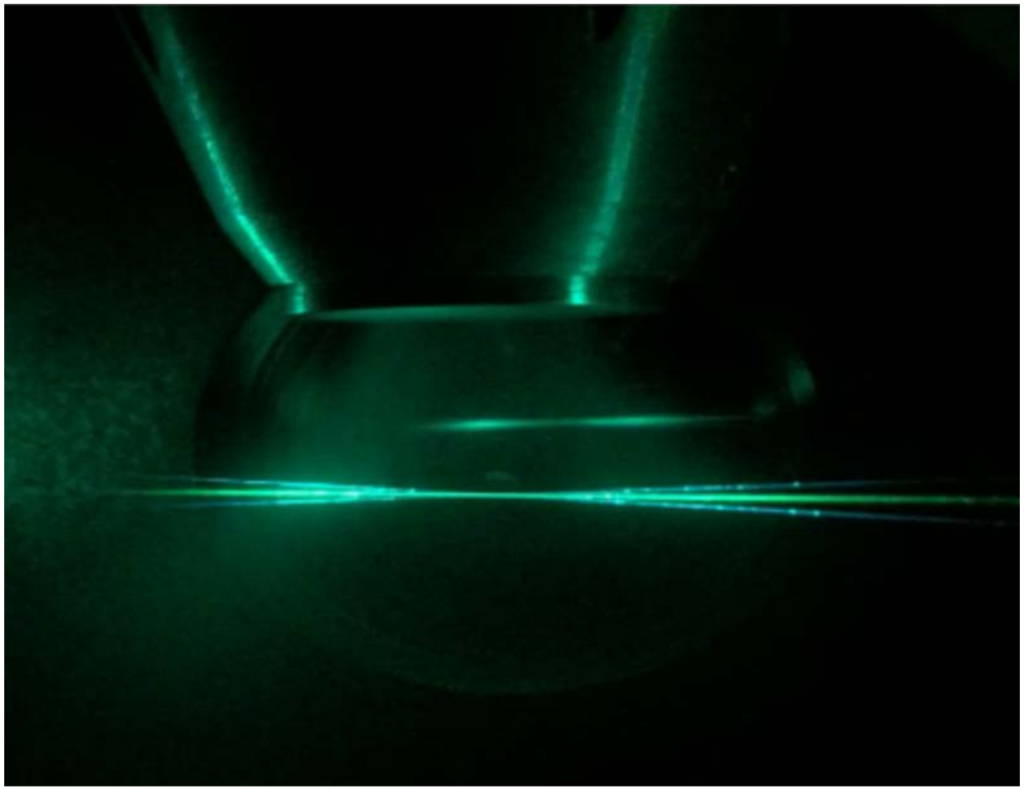
April 2019 ASCENT Meeting

Objectives and Outline

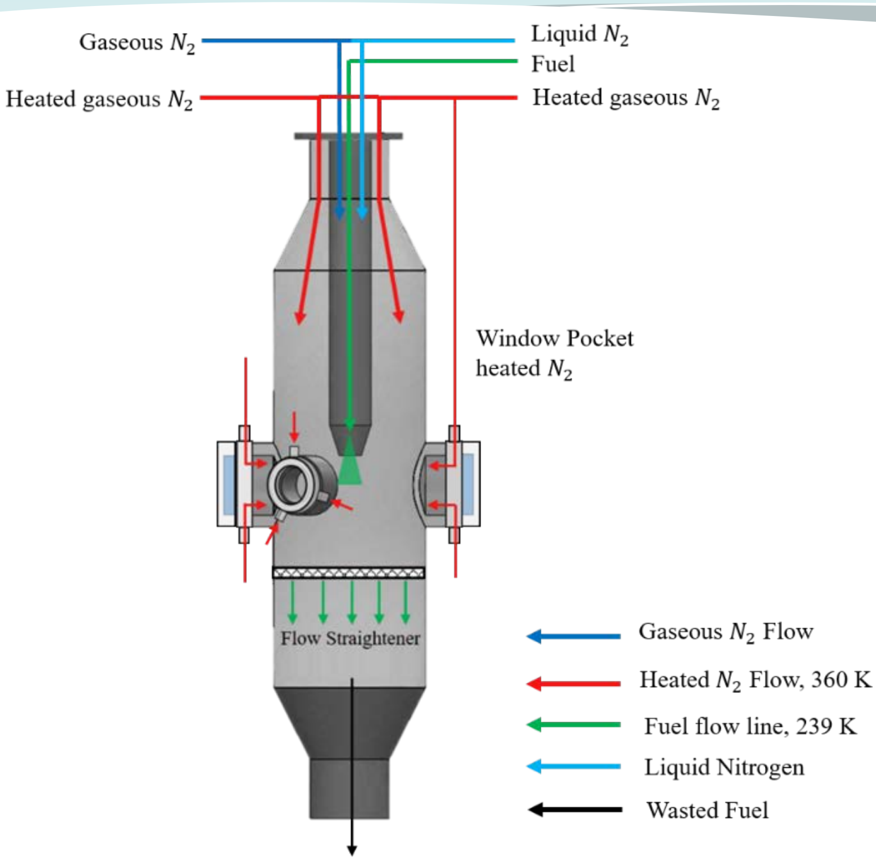
- Objectives of Project 29A: Measure the spray characteristics of the nozzles used in the NJFCP Referee Rig Combustor and to develop models for characterizing the atomization and vaporization of the reference fuels
- Experimental apparatus at Purdue University
- NJFCP Fuels
- Spray measurements at Lean Blow Off (LBO) and Cold Start conditions
- Spray correlation development
- Incorporation of spray data into the numerical simulations of the Referee Rig

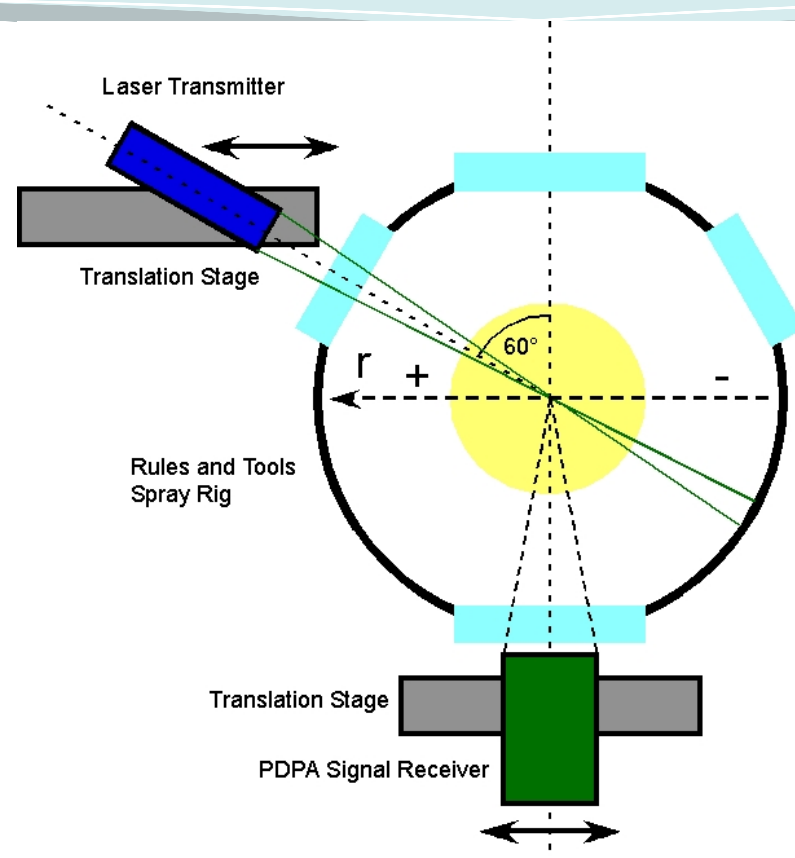
Experimental Apparatus: Referee Rig Nozzle





Variable Ambient Pressure Spray (VAPS) Test Rig and Phase Doppler Anemomometry (PDA) System





NJFCP Fuels

Category C Fuels for NJFCP

Fuel ID	Composition	Key aspects for combustion testing
C-1, POSF 11498	Gevo ATJ fuel (100%)	Extremely low cetane, unusual boiling range, C12 and C16 iso-paraffins
C-2, POSF 12223	84 vol% C14 iso-paraffins/16 vol% trimethyl benzene	On-spec jet fuel, extremely asymmetric boiling range
C-3, POSF 12341	64 vol% high viscosity jet fuel (JP-5 Category A-3 fuel)/36 vol% farnesane (trimethyl dodecane)	Very high viscosity jet fuel, 8 cSt at -20 C (jet fuel spec limit)
C-4, POSF 12344	60 vol% Sasol IPK/40 vol% Gevo ATJ	Low cetane fuel, but broader, more conventional boiling range
C-5, POSF 12345	73 vol% C10 iso-paraffins/27 vol% trimethyl benzene	Extremely "flat" boiling range (all fuel boils at same temperature)
C-6, POSF 10289	Virent HDO SK	High cycloparaffin, only to Stanford/Princeton
C-7, POSF 10376	High flash JP-5 (distilled)	70 C flash JP-5
C-8, POSF 12923	High Aromatic	Approximates high aromatic fuels such as blends containing Virent HDO SAK or KiOR HDCJ
C-9, POSF 12933	High Derived Cetane	Approximates highest cetane achievable from use of 100% SPK or HEFA-type fuels

Category A Fuels for NJFCP

Fuel ID	Composition	Key aspects for combustion testing
A-1, POSF 10264	JP-8	"Good" jet fuel low aromatic content
A-2, POSF 10325	Jet A	"Average" jet fuel
A-3, 10289	JP-5	"Bad" jet fuel, high flash point, low hydrogen content

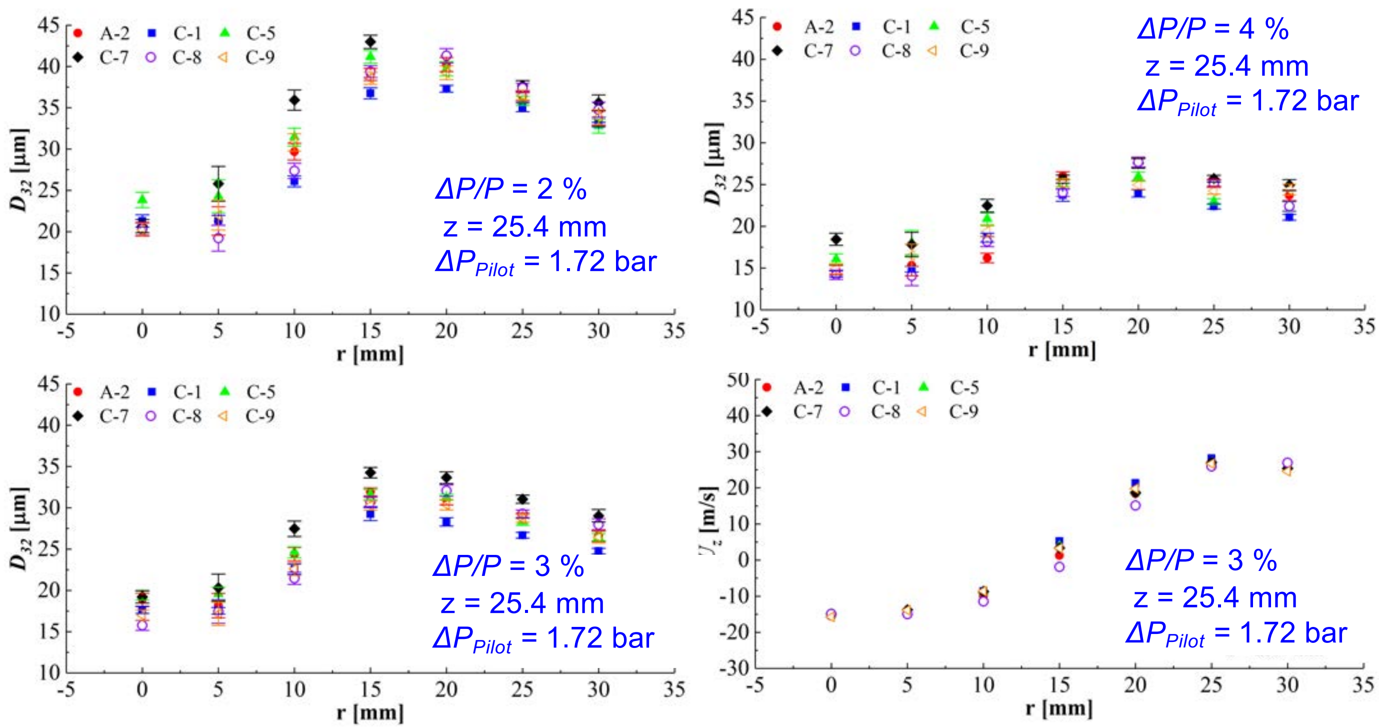
Summary of Measurements at Lean Blowout Conditions

Lean Blowout				
Injector	**Fuel Temp**	**Airbox N2 Temp**	**Vessel N2 Temp.**	**Vessel N2 Press.**
100 % Pilot	120 °F (322 K)	250 °F (394 K)	250 °F (394 K)	30 psi (2 bar)

Fuel	**Measurement plane**	**Parameters**			
A-2	12.7 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	25.4 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar) 50 psid (3.45 bar) 75 psid (5.17 bar)	25 psid (1.72 bar)
	38.1 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)

Performed similar measurements for C1, C5, C7, C8, C9

Results : Lean Blowout – Fuel type Comparison



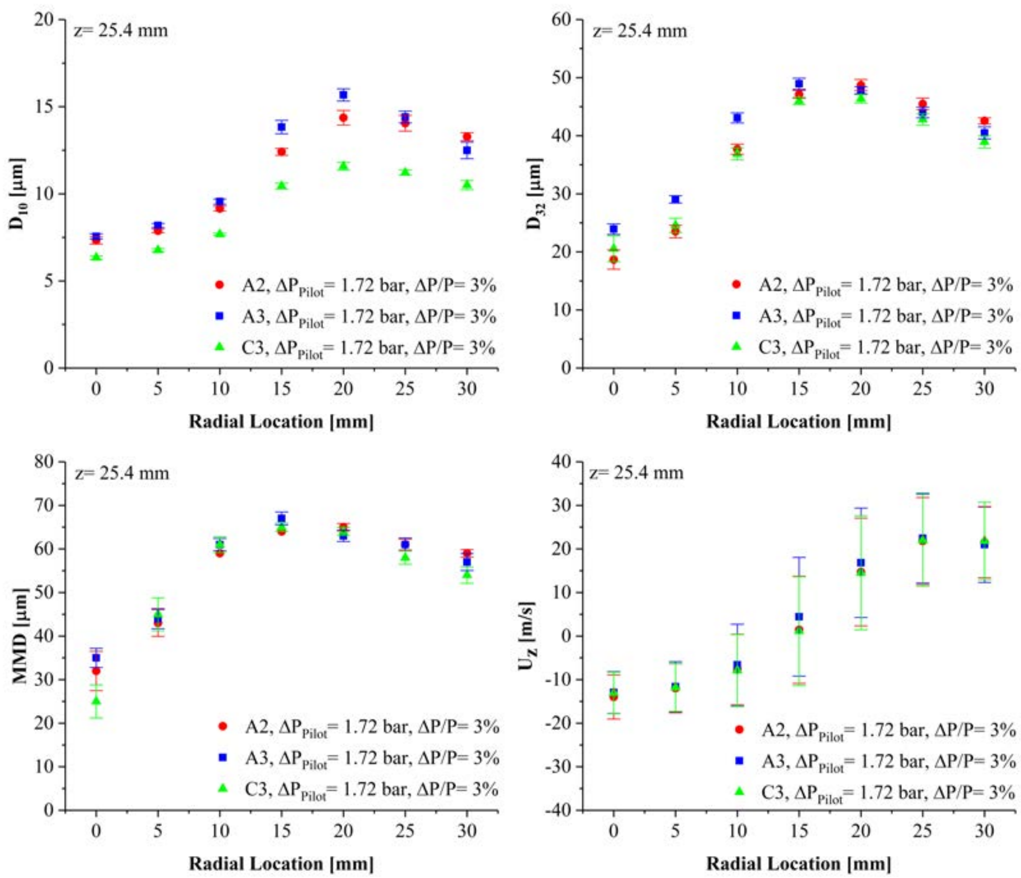
- **No definitive trend observed between mean drop sizes and estimated fuel properties**
- Uncertainty bars for axial velocity are removed for a clear visualization to aid with comparison
- **Airblast effect overwhelmed the effect of the fuel properties on drop size and axial velocity**

Summary of Measurements at Cold Start Conditions

Injector	Fuel Temp	Airbox N2 Temp	Vessel N2 Temp.	Vessel N2 Press.
100 % Pilot	-30 °F (239 K)	-30 °F (239 K)	190 °F (360 K)	14.6 psi (1 bar)

Fuel	Measurement plan	Parameters			
A-2	12.7 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	25.4 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	38.1 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
A-3	12.7 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	25.4 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	38.1 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
C-3	12.7 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	25.4 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)
	38.1 mm	*ΔP/P*	2.0%	3.0%	4.0%
		ΔPpilot	25 psid (1.72 bar)	25 psid (1.72 bar)	25 psid (1.72 bar)

Results : Cold Start – Fuel type Comparison

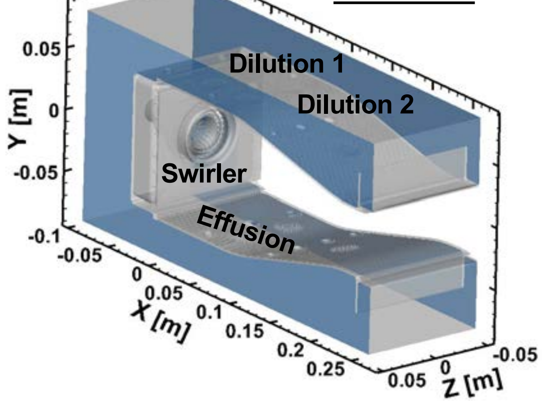


- A-3 fuel formed the largest D_{10} and C-3 fuel formed the smallest D_{10}
  - The variations are within ± 5 µm
- A-3 fuel was observed to show the largest D_{32} within r = ± 15 mm (recirculation zone)
  - The variations are within ± 7 µm
- No significant variations in MMD and U_z among fuels
- No significant trends with physical property were observed
  - **Effect of airblast appears to overwhelm effects of fuel physical properties.**

Note:
- Surface tension & density are similar for all three fuels at cold start condition (<~2% difference)
- Viscosity for C-3 is much higher than A-2 and A-3 at cold start condition (>~30% difference)

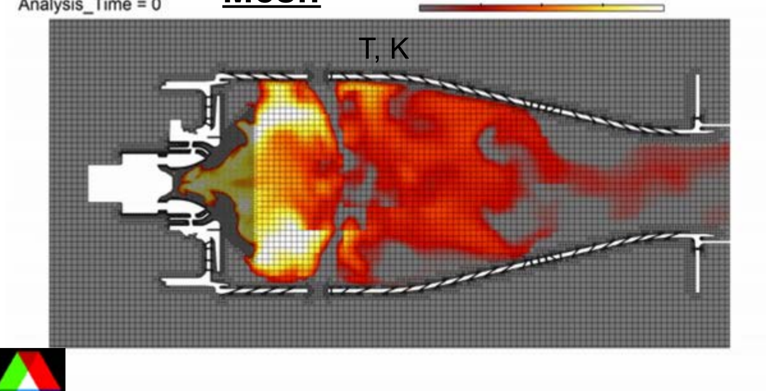
CFD Simulations: CONVERGE, Adaptive Mesh Refinement

Domain



Solver	**Compressible, multiphase, multispecies**
Turbulence	**LES with one equation dynamic structure SGS closure**
Grid	**10, 20, 30 Million Cells with Adaptive mesh refinement**
Spray	**Lagrangian particle tracking, secondary breakup, Frossling**
Comb.	**Laminar finite rate chemistry, FGM, PaSR**
Fuels	**A-2, C-1**

Mesh



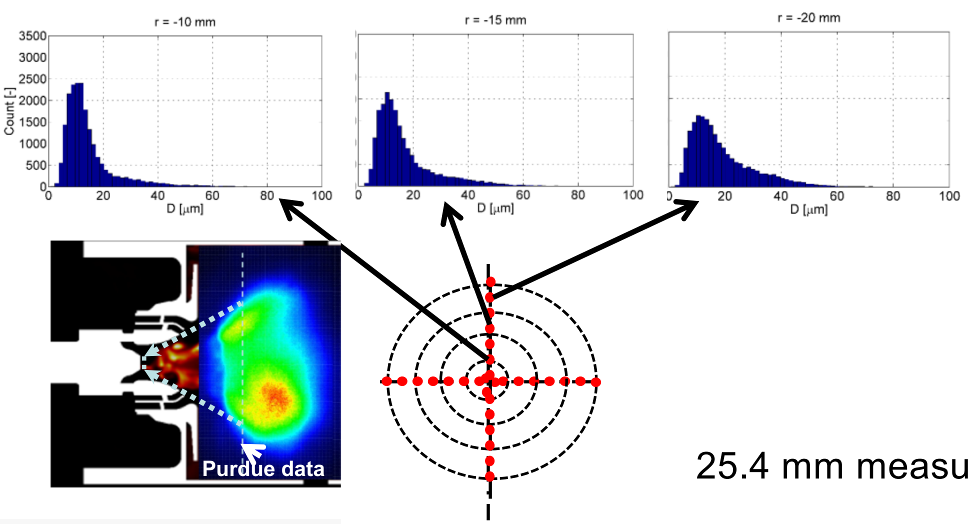
Reaction Mechanism

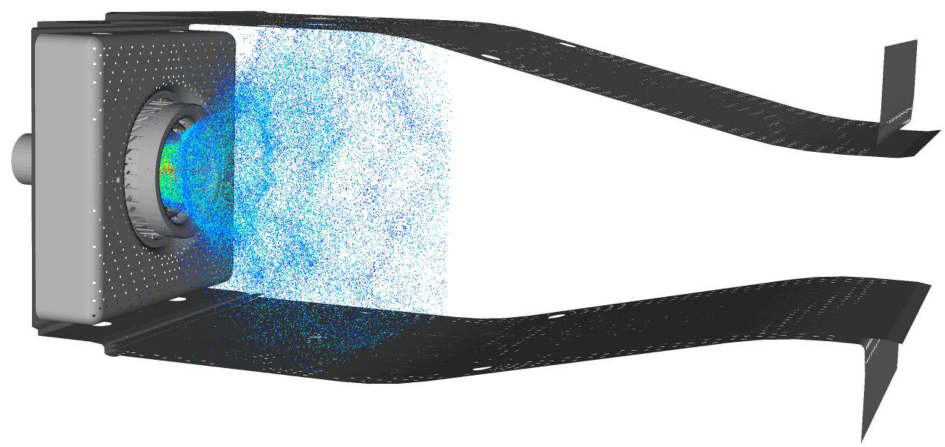
	A-2	C-1
HyChem Detailed	119	119
HyChem Skeletal	41	34
HyChem Reduced	31	28
Dryer’s Compact	41	35

Spray data for CFD simulations

Vaidya, UTRC; Hasti, Purdue

1. Spray boundary conditions for CFD are based on the non-reacting Purdue spray rig PDPA test data at 25.4 mm from deflector plate
2. UTRC spray injection procedure uses 6 concentric rings to represent spray at 2 mm from the nozzle exit
3. Project data from measured plane to injector face
4. Define annular concentric strips
5. For each strip, sample drop size from PDPA data
6. Specify drop size and velocity distribution and mass-flow rate at six annular locations for the Lagrangian Stochastic Spray Simulations





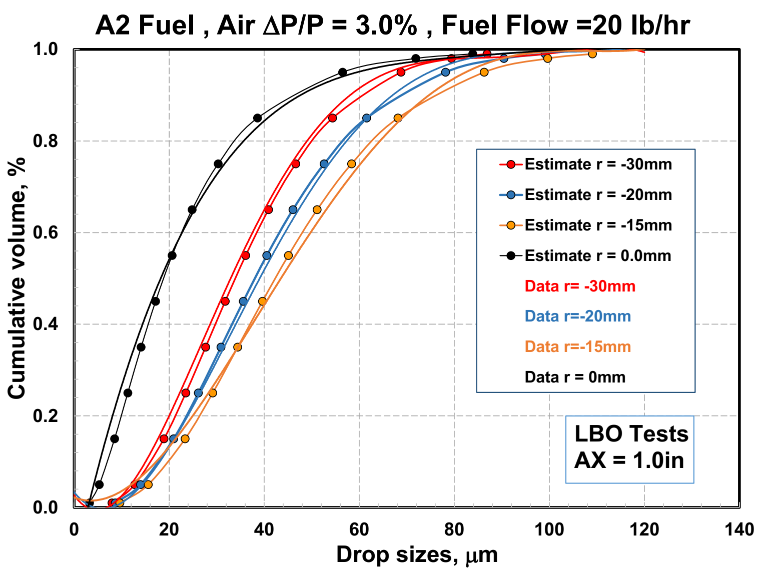
25.4 mm measurement axial location, 60 mm diameter of measurement

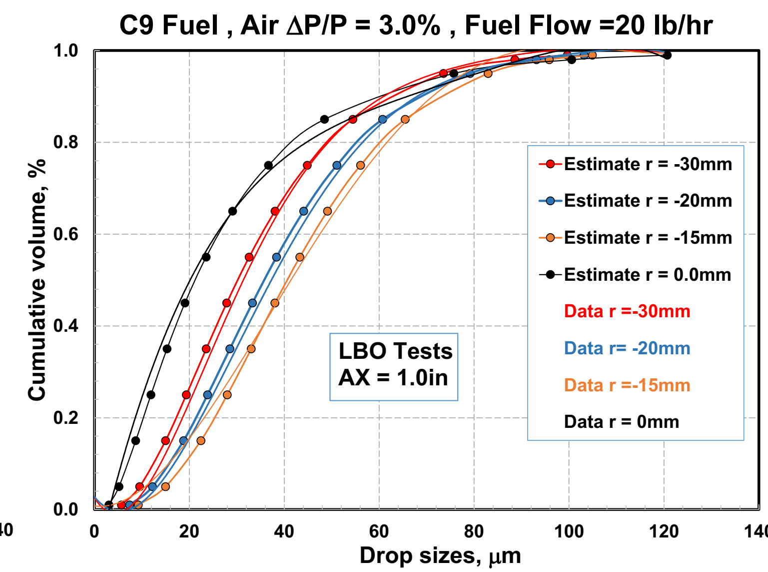
Air-assist Correlations Involve Key Flow Conditions and Fuel Parameters

$$\text{SMD}, \mu m = \frac{0.017 \,.\, (\mu_f \,.\, \sigma_f)^{0.25} \,.\, FAR^C \,.\, (T_3 / 288)^{0.67}}{(U_{air} \,.(u_1.u_2)).(b+(a.(u_{f1}/u_{a1}))^3 - (a.(u_{f1}/u_{a1}))^2 + a.(u_{f1}/u_{a1}))^{0.5}}$$

U_{air}	=	$(2 \,.\, \Delta P / P_{air} \,.\, P_{air} .1000 / \rho_{air})^{0.5}$, m/s
u_1, u_2	=	parameters adjusting air velocity
u_1	=	$(0.035 / \Delta P / P_{air})^{0.38}$
u_2	=	$(\Delta P/P_{air} / 0.027)^{0.23}$
u_f	=	$(\Delta P_f \,.\, 6895 \,.\, 2 / \rho_f)^{0.5}$, m/s
u_{f1} / u_{a1}	=	$1.4 \,.\, u_f / (U_{air} \,.u_1)$
FAR	=	ratio of fuel flow to air flow thru nozzle
μ_f	=	fuel viscosity, kg/m.s
σ_f	=	fuel surface tension, N/m
a, b, c	=	parameters depending on flow number and given by:
a	=	$2^{(2.65 / FN^{1.86})}$
b	=	$0.875 \,.\, FN^{0.254}$
c	=	$0.0076 \,.\, (U_{air} \,.\, u_1) - 0.0022 \,.\, (U_{air} .\, u_1) \,.\, \exp(ce) - 0.1$
ce	=	$1.122 / FN^{0.4}$
FN	=	flow number, lb /hr /psid$^{0.5}$

Comparison Between Data and Estimates for Drop Size Distributions of A2 and C9 Fuels





- **Lowest drop sizes in sprays occur at spray centerline, and highest at around radial distance of 15mm**
- **Drop size distributions of the two fuels are close to each other**

Future Work

- **Bring the VAPS test rig back online in the new High Pressure Combustion Facility**
  – Allows for greater access for optical diagnostic techniques such as Structured Laser Illumination Planar Imaging (SLIPI)
- **Investigation of spray characteristics at High Altitude Re-light conditions**
  – Measurements at sub-atmospheric ambient pressure
- **Investigation of spray characteristics with Shell IH2 fuel**
- **Continued work on development of spray correlations**
- **Continued work on incorporating latest spray data into the numerical simulations of the Referee Rig**