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ALTERNATIVE AVIATION FUELS FOR USE IN MILITARY APUS AND ENGINES VERSATILE AFFORDABLE ADVANCED TURBINE ENGINE (VAATE), PHASE II AND III

Delivery Order 0007: Alternative Aviation Fuels for Use in Military Auxiliary Power Units (APUs) and Engines

Brad Culbertson and Randy Williams
Honeywell International Inc.

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Final Report

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14. ABSTRACT
Evaluations of various alternative jet fuel blends have been evaluated at Honeywell Aerospace sites in Phoenix, Arizona. Evaluations included component, combustor rig, and engine testing on Honeywell military engines and Auxiliary Power Units (APUs). This report summarizes and references reports prepared for a Defense Logistics Agency (DLA) Energy evaluation, Green Diesel (GD) blend evaluation, and a fully synthetic fuel atomizer spray evaluation in conjunction with the US Navy. The DLA Energy tests were evaluating fuels relative to the National Jet Fuel Combustion Program (NJFCP). The Green Diesel evaluations were performed with both high freeze point and low freeze point Green Diesel fuels blended with Jet A and JP-8 petroleum derived fuels. The fully synthetic fuel used for the atomizer spray evaluation was 100 percent Catalytic Hydrothermolysis Jet made to JP-5 specifications (CHCJ-5).

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1.0 EXECUTIVE SUMMARY

Evaluations of various alternative jet fuel blends have been evaluated at Honeywell Aerospace sites in Phoenix, Arizona. Evaluations included component, combustor rig, and engine testing on Honeywell military engines and Auxiliary Power Units (APUs). This report summarizes and references reports prepared for a Defense Logistics Agency (DLA) Energy evaluation, Green Diesel (GD) blend evaluation, and a fully synthetic fuel atomizer spray evaluation in conjunction with the US Navy. The DLA Energy tests were evaluating fuels relative to the National Jet Fuel Combustion Program (NJFCP). The Green Diesel evaluations were performed with both high freeze point and low freeze point Green Diesel fuels blended with Jet A and JP-8 petroleum derived fuels. The fully synthetic fuel used for the atomizer spray evaluation was 100 percent Catalytic Hydrothermolysis jet fuel made to JP-5 specifications (CHCJ-5).

These new evaluations follow the successful Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), Hydroprocessed Esters and Fatty Acids SPK (HEFA-SPK), and Alcohol-to-Jet SPK (ATJ-SPK) fuel blend evaluation programs that were all efforts to approve the fuel blends up to 50 percent of the synthetic component when blended with conventional petroleum derived fuel. The full fuel evaluations used a combination of APU, engine, rig, and component testing to evaluate the fuel blends. Final reports for each of these full fuel evaluations are listed in Section 0 REFERENCES.

For the DLA Energy and the Green Diesel evaluations, a 131-9[B] APU (C-40) combustor rig test evaluated combustion system performance, ignition, and lean blowout (operability). DLA Energy rig test results illustrated the similarity of several fuels and test fluids for pattern factor and radial profile but showed significant differences in operability (LBO and ignition) results. The GD rig tests showed no adverse fuel effect on combustion system performance (pattern factor and profile), ignition characteristics. The low freeze point GD blend appeared to decrease the lean blowout margin when compared to baseline petroleum derived fuel.

Atomizer spray testing was conducted on the DLA Energy fuels, the GD blends, and 100 percent CHCJ-5 fuel. DLA Energy sprays resulted in significant impact to droplet sizes and spray angles when fuels were chilled to cold conditions. The 100 percent CHCJ-5 showed acceptable atomizer spray characteristics, with results similar to baseline petroleum derived fuel. Some of the GD fuel blend results appeared to deviate from the baseline fuel with some hardware at some conditions, which suggests that the fuel needs to be reevaluated.

2.0 INTRODUCTION - GENERAL METHODS, ASSUMPTIONS, AND PROCEDURES

This report, prepared by Honeywell Aerospace, Phoenix, AZ, hereinafter referred to as Honeywell, summarizes the evaluation of several different fuels, fluids, and fuel blends on combustor rig and atomizer component testing. Testing the fuel and fuel blends was part of a United States Air Force (USAF) funded effort titled "Evaluation of Alternative Aviation Fuels for Use in Military Auxiliary Power Units and Engines" for contract FA8650-09-D-2925 Task Order 0007. This summary report is submitted to the Air Force Research Laboratory (AFRL) in accordance with contract data requirements.

Table 1 provides the summary of ATJ SPK fuel evaluation tests. Tasks 2.2, 3.0, 4.0, 5.1, 5.2, 6.1, 6.3, and 7.1 were not funded during this program, so no results are reported herein.

Table 1. Summary of the Military APU and Engine Fuel Evaluation Tests.

Task	Description	Fuel Source	Test Asset	Test Facility
Component Tests				
Task 1.1	Atomizer & Check Valve Testing	DLA Energy Diamond GD Neste GD CHCJ-5	Various APU Atomizers	Fuel Component Lab
Task 2.2	Fuel Pump Endurance Test	N/A	N/A	N/A
APU Tests				
Task 3.0	Fighter APU Test	N/A	N/A	N/A
Task 4.0	Large APU Test	N/A	N/A	N/A
Task 6.1	Referee Propulsion Combustor Rig Test	N/A	N/A	N/A
Task 6.2	Referee APU Combustor Rig Test	DLA Energy Diamond, F-76, Neste GD	131-9[B] APU	C100
Task 6.3	APU Ground Start Test	N/A	N/A	N/A
Task 7.1	APU Endurance Test	N/A	N/A	N/A
Propulsion Engine Tests				
Task 5.1	UAV Engine Test	N/A	N/A	N/A
Task 5.2	Propulsion Engine Combustor Rig Test	N/A	N/A	N/A

Many military APUs in the USAF inventory do not have commercial equivalents and are not qualified to Federal Aviation Administration (FAA) Technical Standard Order (TSO) requirements. Approval of new fuels for these APUs would be based on Honeywell and USAF requirements. However, a number of military APUs do have commercial equivalents with FAA TSO approval, and commercial requirements for fuel approval must be considered. Table 2 provides a summary of the Honeywell APUs in the USAF inventory.

Table 2. Summary of Honeywell APUs in USAF Inventory.

Aircraft Model	Designation	Honeywell APU
A-10	Thunderbolt	36-50
B-1		
B-1A		165-7
B-1B	Lancer	165-9
B-2	Spirit	131-3A
C-130	Hercules	85-71A
C-130H	Hercules	85-180L
C-130J		85-180L(A)
WC-130	Hercules	85-98
KC/RC/WC-135		
KC-135	Stratotanker	85-180L
RC-135U	Combat Sent	JFS100-135
WC-135	Constant Phoenix	85-98CK
C-17	Globemaster III	331-250[G]
C-20		
C-20B		36-100G
C-20H		36-100G
C-22		
C-22B		85-98
C-22C		85-98
C-25		660-4
C-32		331-200[E]

Aircraft Model	Designation	Honeywell APU
C-37A		RE220[GV]
C-38		36-150W
C-40B/C		131-9B
C-5		
C-5A		165-1A
C-5B	Galaxy	165-1B
C-9A	Nightingale	85-98D
E-3	Sentry (AWACS)	165-1
E-4B		660-4
E-8C	Joint STARS	331-350[J]
F-15	Eagle	JSF190-1
F-22A	Raptor	G250
F-35	Lightning II	G230
H-60	Black Hawk	36-150[BH]
KC-10	Extender	700-4B
T-43A		85-129
VC-25A	Air Force One	331-200[P]

2.1 FAA Substantiation Requirements

FAA substantiation requirements for new fuels and additives are detailed in FAA Advisory Circular AC20-24C. The material outlined in this document is intended for evaluation of fuels and oils new to the market.

The advisory material requires that the suitability and durability of all new material (fuel or oil) be established on the basis of experience or test and that the material conform to an approved specification. ASTM D1655 and MIL-DTL-83133 are listed as examples of historically accepted aviation fuel specifications. The fuel specifications are identified as operating limitations for fuel.

ASTM D4054 is listed as providing a suitable procedure for evaluating new jet fuels. The laboratory, rig and engine tests specified in D4054 are noted to be sufficient to fully evaluate the fit for purpose or suitability of new fuels. The U.S. Department of Defense (DOD) document MIL-HDBK-510-1 was noted to be similar to the D4054 specification.

New fuels found to possess performance characteristics and chemical compositions essentially identical to conventional jet fuel are called drop-in fuels. For fuels considered drop-in jet fuels and where current operating limitations are adequate to accommodate the fuel (as in D7566 or D1655), then the AC notes further FAA testing is not required. SAIB NE-11-56 clarifies that fuel produced to D7566 requirements and released as D1655 fuel is acceptable for use on aircraft and engines certified for operation on D1655 fuels, provided it is re-identified as D1655 fuel.

2.2 ASTM Standard Practice

ASTM D4054 provides laboratory procedures for the qualification and approval of new fuels and fuel additives for use in commercial and military gas turbine engines. The document provides detailed test requirements to establish fuel compatibility with other turbine fuels, approved additives, fuel system components, and aircraft engines. The Original Equipment Manufacturer (OEM) review process and the process to change the ASTM fuel specification to include a new fuel are also outlined.

2.3 Military Handbook – Aerospace Fuel Certification

The MIL-HDBK-510-1A Aerospace Fuel Certification Handbook documents the USAF process to evaluate and approve new fuels and fuel additives for Air Force equipment. The document defines the process to assure a new kerosene type fuel is suitable for aviation, support equipment and vehicles, is interchangeable with the logistics infrastructure (i.e., a drop-in fuel) and meets USAF standards for environment, safety and health. Any new fuel is compared to the baseline JP-8 fuel. The USAF approval process requires each weapon system manager to independently determine if a new fuel is fit for purpose, and meets operational, performance, durability, safety, and other weapon system considerations. The handbook also contains an extensive collection of specification and fit for purpose data for aviation jet fuels.

2.4 Facilities

2.4.1 Combustion Test Facility

The C-100 combustion test facility, located at the Phoenix site, was designed for the full range of combustor operation from sub-atmospheric (high altitude), cold air and fuel, to high-pressure, high-temperature test conditions. The central facility air supply and an inline pre-heater/heat exchanger provide non-vitiated inlet air up to 1,000 °F and 250 psia with airflow rates up to 20 lb/s. Intake air is filtered to remove atmospheric particulates, pressurized in a central compressor room, and heated with an indirect fired heater to the desired operating conditions. The combustor rig exhaust is ducted through an exhaust stack to ambient conditions for performance testing and to a central vacuum system for altitude ignition or relight testing. Downstream of the combustion system, a computer-controlled temperature, pressure and emissions rake allows for complete mapping of the combustor exit plane. The control room houses the required equipment for processing, recording, and displaying analog and digital test data.

2.4.2 Atomizer Spray Test Facility

The atomizer bench testing was completed in the fuel component laboratory at the Honeywell facility in Phoenix, Arizona. Tests were completed in the Malvern test stand which allows various fuels to be tested at ambient and cold conditions. A heat exchanger is used to chill the fuel to a temperature of 40°C. Fuel temperatures and pressures were measured at the atomizer inlet (as well as throughout the fuel system) and fuel flow is measured using a Micro Motion mass flow meter upstream of the heat exchanger.

Spray droplet size is measured with a Malvern Spraytec particle analyzer. The Spraytec determines the spray droplet size distribution by analyzing the diffraction pattern produced by a laser beam passing through the spray. The Malvern Spraytec software includes corrections for multiple scattering in high concentration sprays. Drop size data is presented as SMD, which is a droplet with the same volume-to-surface area ratio as the entire spray. SMD has been shown to provide a good indication of atomization quality for correlating gas turbine combustor ignition and lean stability characteristics.

2.5 Instrumentation Requirements

Instrumentation sufficient to demonstrate compliance with the test requirements was included in each test. Standard engine instrumentation related to fuel type would include engine inlet fuel pressure and temperature, and fuel flow. For each test, the required special instrumentation to monitor and evaluate fuel effects on engine performance, operability, or emissions was added. This equipment was certifiable and traceable by Honeywell Quality and Laboratory Procedural Standards to the National Institute of Standards and Technology (NIST). Details on instrumentation for any particular test can be found in the applicable test plan or test report.

2.6 Inspection Requirements

Following the completion of each test, the component, engine, or APU was either disassembled for inspection by Honeywell engineering, or borescope inspected to check for any distress. In general, there were no fuel problems reported on any engine or APU related to the 50/50 ATJ blend fuels.

2.7 Emissions Test Equipment

Gaseous and smoke emissions were measured during the 131-9[B] APU combustor rig using averaging probes, heated sample line, and a mobile emissions truck (Figure 1). Exhaust samples analyzed for gaseous emissions were measured in accordance with the procedures specified in International Civil Aviation Organization (ICAO) Annex 16 Appendix 3 and Society of Automotive Engineers (SAE) ARP1256D. Gaseous emissions were measured with gaseous emission analyzers which were calibrated prior to and after sampling. Non-Dispersive Infra-Red (NDIR) analyzers were used to measure carbon dioxide (CO_2) and carbon monoxide (CO) emissions. Chemiluminescence type instruments were used to measure oxides of nitrogen (NO_x) emissions. Unburned hydrocarbons (HC) were measured using a Flame Ionization Detector (FID) and oxygen (O_2) paramagnetic type analyzer. Gaseous emissions were reduced using the procedures from SAE ARP1533B. Optical smoke emissions were measured with a

Rotadata optical smoke meter and reported as SAE smoke number.

Figure 1. Honeywell Emissions Truck.

2.8 Test Fuels

Rig and component testing were completed with numerous fuels in support of several different agendas. The DLA Energy evaluation, closely aligned with the NJFCP, evaluated six fuels. Three of those fuels were petroleum derived and three were experimental fluids or blending components. The two Green Diesel efforts utilized GDs from both high freeze point and low freeze point type Green Diesels. The Navy CHCJ-5 evaluation utilized the AFRL contract to obtain atomizer spray data on 100 percent CHCJ-5. Table 3 summarizes which ATJ SPK feedstocks were used for the various tests. The neat ATJ evaluated were fully additized by the USAF with Fuel System Icing Inhibitor (FSII), Static Dissipator Additive (SDA), Corrosion Inhibitor/Lubricity Improver (CI/LI) and Anti-Oxidant (AO) per the MIL-DTL-83133 specification, prior to shipment to Honeywell.

Table 3. Fuel Use Summary.

Test	DLA Energy	Green Diesel	Navy CHCJ-5
Atomizer Spray Test	A-1, A-2, A-3 C-1, C-2, C-5	2% Diamond 30% Neste	100% CHCJ-5
131-9[B] APU Combustor Rig Test	A-1, A-2, A-3 C-1, C-2, C-5	30% Neste	N/A

AFRL supplied the six fuels under evaluation for the DLA Energy program. Detailed information for the fuels can be found in the individual reports, referenced in Section 0 REFERENCES. In general the Category A fuels represent the best-case (A-1), nominal (A-2), and the worst-case (A-3) fuels found in current use. The A-1 fuel was sought to have low aromatic content, low viscosity, and was desired to be relatively volatile. This fuel happened to be a JP-8 fuel. The A-2 fuel was average in aromatic content, viscosity, and volatility, and happened to be a nominal Jet A fuel. The A-3 had higher aromatic content, higher viscosity, and a relatively low volatility; this fuel was a JP-5 fuel.

The three Category C fluids were meant to probe various physical and chemical characteristics of the fuels and their influences on combustion parameters. The C-1 fluid is 100 percent Gevo ATJ which has a low cetane number and composed of primarily two iso-paraffin molecules (C-12 and C-16). The C-2 fluid was a blend of C-14 iso-paraffin with 1,3,5-trimethylbenzene, which is a bi-modal fluid with an aromatic front end of distillation. The C-5 fluid was a blend of C-10 iso-paraffin with 1,3,5-trimethylbenzene, which has a flat distillation range and a high aromatic content. One other unique characteristic of the C-5 fuel was the relatively low viscosity of the fluid, on the order of 25-30 percent of A-2 viscosity at cold temperatures.

For the Green Diesel evaluations, the individual fuel producers supplied drums of Green Diesel blending components, with the help of the Federal Aviation Administration (FAA) and AFRL. The GD fuels were evaluated in different efforts. At the time of the initial evaluation, the high freeze point GDs from a Valero refinery (Diamond GD, DGD) and a Solazyme refinery (F-76) were blended at low blend ratios (2 to 5 percent) with Honeywell Jet A. Later evaluations, a low freeze point GD from Neste was blended at 30 percent with Honeywell JP-8.

For the CHCJ-5 atomizer spray evaluations, the US Navy supplied the 100 percent CHCJ-5 which was produced by Applied Research Associates (ARA) – Chevron. The CHCJ-5 was evaluated as received from the Navy.

All testing was conducted at the Phoenix site, where the standard laboratory Jet A or JP-8 was used for baseline testing and blending. When changing fuels, the cell fuel systems were purged and flushed with the next fuel to be tested. Prior to testing, a fuel sample was obtained at the rig or component inlet and analyzed for specific gravity to ensure the fuel system was purged, the correct fuel was being used, and to obtain the fuel properties needed to conduct the test. At the completion of the testing with each fuel, another sample was obtained for more extensive fuel analysis.

The data from tests with Jet A and JP-8 fuel formed the baseline for comparison with the GD blends. The data from tests with JP-5 (DLA Energy A-3) formed the baseline for comparison with the 100 percent CHCJ-5 fuel. Key fuel properties for the individual fuel evaluations are found in respective reports, Appendix 2 and Appendix 3 for the GD blends and 21-15778 for the CHCJ-5 fuel.

2.9 Fuel Analysis

Samples were obtained from the fuel tanks, drums, or at the test rig inlet and analyzed to confirm the specification fuel properties. Pretest samples were analyzed to verify the correct test fuel was being used and the test cell had been thoroughly purged of the previous fuel, and to provide fuel properties needed to run the test. Posttest fuel samples were analyzed in more detail, to verify critical fuel properties and fuel quality. Fuel samples were taken in standard laboratory polyethylene sample bottles.

3.0 ATOMIZER AND CHECK VALVE BENCH TESTING (TASK 1.1)

APUs used in military transport and tanker service are similar to those used in commercial transport aircraft. These APUs are typically operated to provide a power source for the aircraft air conditioning units and electrical systems on the ground, and for main engine starting. These APUs are also used in-flight as an alternate electrical power source in the event of a main engine system failure. APU start times are typically 30-60 seconds, though more rapid starts are required for some applications. In-flight starting of APUs can be challenging, especially at higher altitudes or after a long flight that cold soaks both the APU and fuel.

APUs used in fighters and bombers, such as the JFS190 (F-15), 36-200 (F-18), 85-series (C-130J), 165-9 (B-1B), G250 (F-22), G230 (JSF), and 131-3[A] (B-2), are very different from commercial APUs. These units typically have very rapid start requirements and are used to start the main engines on the ground, for emergency main engine starting, or to recover aircraft control in-flight. To achieve these rapid starts, properly atomized fuel must be delivered to the combustion chamber and ignited before the APU accelerates through the combustor ignition window.

Proper atomizer performance is a critical aspect to reliable cold and altitude starting for both transport and fighter APUs. Pressure atomizers, which are sensitive to fuel properties, are used in most military APUs to ensure adequate atomization over the flight envelope. Several fuels were evaluated with atomizer spray bench testing at ambient and cold conditions to assess their impact on APU atomizer performance.

3.1 Test Fuels

Over the course of three separate efforts, eleven fluids were used for spray characterization testing which included standard calibrating fluid (MIL-PRF-7024 Type II), Viscor 12 cSt fluid, the six DLA Energy fuels (A-1, A-2, A-3, C-1, C-2, and C-5), 100 percent CHCJ-5, and two Green Diesel blends (2 percent DGD and 30 percent Neste GD).

The 7024 calibrating fluid and the Viscor 12 cSt fluid were supplied from the test facility in 30-gallon storage reservoirs. The test fuels and fuel blends were supplied to the Malvern test stand in 55-gallon barrels. The DLA Energy fuels and the 100 percent CHCJ-5 fuels were evaluated as delivered to Honeywell; these fuels were evaluated neat or were pre-blended, so no blending was required. The GD blends were prepared using 55-gallon drums. For the 2 percent DGD blend, approximately 1 gallon of neat Diamond GD was added to an empty, clean, and dry 55-gallon barrel. A graduated aluminum measuring stick was used to gauge the height of the fuel in the drum (~0.75 inch), 49 gallons of Jet A was then added to the drum order to achieve a 2/98 mixture of DGD and Jet A. The 30 percent Neste GD blend was created similarly but with 15 gallons of the neat Neste GD (~10 in) with 35 gallons of JP-8 (~24 in). Prior to blending the Neste GD with JP-8 rather than Jet A, OEM consensus was sought and achieved. Prior to obtaining spray data, fuel properties for each fluid under test were verified by the Honeywell Chemistry Laboratory. Detailed fuel properties can be found in their respective test reports, but a summary of fuel properties can be found in Table 4.

Table 4. Atomization Test Fuel Properties.

Fluid	Specific Gravity	Freeze Point °C	Viscosity at 25°C, cSt	Viscosity at -40°C, cSt
DLA A-1	0.781	-50	1.40	6.6
DLA A-2	0.803	-49	1.65	9.3
DLA A-3	0.827	-59	2.00	13.4
DLA C-1	0.762	<-80	1.92	10.2
DLA C-2	0.782	-45	1.75	10.6
DLA C-5	0.773	-80	0.95	2.9
100% CHCJ-5	0.803	-52	1.67	9.1
2% DGD	0.817	-41	1.81	11.2
30% Neste GD	0.781	-44	1.90	12.0

3.2 Atomizer Spray Bench Testing

Honeywell completed fuel atomizer bench testing of ambient and cold fuels and fuel blends. Atomizer performance parameters, including flow and spray characteristics, were measured over a range of typical APU engine start and operating conditions. Test results show that both the ambient and cold atomization characteristics of the fuels and fuel blends are very similar to the petroleum-derived baselines and appear to be driven by fluid viscosity.

3.2.1 Fuel Atomizer Configuration

Pressure type fuel atomizers are used in most APUs to ensure reliable starting and operation up to maximum start altitude after an extended cold soak. Depending on the particular evaluation, either two or three representative pressure-type fuel atomizers were selected for testing. For the DLA Energy evaluation, a small flow number (FN) atomizer and a large FN atomizer were evaluated. For the 100 percent CHCJ-5 and Green Diesel evaluations, a medium FN atomizer was added to the small and large FN atomizer evaluations.

Atomizer FN (Equation 1) is an indication of the size of the atomizer and is relatively constant for different operating conditions.

$$FN = W_f / \Delta P_f^{\,0.5} \qquad [1]$$

Where:

W_f = fuel flow, pph (lb/h)

ΔP_f = differential fuel pressure, psid

Droplet size, or Sauter Mean Diameter (SMD), is an indication of atomizer performance. The SMD indicates the size of the droplets in the spray generated by the atomizer, thus providing a relative indication of atomizer performance when comparing results from the test fluids. Fluid properties and atomizer operating conditions can affect SMD by the general expression (Lefebvre, Gas Turbine Combustion, 1983) of:

$$SMD = (K*(\sigma*\upsilon*SG)^{0.25}*W_f^{0.25})/(\rho_{air}^{0.25}\Delta P_f^{0.5}) \quad [2]$$

Where:

K = constant

σ = fuel surface tension, dynes/cm

υ = fuel viscosity, cSt

SG = fuel specific gravity

ρ_{air} = air density, lb/ft^3

For additional detail on the atomizer hardware used to evaluate the fuels and fuel blends, Honeywell Documents 21-15778 and 21-15991 detail the hardware and fuels under test.

3.2.2 Test Facility

All of the atomizer bench testing was completed in the fuel component laboratory at the Honeywell facility in Phoenix, Arizona. Tests were completed in the Malvern test stand which allows various fuels to be tested at ambient and cold conditions. A schematic of the test setup is shown in Figure 2 and a photograph of the facility is shown in Figure 3.

Needle valves were employed to either bypass or route fuel through a heat exchanger when testing ambient or cold fuel. The heat exchanger was used to chill the fuel to a temperature of -40°C. Duratherm Heat Transfer Fluid was circulated through a counter-flow heat exchanger setup with the test fuel. The Duratherm fluid was chilled by flowing through a methanol containing cold cart. The cold cart was chilled by a liquid nitrogen (LN2) coil used to continuously maintain the methanol bath temperature with precise control. This setup was new for the spray lab and was a vast improvement on previous fuel chilling techniques. The counter-flowing Duratherm strategy allowed for precise temperature control of the test fluids without over-chilling the fluid. Over chilling has previously been used to ensure -40°F fuel temperatures at the atomizer exit and is not desirable, as it has the potential to cause wax crystals in the fuel and impact the atomization results.

Fuel temperatures and pressures were measured at the atomizer inlet (as well as throughout the fuel system) and fuel flow was measured using a Micro Motion mass flow meter upstream of the heat exchanger.

Spray droplet size was measured with a Malvern Spraytec particle analyzer. The Spraytec determines the spray droplet size distribution by analyzing the diffraction pattern produced by a laser beam passing through the spray. The Malvern Spraytec software includes corrections for multiple scattering in high concentration sprays. Drop size data is presented as SMD, which is a droplet with the same volume-to-surface area ratio as the entire spray. SMD has been shown to provide a good indication of atomization quality for correlating gas turbine combustor ignition and lean stability characteristics.

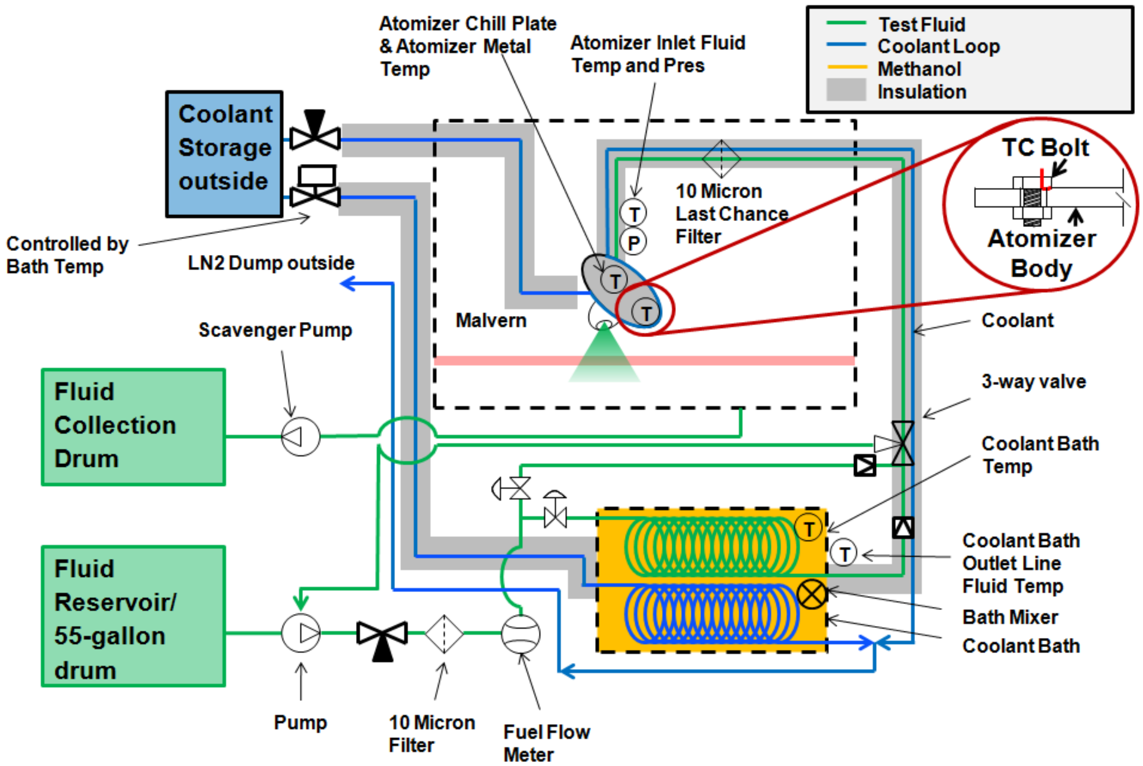

Figure 2. Malvern Test Stand Schematic.

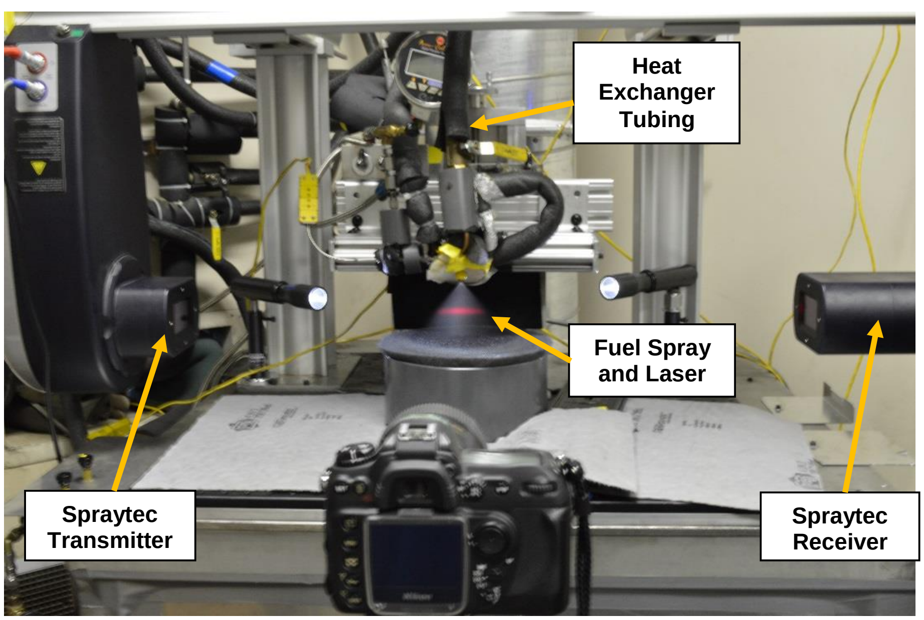

Figure 3. Updated Malvern Test Stand.

3.2.3 Test Conditions

Each atomizer was tested over a range of conditions representative of APU operation. For pressure atomizers, this requires a range of inlet fuel pressures. Measurements were taken with the fuels and atomizers at room temperature and at -40°F (-40°C) to simulate cold operation. For the Viscor calibration fluid only, the fluid temperature was controlled to achieve a 12 cSt viscosity during evaluation. Prior to testing, the Viscor fluid was sampled and analyzed for its 12 cSt temperature. That temperature (77°F or 74°F depending on batch) was maintained throughout testing to provide 12 cSt viscosity fluid to the atomizers under evaluation.

3.2.4 Test Results

The atomization and spray characteristics using the DLA Energy fuels, the Green Diesel fuel blends, and the 100 percent CHCJ-5 are detailed in their individual Honeywell Documents, 21-15991, Appendix 2 and Appendix 3, and 21-15778, respectively. Overall, warm fuels and fuel blends appear to behave similarly. However, at cold fuel (-40°C) conditions, the fuels and fuel blend droplet sizes and spray angles are predominantly driven by the fluid viscosity, with larger droplets and narrow spray angles occurring with higher viscosity fluids.

3.3 Summary

Atomizer spray performance at ambient and cold conditions was shown to not significantly degrade with use of the DLA Energy Category C fuels, the Green Diesel blends, nor the 100 percent CHCJ-5 fuel. Some fuels resulted atomizer performance decreasing at low pressures under cold fuel conditions due to viscosity near the 12 cSt limit at the -40°C test temperature. Fuel low temperature operating limits are typically set to a maximum viscosity of 12 cSt to ensure reliable APU cold starting.

Data for all fluids tested showed that increasing fuel pressure improves atomizer performance, thus generating smaller drop sizes and wider spray angles. This trend is due to the increase in pressure forces that overcome the fluid surface tension and viscosity. Cold sprays generated larger drop sizes due to the higher surface tension and viscosity occurring at low fuel temperatures.

4.0 131-9 COMBUSTOR RIG TESTS (TASK 6.2)

The 131-9 APU combustor rig evaluated combustor performance, lean stability and ignition performance of all six DLA Energy fuels and a 30 percent Neste Green Diesel blend with 70 percent petroleum-derived JP-8. There were no significant effects on combustor performance including thermodynamic pattern factor (PF) and radial profile due to fuel type. There were no significant differences in lean blowout fuel-air ratios or lean ignition fuel-air ratios for the Neste GD fuel blend evaluation, though some of the DLA Energy fuels did vary in operability results.

4.1 Introduction and Test Summary

The 131-9[B] combustor rig tests were conducted by Honeywell Aerospace, Phoenix, Arizona, supporting multiple efforts the contract, “Evaluation of Alternative Fuels for Use in Military Auxiliary Power Units and Engines Program” funded by USAF/AFRL Contract No. FA8650-09-D-2925 Task Order 0007.

4.1.1 General Information

Figure 4 shows a photograph of the combustor rig installed in the C-100 test cell. The rig is operated at full-engine conditions and is designed to duplicate the 131-9[B] engine combustion system aerodynamics from the deswirl exit to the turbine stator inlet plane. Engine components include the axial deswirl, combustor, outer transition liner, fuel atomizers, fuel manifolds, igniter plugs, ignition exciter, and inner transition liner.

The standard 131-9 ignition system, consisting of an igniter exciter and igniter was used. The igniter is located at roughly the 8 o’clock position, viewed from aft, looking forward. A dummy igniter position for instrumentation purposes is located near bottom dead center.

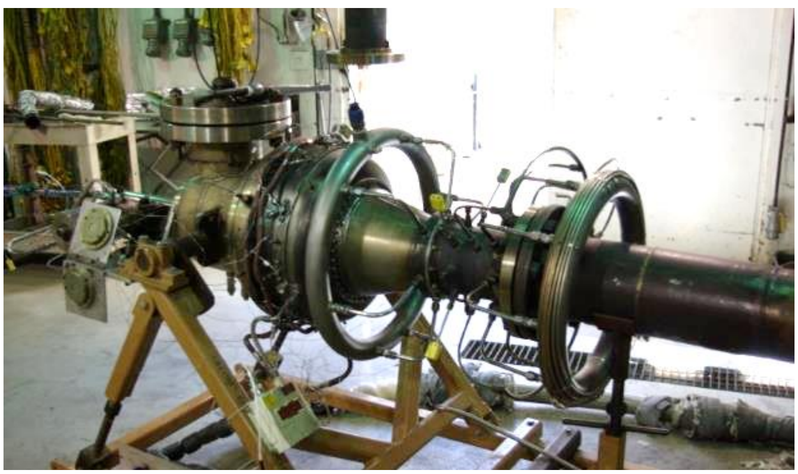

Figure 4. 131-9 Combustor Rig Installed in C-100 Test Cell.

4.1.2 Combustion System Hardware

The 131-9 combustor rig was used for multiple development tests in between DLA Energy and Neste GD blend evaluations. It was necessary to disassemble the rig in order to reassemble it as a 131-9[B] configuration for each fuel evaluation. The aero hardware that was utilized for this testing included the deswirl, combustor, containment ring, and the combustor case.

4.1.3 Fuel System

The 131-9[B] production fuel system, which consists of the fuel flow-divider and fuel atomizers, was used for this rig test. Fuel atomizers were flow tested prior to rig testing and after the test was completed. The multiple rig builds were required to complete the multiple test series, the atomizers were installed in the same locations and are documented in their respective test reports, which can be found in Honeywell Document 21-15989, Appendix 2 and Appendix 3.

4.1.4 Test Objectives

The overall goal of the DLA Energy combustor rig test was to probe various chemical and physical fuel properties and their impact on combustor performance and operability. For the Neste GD blend evaluation, the intent of the test was to determine if the 30 percent Neste GD blend resulted in any adverse effects on the 131-9 combustion system.

4.2 Hardware and Rig Inspections

4.2.1 Rig and Relevant Hardware

Standard pretest procedures were followed in order to ensure test hardware was ready for test and met specifications. Hardware was checked to make sure that the part and serial numbers were correct. Basic functionality checks were performed during assembly, such as verifying that the rotating drum turned freely and the igniter box was working properly.

4.2.2 Instrumentation Check

Instrumentation was also checked for basic functionality, which included thermocouple (TC) resistance to ground checks. All leads were securely tacked down with the proper identification names. Upon arriving at the test cell, a final instrumentation inspection was completed during the rig installation ensuring the test setup was complete.

4.2.3 Standard Instrumentation

Standard cell instrumentation was used during this test to monitor the usual rig test parameters such as inlet and exit conditions of airflow, temperature, pressure, and fuel flow.

4.2.4 Data Acquisition

Digital data acquisition recorded all measured parameters. Temperature and pressure traverses of the combustor exit gas path were performed with a rotating drum bearing a pressure rake and a temperature rake to cover the entire exit annulus. The fast-scan method was employed for all cases using both forward and reverse traverses in order to ensure repeatable data.

4.2.5 Test Fuels

Over the course of two separate efforts, nine fuels were evaluated on the 131-9 APU combustor rig which included the six DLA Energy fuels (A-1, A-2, A-3, C-1, C-2, and C-5) as well as the 30 percent Neste GD blend Jet A and JP-8 baselines.

The test fuels and fuel blends were supplied to the C-100 combustor test cell in 55-gallon barrels. The DLA Energy fuels were evaluated as delivered to Honeywell; these fuels were evaluated neat or were pre-blended, so no blending at Honeywell was required. The 30 percent Neste GD blend was prepared using 55-gallon drums. The 30 percent Neste GD blend was created by filling an empty, clean, and dry 55-gallon drum with 15 gallons of the neat Neste GD. A graduated aluminum measuring stick was used to gauge the height of the fuel in the drum (~10 in). The drum was then filled with 35 gallons of JP-8 (~24 in). Prior to collecting rig test data, fuel properties for each fluid under test were verified by the Honeywell Chemistry Laboratory. Detailed fuel properties can be found in their respective test reports, but a summary of fuel properties from the combustor rig tests can be found in Table 5.

4.2.6 Fuel Sample Analysis

Before testing with each fuel, the test cell fuel system was flushed with the new test fuel. Fuel samples were obtained at the beginning and the end of the rig tests. Samples were analyzed confirming the fuel system was thoroughly flushed.

Table 5. Combustor Rig Test Fuel Properties.

Fluid	Specific Gravity	LHV MJ/kg	Freeze Point °C	Viscosity at 25°C, cSt	Aromatics %t
DLA A-1	0.781	43.5	-50	1.40	10.0
DLA A-2	0.804	43.2	-49	1.65	15.0
DLA A-3	0.827	43.1	-50	2.01	15.0
DLA C-1	0.761	44.0	< -80	1.93	1.0
DLA C-2	0.782	43.5	-45	1.75	14.5
DLA C-5	0.772	43.3	-58	0.93	26.0
30% Neste GD	0.780	43.7	-44	1.89	7.0

4.3 Test Results

Test results are detailed in the individual reports found in 21-15989 and Appendix 3. DLA Energy combustor rig test results illustrated that viscosity appeared to play a primary role in both ignition and lean blowout results. Smoke emissions appeared to have additional drivers other than aromatic content or hydrogen-to-carbon ratio. Combustor performance parameters like pattern factor, radial profile, and gaseous emissions appeared to be rather insensitive to the various fuel properties.

As for the 30 percent Neste GD blend evaluation, the GD blend performed similarly to the Jet A and JP-8 baseline fuels with respect the combustor performance (pattern factor and radial profile), gaseous, and smoke emissions as well as cold and altitude ignition. However, there were a few lean blowout conditions that the 30 percent-Neste GD blend performed worse than the baseline Jet A fuel.

4.4 Conclusions

For the DLA Energy evaluation, six fuels with varying physical and chemical properties were evaluated to determine their impact on 131-9[B] APU combustion system performance, gaseous and smoke emissions, operability (LBO), and ignition characteristics. Combustion performance measurement results indicated that all fuels were acceptable and showed no adverse effects on combustion system performance (pattern factor and radial profile). The fuels did produce different smoke emissions which were largely correlated to the fuel hydrogen content. Gaseous emissions were similar with all fuels. Ignition and LBO characteristics appeared to be primarily based on the fuel viscosities with the lowest viscosities resulting in the lowest LBO and ignition FARs.

For the Neste GD evaluation, combustor rig test results showed there was no adverse effect of a 30 percent blend of low freeze point GD SPK and conventional petroleum derived jet fuel on combustion performance (pattern factor and profile), ignition characteristics, and exhaust gaseous emissions, with a significant reduction in exhaust smoke emissions. However, a few lean blowout conditions resulted in higher blowout FARs when compared to the baseline Jet A fuel.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This report, prepared by Honeywell Aerospace (Phoenix, Arizona), summarizes testing and analysis of multiple fuel evaluation efforts. Fuel evaluations for DLA Energy, multiple Green Diesel evaluations, and a 100 percent CHCJ-5 fuel effort supporting a Navy fuel evaluation were all part of the USAF contract FA8650-09-D-2925 Task Order 0007. As part of the USAF contract, Honeywell conducted atomizer spray tests and 131-9 APU combustor rig tests using several fuels and fuel blends.

Atomization spray characteristics were evaluated using multiple fuels and fuel blends. The droplet sizes and spray angles appeared to be attributed to fuel viscosities; with the higher the fuel viscosity resulting in the larger droplets. The greatest differences were observed in smaller atomizers where viscosity effects were pronounced. There were no adverse effects on atomizer performance with the GD blends. Atomizer spray performance at ambient and cold conditions was shown to not significantly degrade with use of the GD blends. This difference in droplet size was well correlated to the fluid viscosities.

The DLA Energy fuels and a Neste GD fuel blend were used with a 131-9 APU combustor rig test in order to evaluate their impact to combustor performance, operability, and ignition characteristics. The performance (pattern factor and radial profile) of all fuels were similar. For the DLA Energy evaluation, combustor operability appeared to be impacted by the fuel viscosities. Results from the 30 percent Neste GD blend were compared to results with a baseline Jet A and baseline JP-8 fuel and results indicated that the Neste blend was similar at most conditions but appeared to be worse than the baseline Jet A fuel for multiple LBO conditions.

REFERENCES

Document Number	Title
FAA Advisory Circular	
AC20-24C	Approval of Propulsion Fuels and Lubricating Oils
SAE and ASTM Documents	
ASTM D1655	Standard Specification for Aviation Turbine Fuels
ASTM D4054	Standard Practice for Qualification and Approval of New Aviation Fuels and Fuel Additives
ASTM D7566	Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons
SAE ARP1179D	Aircraft Gas Turbine Engine Exhaust Smoke Measurement
SAE ARP1256D	Procedure for the Continuous sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines
SAE ARP1533B	Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines
Military Documents	
MIL-DTL-5624	Turbine Fuel, Aviation, Grades JP-4 and JP-5
MIL-DTL-83133	Turbine Fuels, Aviation, Kerosene Types, NATO F-34 (JP-8), NATO F-35, and JP-8+100
MIL-HDBK-510-1	Aerospace Fuel Certification
MIL-PRF-7024	Calibrating Fluids, Aircraft Fuel System Components
MIL-PRF-7808	Lubricating Oil, Aircraft Turbine Engine, Synthetic Base
MIL-STD-45662	Calibration System Requirements
Misc. Documents	
ICAO Annex 16	Volume II Aircraft Engine Emissions
Honeywell Documents	
21-14520	Summary of USAF Evaluation of Fischer-Tropsch Jet Fuel for Use in Military Auxiliary Power Units and Military Engines
21-15351B	Evaluation of Hydroprocessed Esters and Fatty Acids (HEFA) for Use in Military Auxiliary Power Units and Engines
21-15516	Evaluation of Alternative Fuels for Use in Military Auxiliary Power Units and Engines

Document Number	Title
21-15778	Navy Aircraft Biofuels Program Atomizer Spray Bench Test Results Using 100 Percent CHCJ-5 Fuel
21-15989	Test Report: DLA Fuel Evaluation in the 131-9 APU Combustor Rig
21-15990	Test Report: DLA Fuel Evaluation in the 131-9 APU Combustor Rig – Unlimited Rights
21-15991	DLA Energy Atomizer Spray Bench Test Report Using Alternative Fuels
21-15992	DLA Energy Atomizer Spray Bench Test Report Using Alternative Fuels – Unlimited Rights
Appendix 1	Defense Logistics Agency (DLA) Energy Fuel Evaluations: Presentation of Atomizer Spray and Combustor Rig Testing
Appendix 2	Honeywell Rig and Engine Tests Using Green Diesel Fuel Blends
Appendix 3	Honeywell Tests to Evaluate a Low Freeze Point Green Diesel Fuel Blend

APPENDIX 1. DEFENSE LOGISTICS AGENCY (DLA) ENERGY FUEL EVALUATIONS: PRESENTATION OF ATOMIZER SPRAY AND COMBUSTOR RIG TESTING

(37 pages)

Randy Williams
Brad Culbertson
Tom Johnson
Honeywell Aerospace

DLA ENERGY FUEL EVALUATIONS

Atomizer Spray and Combustor Rig Testing

June 23, 2016

Honeywell

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Agenda

1

- Program Overview
- Fuel Handling and Blending
- Fuel Properties
- Atomizer Bench Test
- Combustor Rig Test
- Summary

Program Overviews

- Defense Logistics Agency (DLA) Energy evaluation of fuels related to National Jet Fuel Combustion Program (NJFCP)
  - Evaluated six fuels with atomizer spray and combustor rig testing
    - A-1 (JP-8), 'best' case Jet A
    - A-2 (Jet A), 'average' case Jet A
    - A-3 (JP-5), 'worst' case Jet A
    - C-1 (100% Gevo ATJ), low cetane number
    - C-2 (C-14 iso-paraffin blended with 1,3,5-trimethylbenzene), bi-modal with aromatic front end
    - C-5 (C-10 iso-paraffin blended with 1,3,5-trimethylbenzene), 'flat' distillation range
  - Evaluations consisted of atomizer spray and combustor rig testing

Honeywell

3

Fuel Handling

- 100 gallons of each DLA fuel provided by USAF
- Drums supplied to test cell in 55-gallon drums
  - One 'run drum' supplied combustor rig test cell
  - Other drum used to replenish 'run drum' as needed
  - 1-pint fuel sample pre-test
  - 1-pint fuel sample post-test
- Drums placed on spill pallets, electrically grounded, with flame arrestors installed
- Fuel system flushed with test fuel and properties verified prior to test

Drum Setup for Combustor Rig Testing

Atomizer Spray Drum Setup Similar to Combustor Rig

4

Fuel Properties

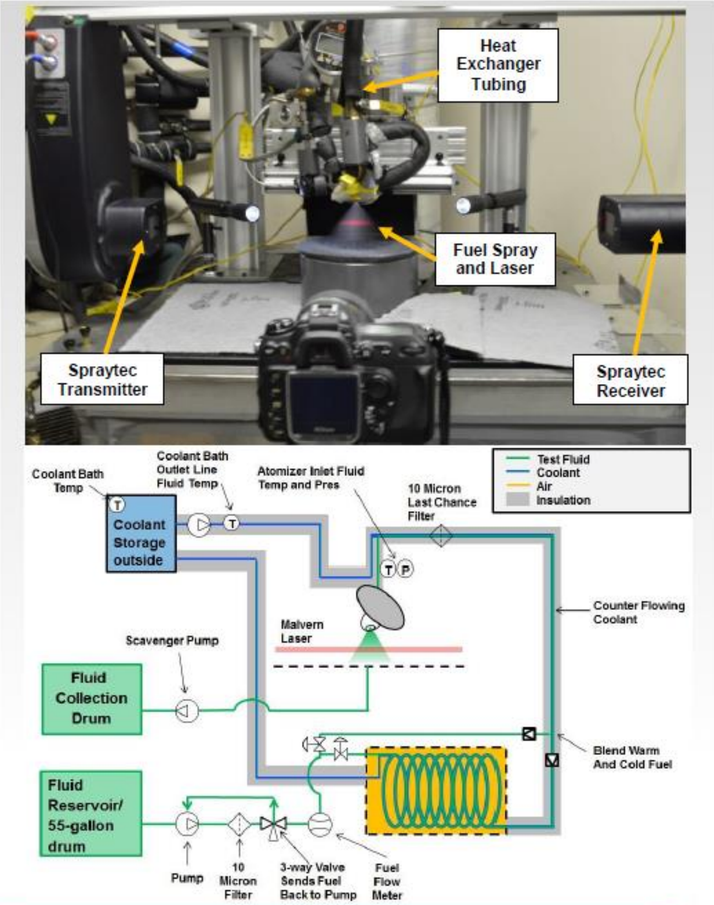
		A-1 (JP-8)	A-2 (Jet A)	A-3 (JP-5)	C-1 (ATJ)	C-2 (C14/TMB)	C-5 (C10/TMB)
LHV	MJ/kg	43.5	43.1	43.1	44.0	43.4	43.3
Density	kg/L	0.780	0.804	0.826	0.761	0.782	0.772
Viscosity @ 25°C	cSt	1.4	1.7	2.0	1.9	1.8	0.93
Viscosity @ -20°C	cSt	3.5*	4.3*	6.2*	5.3*	5.0*	1.9*
Boiling Range	°C	149-256	156-268	182-266	171-264	172-240	157-172
Aromatics	%	10.0	15.0	15.0	1.0	14.5	26.0
Freeze Point	°C	-50	-49	-50	< -80	-45	-58
Smoke Point	mm	32.6	23.7	19.8	37.5	29.6	22.7
Flash Point	°C	36	43	56	46	56	39

*Calculated from 25°C and 40°C viscosities

Fuels Evaluated as Received

Atomizer Bench Spray Test

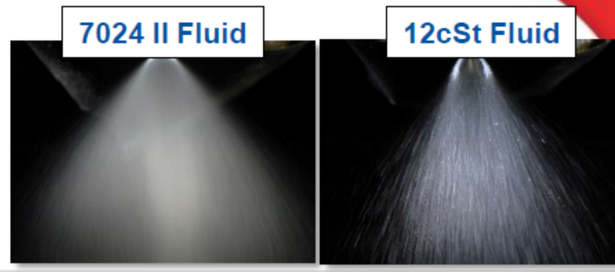
- Two pressure-type atomizers tested
  - Small flow number atomizer
    - Tends to be sensitive to fuel property variations
  - Large flow number atomizer
- All Fuels Evaluated at ambient & cold (-40°C) fuel temperatures
- Calibrating fluid (7024 Type II) and Viscor 12 cSt fluid run at ambient temperatures for comparison
  - 7024 II viscosity similar to warm JP-4
  - Viscor 12cSt viscosity similar to -40°C Jet A
- Fuel pressure, temperature, flow rate, spray angle, and spray droplet size measured
  - Droplet size measured with Malvern Spraytec laser diffraction instrument



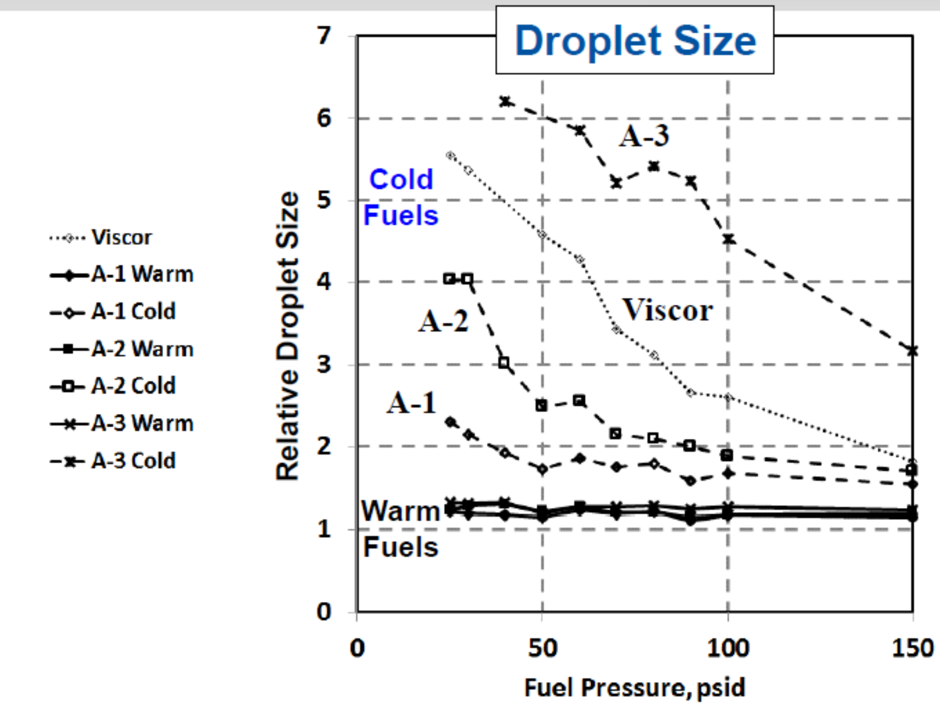
Setup Consistent Throughout All Programs

Small Atomizer Spray Testing

6



- Droplet size with warm Category A fuels are similar to 7024 Type II calibration fluid
- Droplet size highly correlated to fuel viscosity
  - Viscosity at -40°C
    - 6.6* cSt for A-1
    - 8.5* cSt for A-2
    - 13.4* cSt for A-3
- Droplet size with cold A-1 and A-2 fuels well below Viscor (12 cSt) fluid limit
  - A-3 above Viscor limit
- A-3 data shows why 12cSt max viscosity limit at -40°C needed for alternative fuels



*Calculated from 25°C and 40°C viscosities

Droplet Size Highly Dependent on Fuel Viscosity

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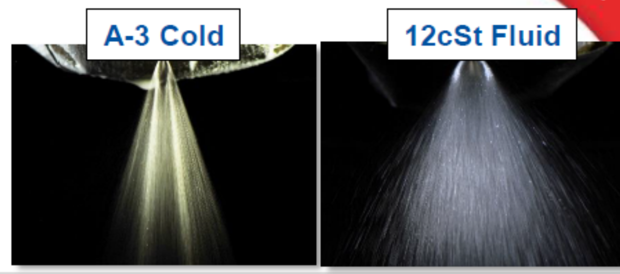
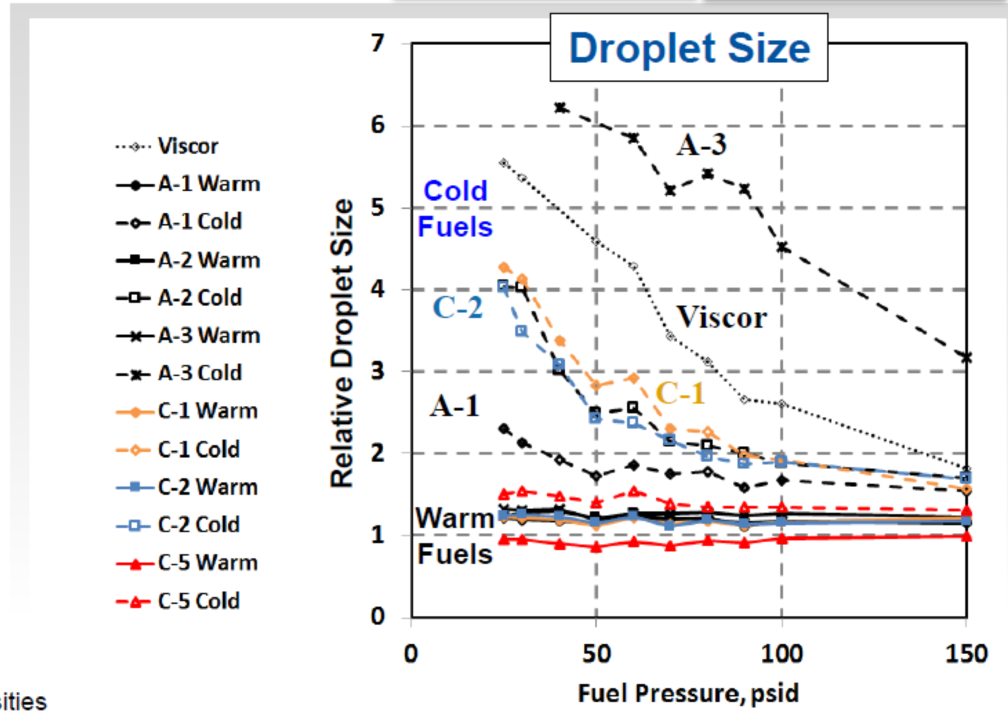
Small Atomizer Spray Testing



- Droplet size with warm Category C fuels are similar to 7024 Type II calibration fluid
- Droplet size highly correlated to fuel viscosity
  - Viscosity at -40°C
    - 10.8* cSt for C-1
    - 10.5* cSt for C-2
    - 2.9* cSt for C-5
- Droplet size with cold C-1 and C-2 fuels similar to A-2 and well below Viscor (12 cSt) limit
- Droplet size with cold C-5 fuel similar to warm fuels



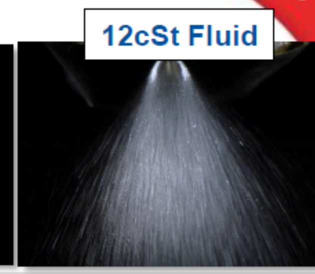
*Calculated from 25°C and 40°C viscosities

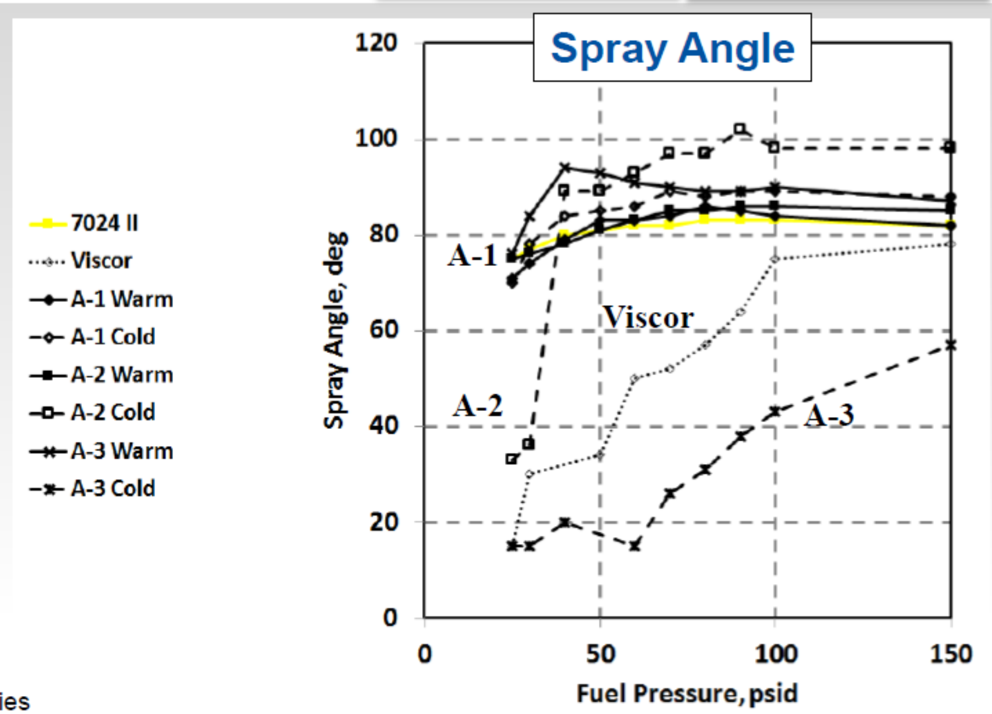
Droplet Size Highly Dependent on Fuel Viscosity

Small Atomizer Spray Testing

- Spray angles with warm Category A fuels are similar to 7024 Type II calibration fluid
- Spray angles with cold Category A fuels vary
  - A-3 spray collapses faster than Viscor spray
  - A-2 spray similar to 7024 II fluid, then collapses ~30psi
  - A-1 spray remains similar to 7024 II fluid throughout pressure range
- Viscosity impacts spray angle at low pressures
  - Viscosity at -40°C
    - 6.6* cSt for A-1
    - 8.5* cSt for A-2
    - 13.4* cSt for A-3

*Calculated from 25°C and 40°C viscosities





Spray Angle Dependent on Fuel Viscosity

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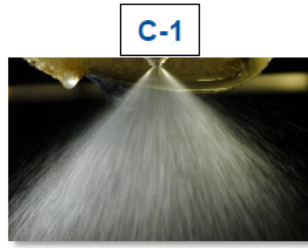
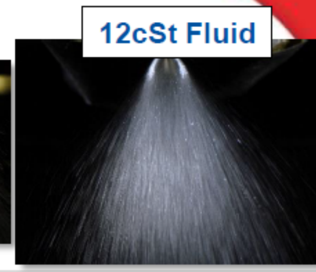
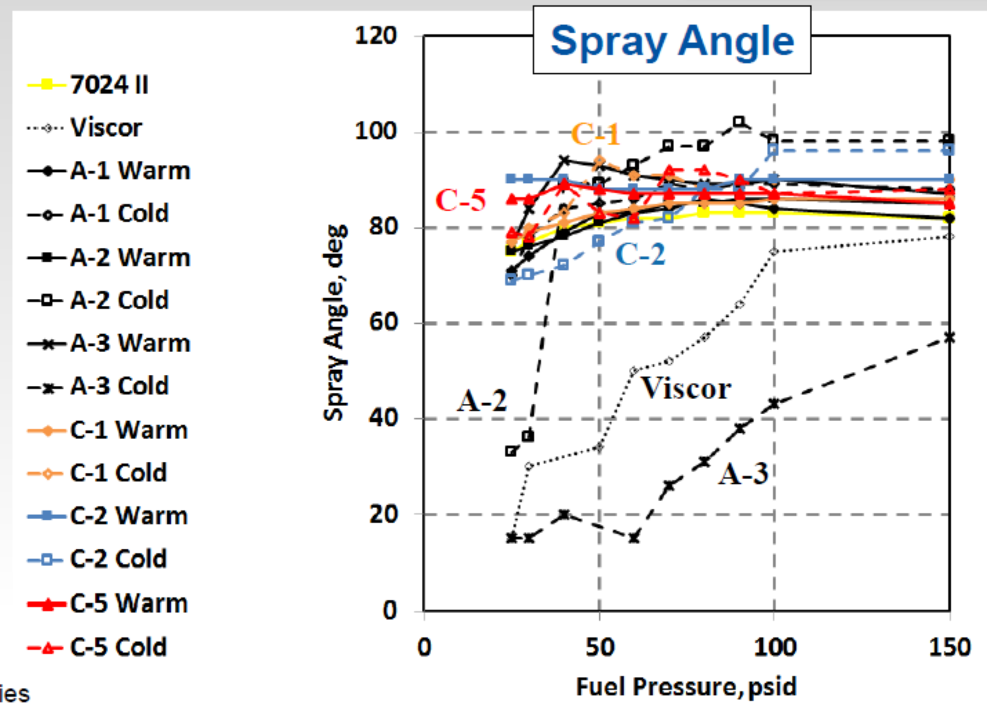
Small Atomizer Spray Testing





- Spray angles with warm Category C fuels are similar to 7024 Type II calibration fluid
- Spray angles with cold Category C fuels are more consistent than Category A fuels
  - C-1 & C-5 maintain spray angle over range of pressures
  - C-2 spray collapses slightly at lower pressures
- Based on viscosity, cold Category C fuel spray angles should lie between A-2 and A-3 fuels
  - Viscosity at -40°C
    - 10.8* cSt for C-1
    - 10.5* cSt for C-2
    - 2.9* cSt for C-5

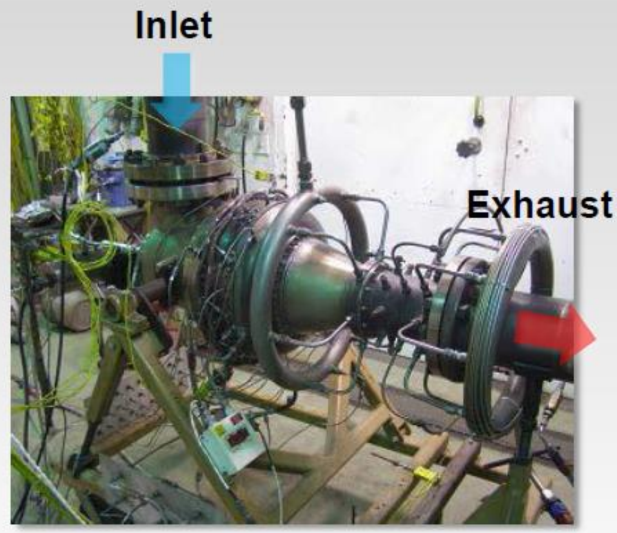


*Calculated from 25°C and 40°C viscosities

Spray Angle Dependent on Fuel Viscosity

Combustor Rig Testing

- Full annular 131-9 (B737 / A320) combustor rig run at full scale conditions
- 131-9 combustor rig used for ATJ (USAF), FAA/Volpe Center emerging fuels, and DLA Energy alternative fuel evaluation programs
  - DLA Energy evaluation November 2015
- Combustor rig evaluated:
  - Combustor performance (pattern factor, radial profile, gaseous and smoke emissions)
  - Ignition characteristics
    - Ground and high altitude (41,000 feet)
  - Lean stability (lean blowout)
    - Ground & in-flight conditions



- Fuel flows adjusted to maintain constant heat input to rig
  - Relative to A-2

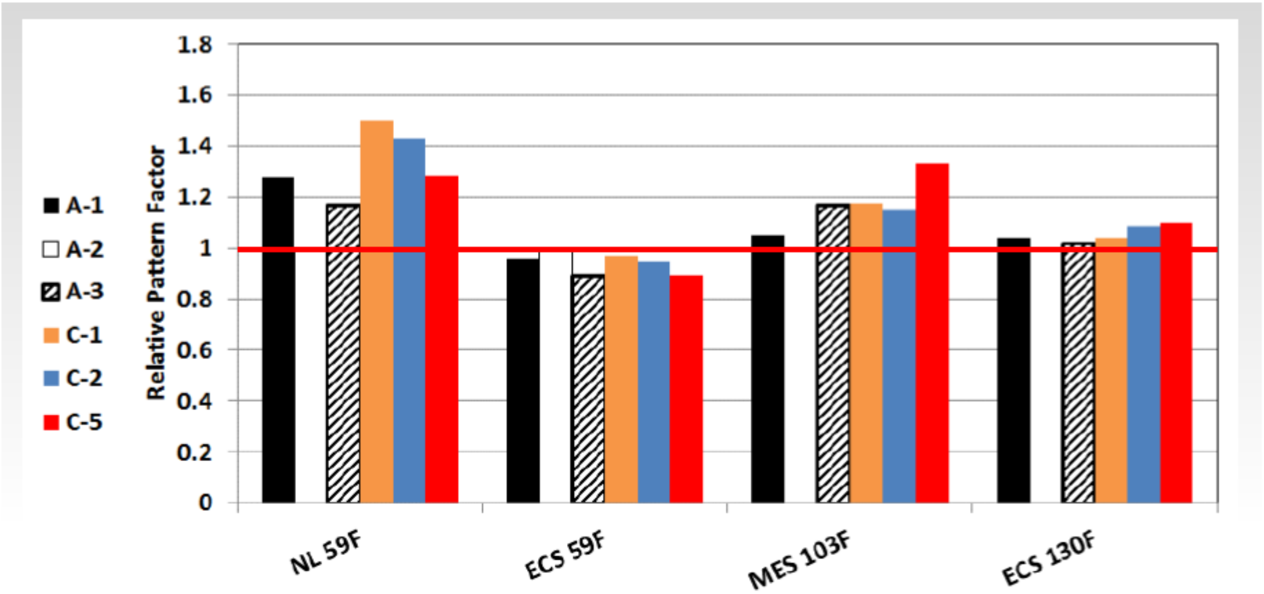
Setup Consistent Throughout All Programs

Combustor Rig Results – Pattern Factor

- Pattern factor (PF) is measure of temperature distribution at combustor exit

$$PF = \frac{(T_{exit, max} - T_{exit, avg})}{(T_{exit, avg} - T_{in})}$$

- Pattern Factors are relative to A-2 fuel



Some Test-to-Test Variation Observed in PF Results

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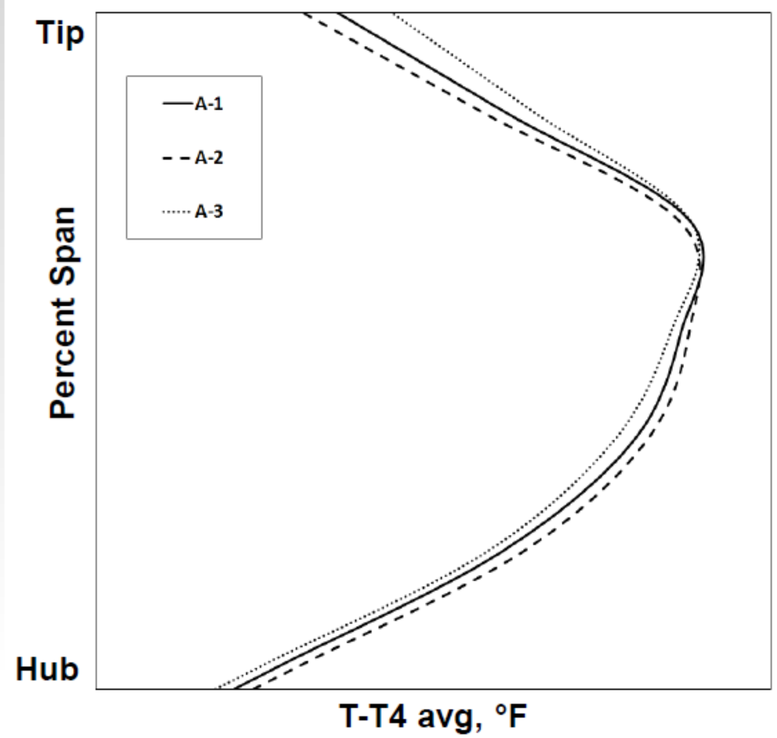
Combustor Rig Results – Radial Profile

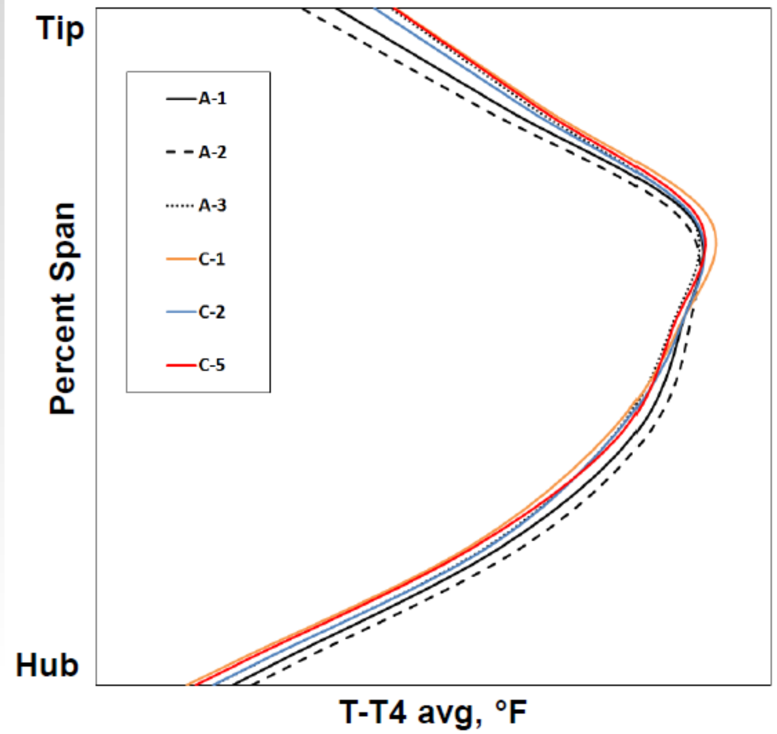
- Radial profile is average radial temperature distribution seen by turbine blades
- Some normal test-to-test variation between Category A fuels



No significant fuel effect on radial profile for Category A fuels

Combustor Rig Results – Radial Profile

- Radial profile is average radial temperature distribution seen by turbine blades
- Some normal test-to-test variation between Category A fuels
- Category C fuels have similar radial profile to Category A fuels and within historical experience
  - Differences near tip and hub may be due to seal leakage or cooling air

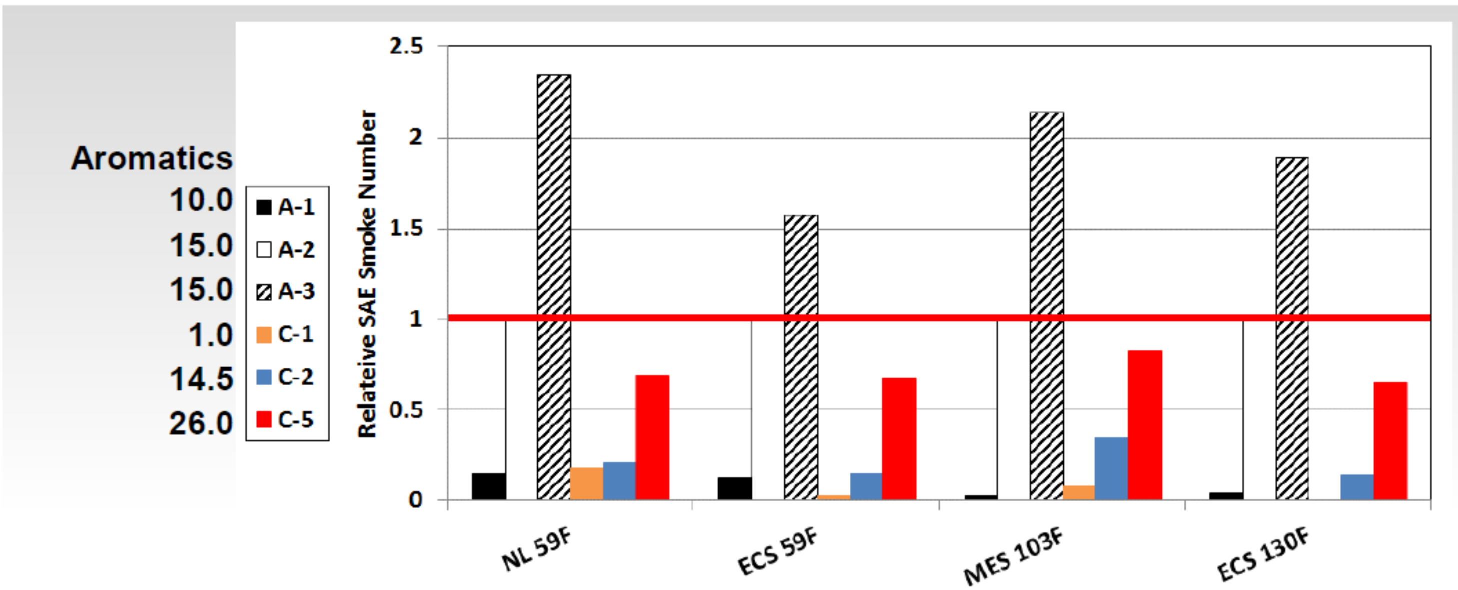


Category C Fuels have Similar Profile to Cat A Fuels

14

Combustor Rig Results – Smoke Emissions

- SAE smoke number measured using Rolls-Royce Optical Smoke Meter (calibrated to ARP1179D measurement)
- 131-9 smoke emissions are very low (≤10)
- Smoke numbers are relative to A-2 fuel
  - A-3 smoke emissions are double A-2



A-1 and Synthetic Fuels Produce Less Smoke

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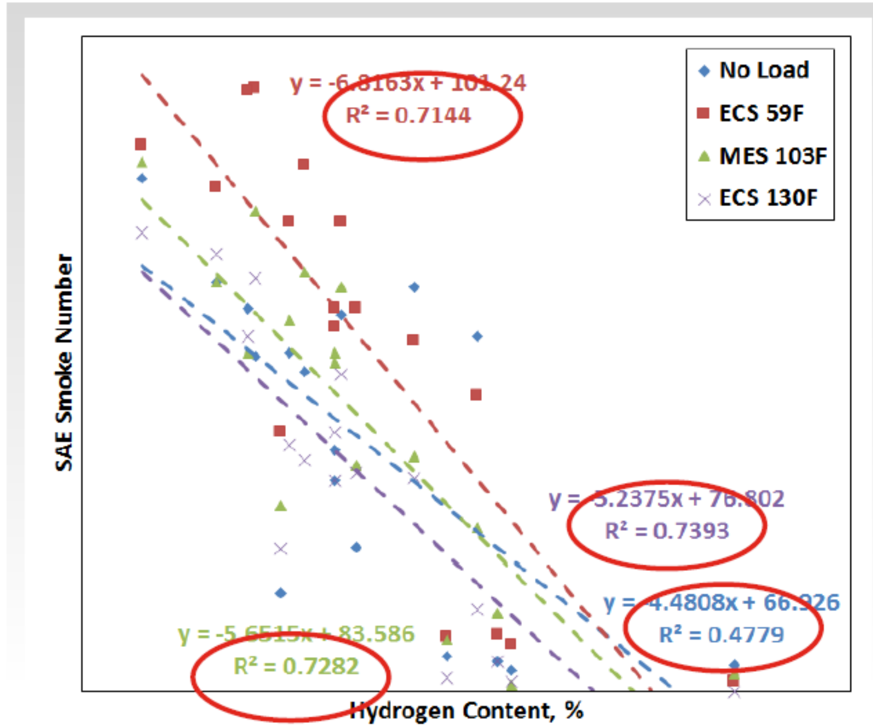
Combustor Rig Results – Smoke Emissions

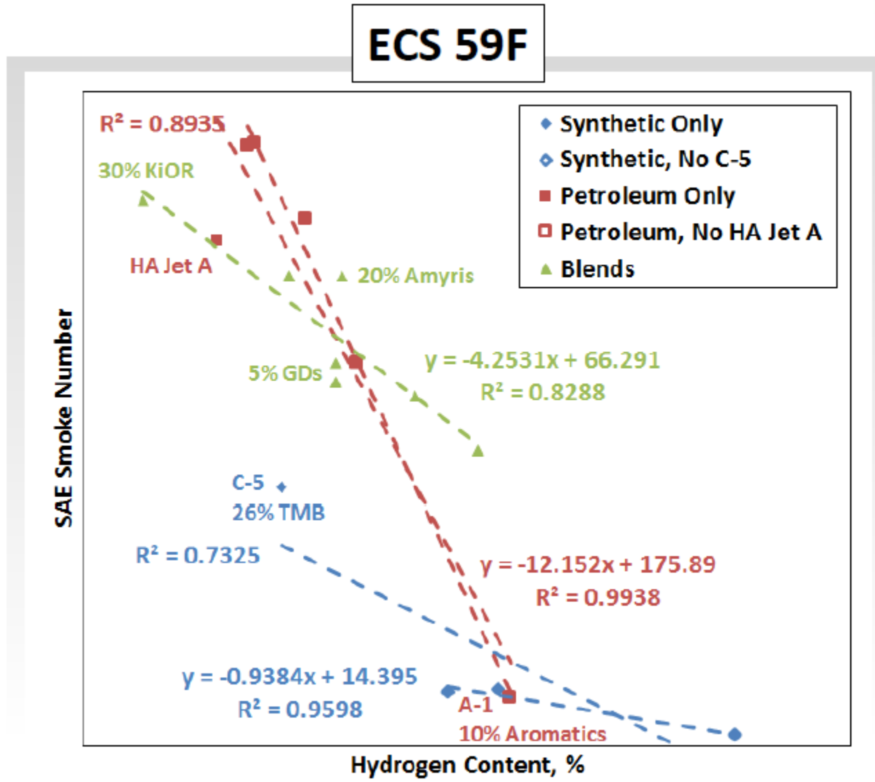
- Hydrogen content is a major factor to smoke emissions
  - Though not the only factor
- Data collected from several rig installations with several petroleum, synthetic, and blended fuels
- All conditions result in similar linear agreements and data scatter



Fuel Hydrogen Content Correlates Reasonably to Smoke Number

Combustor Rig Results – Smoke Emissions

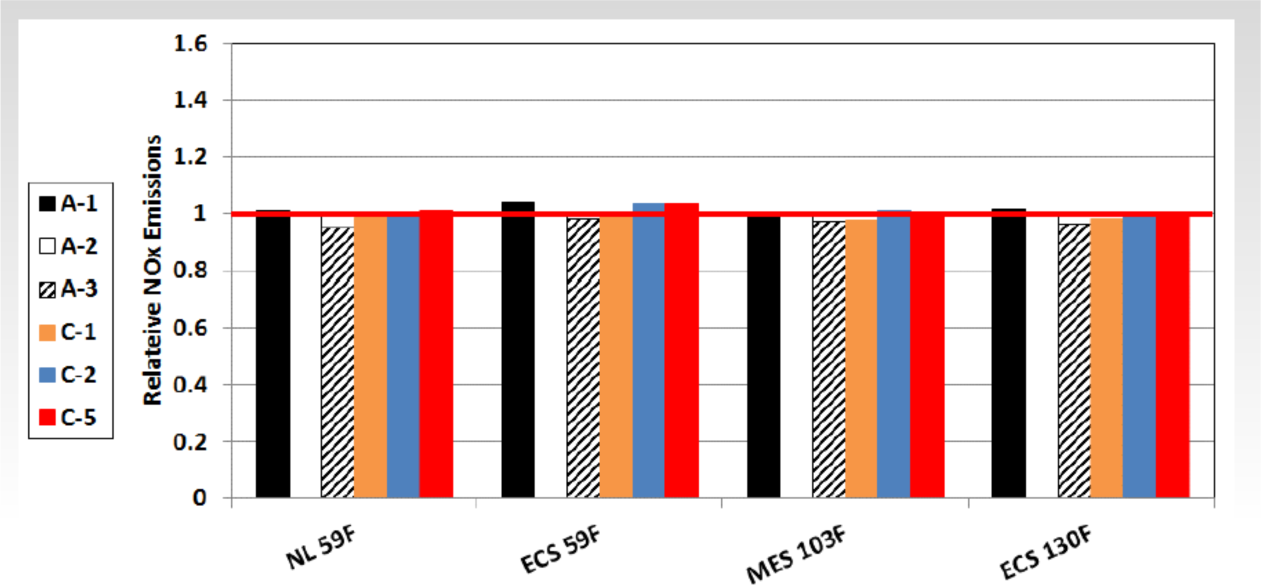
- When broken down into subcategories, the linear agreements improve
  - Petroleum fuel highly dependent on hydrogen content
  - Blends less dependent than petroleum only fuels on hydrogen content
  - Synthetic fuels show even less dependence on hydrogen content
- Category A-1 fuel resulted in similar hydrogen content and smoke number as synthetic fuel
- Degree of hydrotreating plays factor?



Hydrogen Content Correlates Better When Broken Down

Combustor Rig Results – NOx Emissions

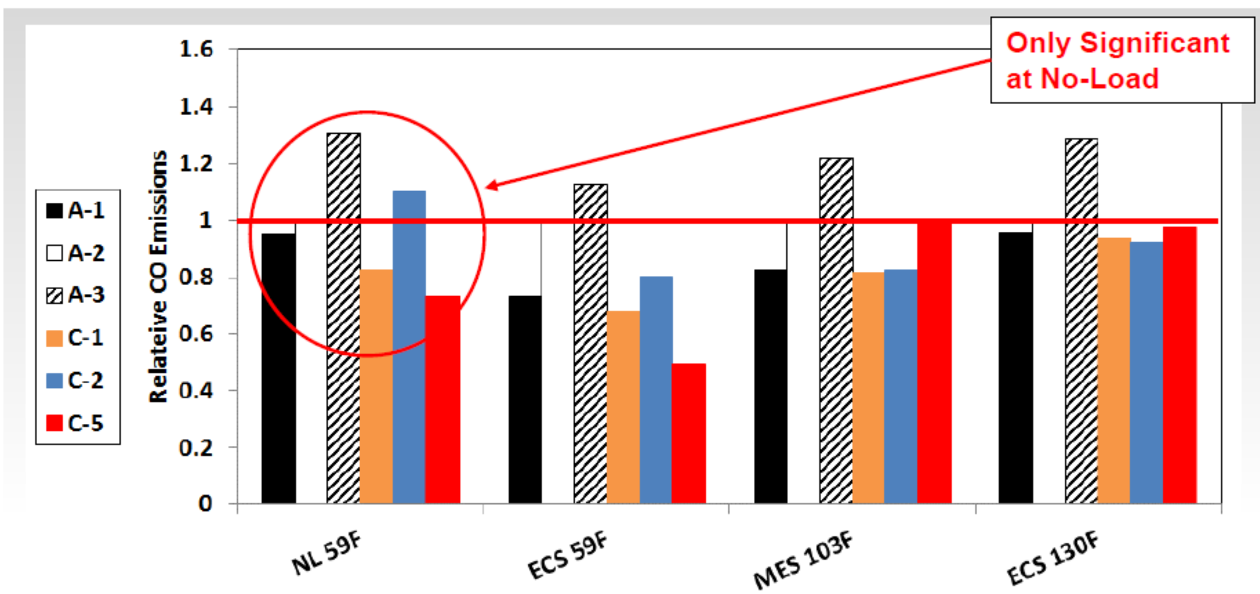
- Nitrogen Oxides (NOx) emissions measured to ARP1256D requirements
- NOx emissions with all fuels are similar
- NOx EI are relative to A-2 fuel



All Fuels Produce Similar NOx Emissions

Combustor Rig Results – CO Emissions

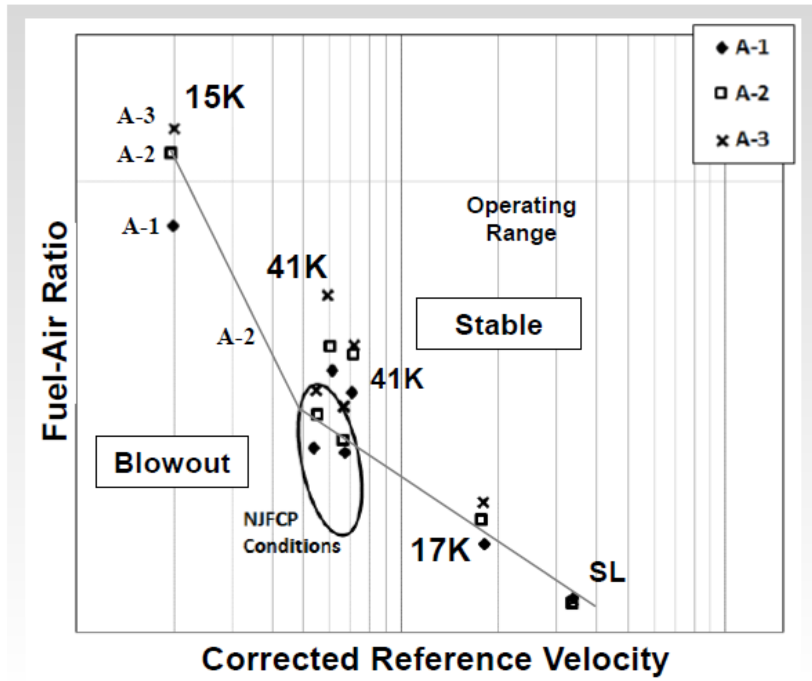
- Carbon monoxide (CO) emissions measured to ARP1256D requirements
- CO emissions are very low at loaded conditions, only significant at No-Load
  - Variation at loaded conditions within measurement error
- CO EI are relative to A-2 fuel



A-3 & C-2 Produce Higher CO Than A-2; C-1 and C-5 Produce Lower CO

131-9 Combustor Rig Results – Lean Blowout

- LBO run over range of flight conditions
  - SL to 41K feet altitude
  - Ambient fuel temperature
- LBO conditions represent no-load operation
  - 15k condition is part speed transient condition
- Also ran NJFCP Area 6 conditions (30 psia, 250°F, 3% & 4.5% DP/P
- Inlet conditions set, then fuel flow is gradually reduced until blowout occurs
- General order of fuels was (best to worst): A-1, A-2, A-3



Some Scatter Between Various Rig Installations

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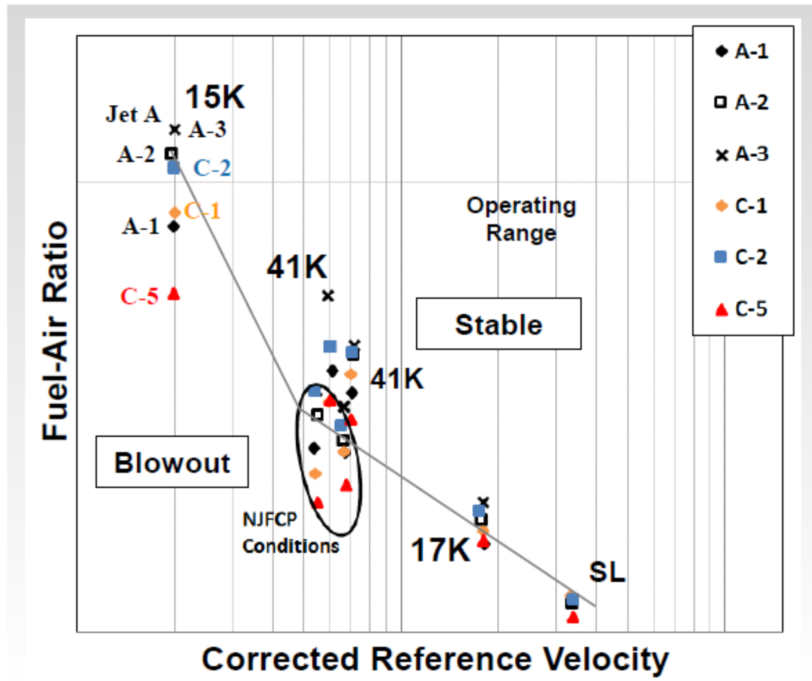
131-9 Combustor Rig Results – Lean Blowout

- LBO run over range of flight conditions
  - SL to 41K feet altitude
  - Ambient fuel temperature
  - No-load and part speed conditions
  - Also ran same conditions as NJFCP Area 6 (30 psia, 250F, 3 and 4.5% DP/P)
- Fuel property effects more visible at more challenging conditions (low V_{ref})
- General fuel order was:
  - Best – C-5
  - A-1 and C-1 similar
  - A-2 and C-2 similar
  - Worst – A-3
  - Some variation condition to condition



C-5 Had Best Blowout Characteristics, A-3 the worst

DLA LBO Order

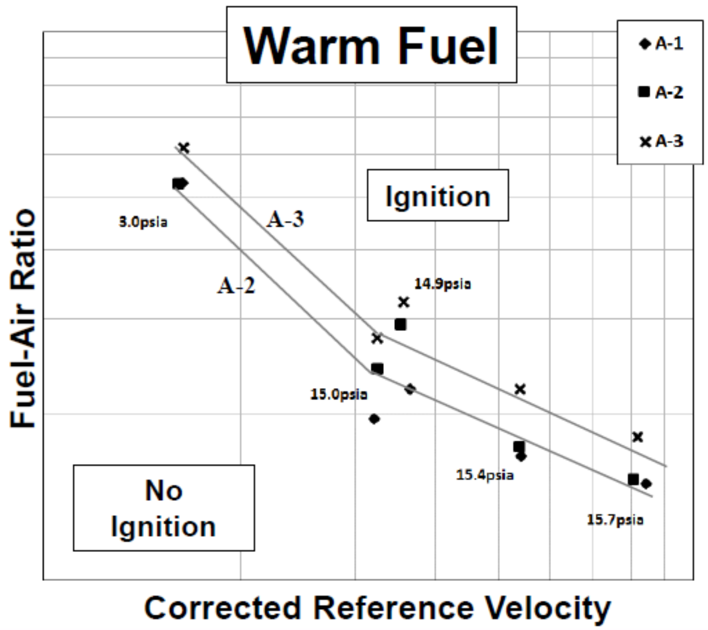
	Sea Level	17k	41k Low M	41k High M	15k 50%	NJFCP 3%	NJFCP 4.5%
Best	C-5	A-1	C-1	C-5	C-5	C-5	C-5
	A-2	C-5	C-5	A-1	A-1	C-1	A-1
	C-2	C-1	A-1	C-1	C-1	A-1	C-1
	A-3	A-2	C-2	A-2	C-2	A-2	A-2
	A-1	C-2	A-2	C-2	A-2	C-2	C-2
Worst	C-1	A-3	A-3	A-3	A-3	A-3	A-3

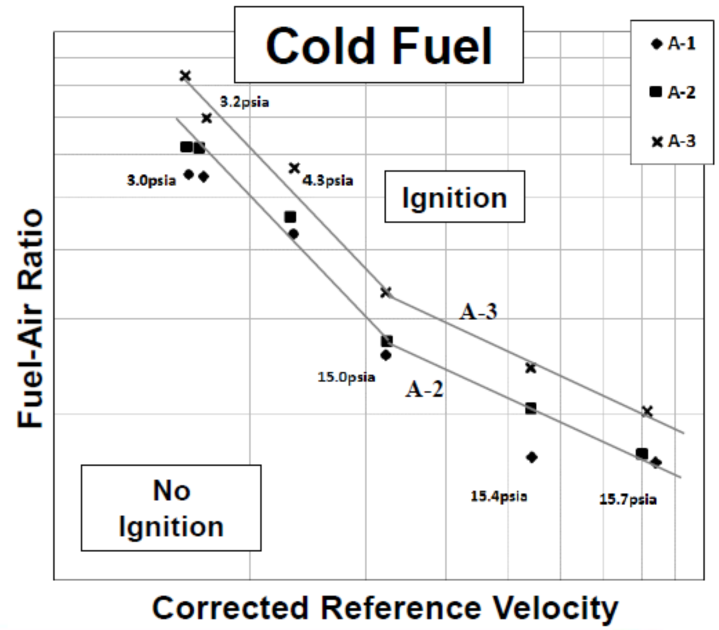
Fuel	C-5	A-1	A-2	C-2	C-1	A-3
Viscosity @ 25°C	0.93	1.4	1.7	1.8	1.9	2.0

C-5 has best LBO, A-3 has worst LBO

131-9 Combustor Rig Results – Ignition

- Lean ignition run over range of flight conditions
  - SL to 41K feet altitude
  - Ambient and cold (-29°C to -37°C) fuel temperatures
- Inlet conditions set - then ignition fuel flow reduced in steps until lean limit defined (1-sec ignition delay)





A-1 and A-2 Similar, A-3 Required Higher Ignition Fuel Flows

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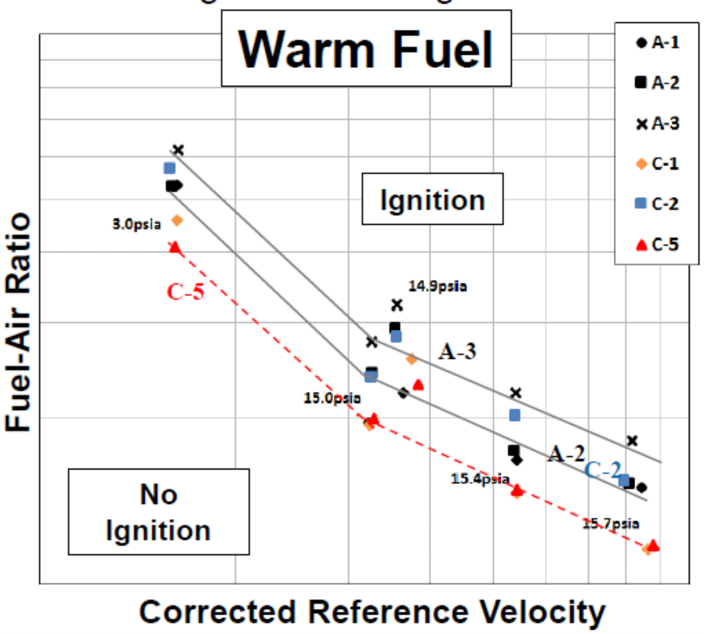
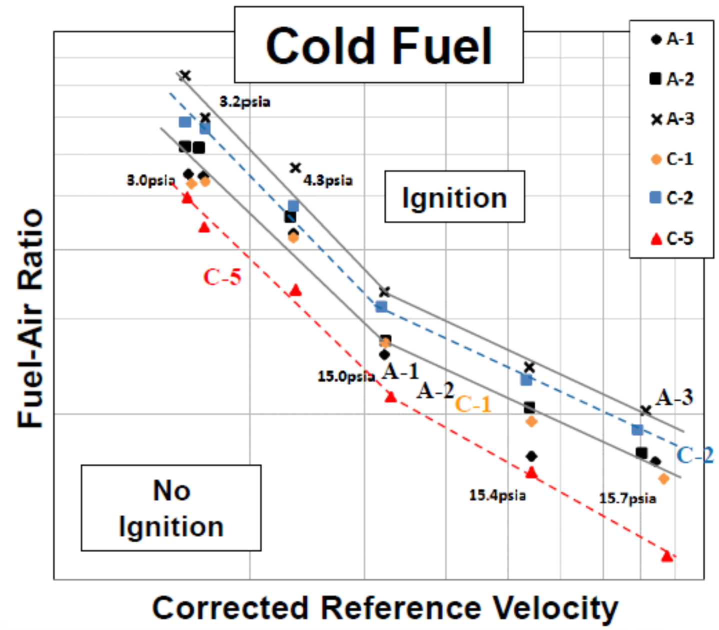
131-9 Combustor Rig Results – Ignition

- For warm fuel C-1 and C-5 ignition FAR lowest (best), A-1 & A-2 & C-2 similar, A-3 ignition FAR highest
- For cold fuel C-5 ignition FAR lowest, A-1 & C1 similar, A-2 & C-2 similar, A-3 highest ignition FAR (worst)
- Lean ignition FAR higher with cold fuel than warm fuel





C-5 Has Best Ignition Characteristics, C-1 & C-2 Similar to A Fuels

DLA Cold Fuel (-35F) Ignition Order

	Sea Level 10%N	41k ISA 15%N	SL -40F 15%N	SL, -40F 10%N	35k Cold Day	41k Cold Day
Best	C-5	C-5	C-5	C-5	C-5	C-5
	C-1	C-1	A-1	A-1	C-1	C-1
	A-1	A-1	C-1	C-1	A-1	A-1
	A-2	A-2	A-2	A-2	A-2	A-2
	C-2	C-2	C-2	C-2	C-2	C-2
Worst	A-3	A-3	A-3	A-3	A-3	A-3

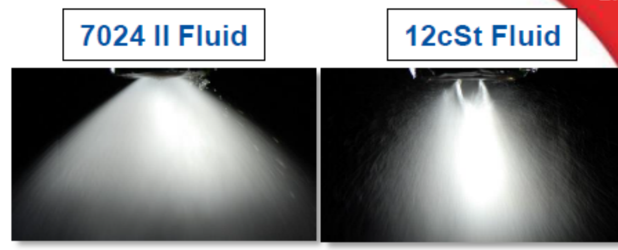
Fuel	C-5	A-1	A-2	C-2	C-1	A-3
Viscosity @ -35°F	2.7	6.0	7.6	9.3	9.7	12.5

Summary & Conclusions

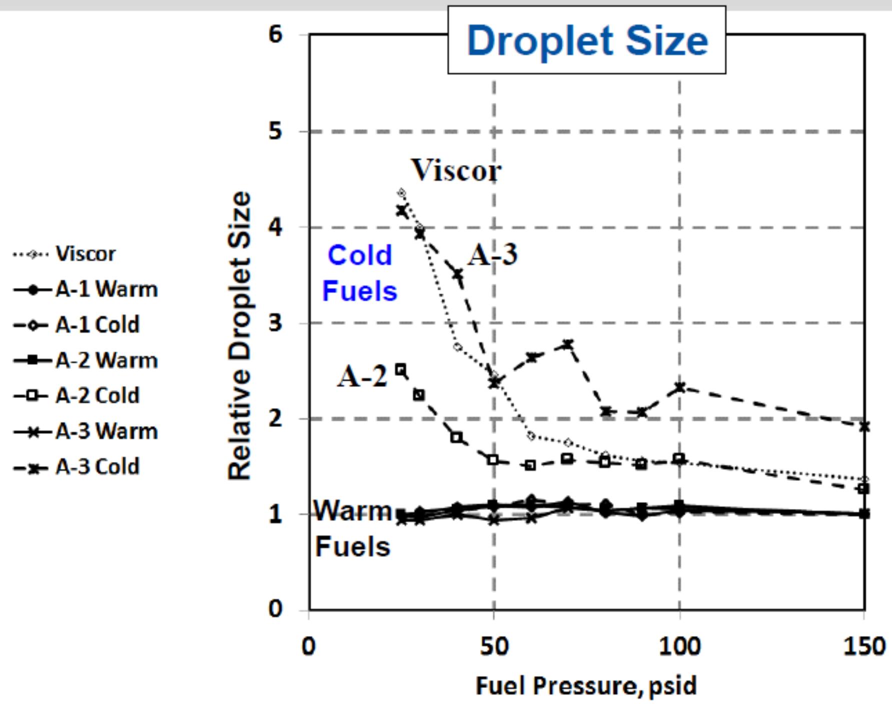
- Atomizer spray droplet size and spray angle dependent on fuel viscosity
- Pattern factor results show some test-to-test variation
- No adverse fuel effect on radial profile
- Smoke emissions impacted by more than aromatics and hydrogen content
  - C-2 with 14.5% aromatics significantly less smoke than A-2 with 15% aromatics
  - C-5 with 26% aromatics less smoke than A-2 with 15% aromatics
  - C-5 produces less smoke than A-3 fuel with similar hydrogen content
    - Suggests impact of hydrotreating and/or fuel heteroatom content in addition to aromatics and hydrogen content
- Fuel viscosity plays a major role in operability characteristics
  - LBO results correlated with fuel viscosity
    - Low viscosity of C-5 resulted in superior operability characteristics
    - C-1 results were outliers with respect to viscosity trend
  - Ignition results correlated with fuel viscosity
    - Similar order as LBO results
    - C-5 resulted in superior ignition characteristics
    - A-3 resulted in worst ignition characteristics
    - C-1 results were outliers with respect to viscosity trend

Backup

Large Atomizer Spray Testing



- Droplet size with warm Category A fuels are similar to 7024 Type II calibration fluid
- Droplet size highly correlated to fuel viscosity
  - Viscosity at -40°C
    - 6.6* cSt for A-1
    - 8.5* cSt for A-2
    - 13.4* cSt for A-3
- Droplet size with cold A-1 and A-2 fuels well below Viscor (12 cSt) fluid limit
  - A-3 above Viscor limit
- A-3 data shows why 12cSt max viscosity limit at -40°C needed for alternative fuels



*Calculated from 25°C and 40°C viscosities

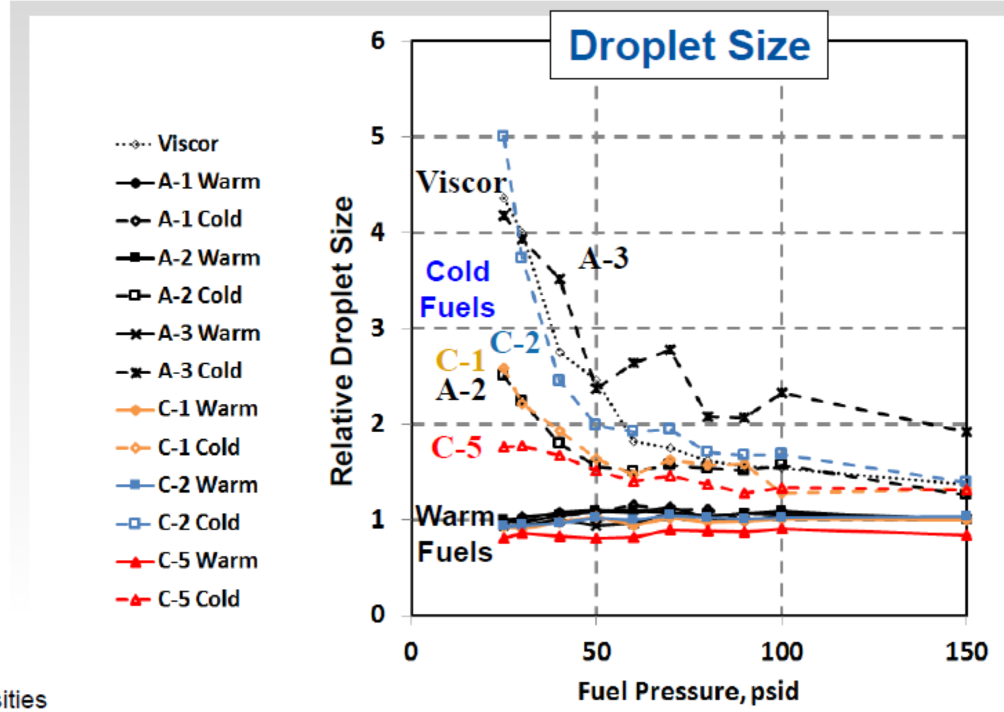
Droplet Size Highly Dependent on Fuel Viscosity

Large Atomizer Spray Testing

- Droplet size with warm Category C fuels are similar to 7024 Type II calibration fluid
- Droplet size correlated to fuel viscosity
  - Viscosity at -40°C
    - 10.8* cSt for C-1
    - 10.5* cSt for C-2
    - 2.9* cSt for C-5
- Droplet size with cold C-1 fuel similar to A-2
- Relative droplet size with cold C-2 fuel increases at low pressures

A-3 Cold

12cSt Fluid



*Calculated from 25°C and 40°C viscosities

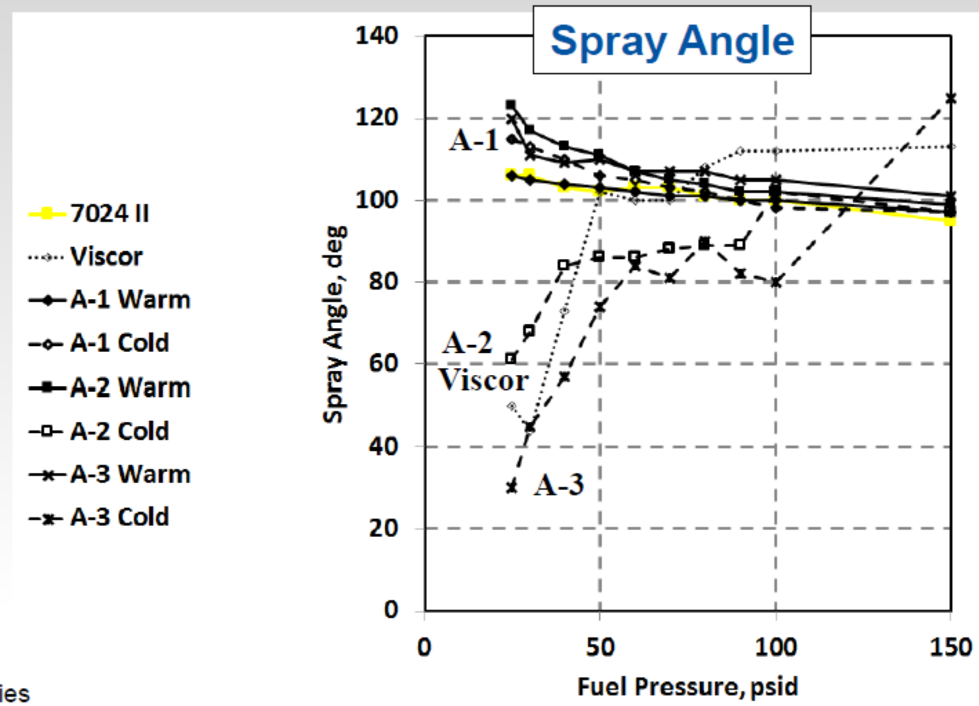
Droplet Size Highly Dependent on Fuel Viscosity

Large Atomizer Spray Testing

A-3 Cold

12cSt Fluid

- Spray angles with warm Category A fuels are similar to 7024 Type II calibration fluid
- Spray angles with cold Category A fuels vary
  - A-3 spray collapses faster than Viscor spray
  - A-2 spray angle open then collapses ~30psi
  - A-1 spray remains similar to 7024 II fluid throughout pressure range
- Viscosity impacts spray angle at low pressures
  - Viscosity at -40°C
    - 6.6* cSt for A-1
    - 8.5* cSt for A-2
    - 13.4* cSt for A-3



*Calculated from 25°C and 40°C viscosities

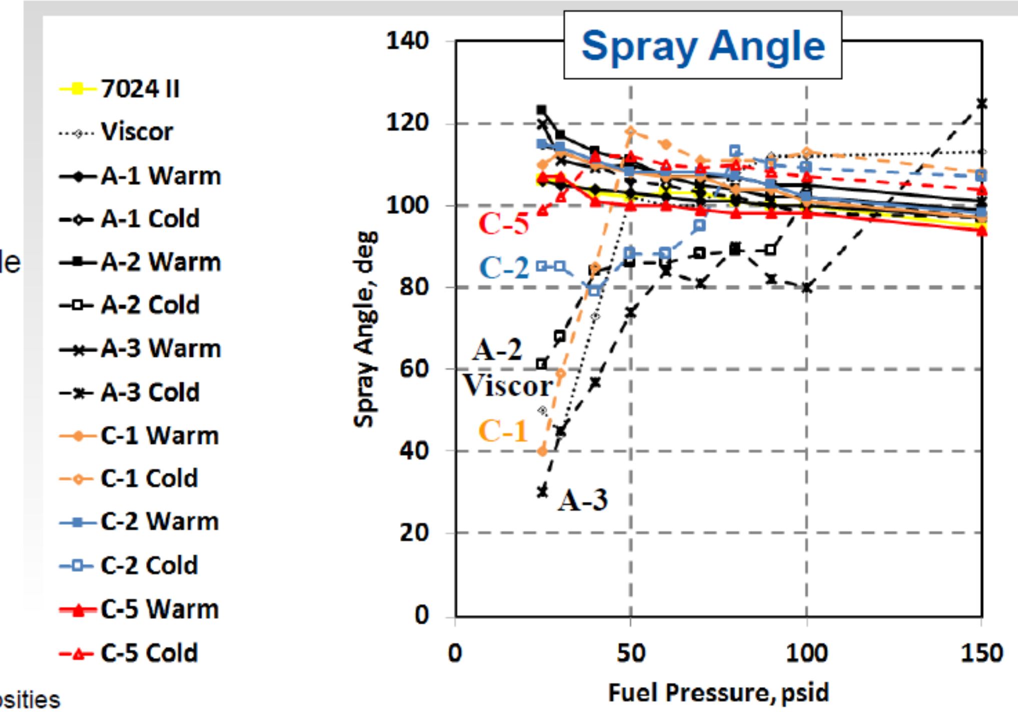
Spray Angle Dependent on Fuel Viscosity

Large Atomizer Spray Testing

C-1

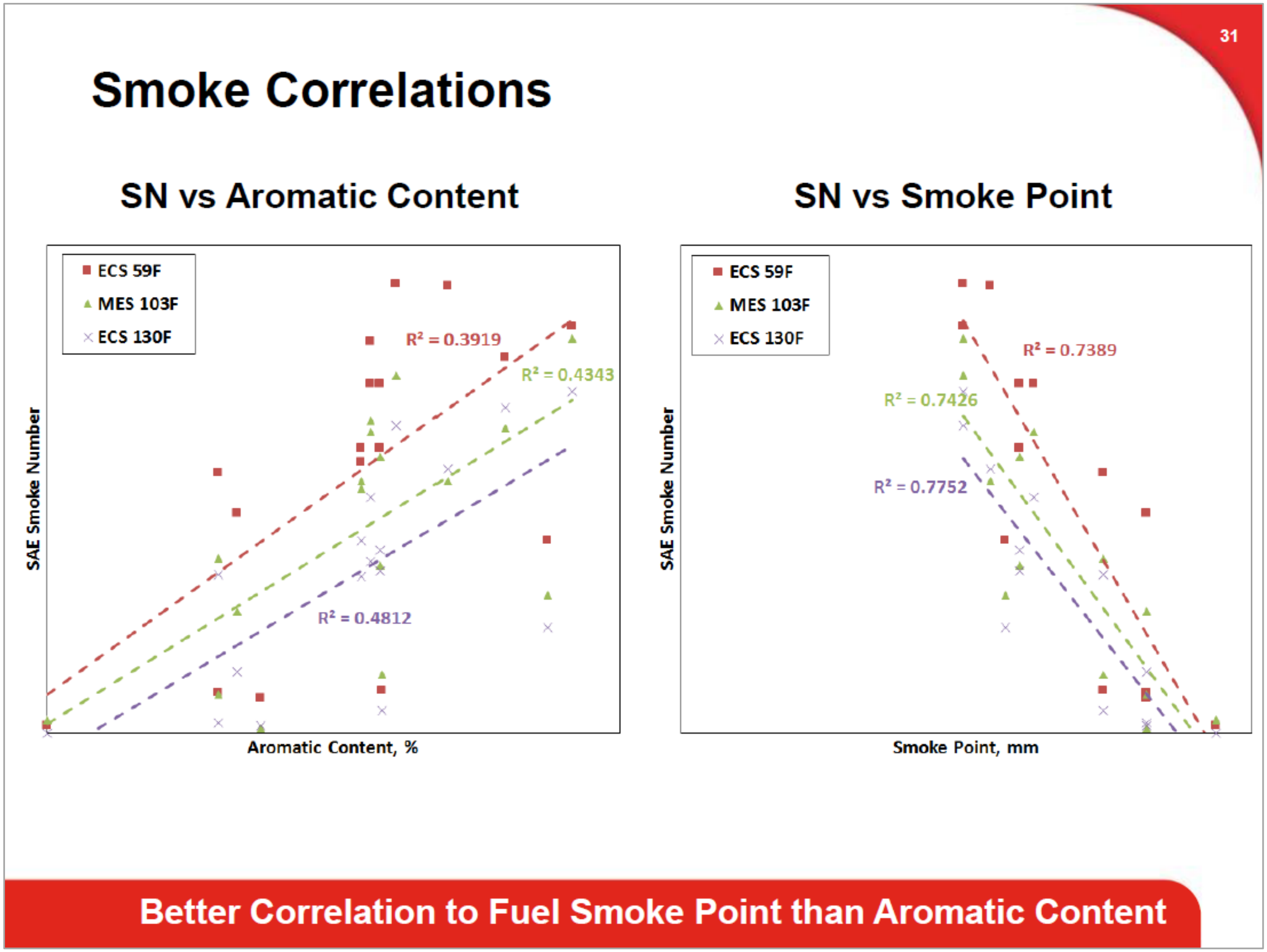
12cSt Fluid

- Spray angles with warm Category C fuels are similar to 7024 Type II calibration fluid
- Spray angles with cold Category C fuels are more consistent than Category A fuels
  - C-1 spray collapses below 50psi
  - C-2 spray collapses slightly at lower pressures
  - C-5 maintains spray angle over pressure range
- Based on viscosity, cold Category C fuel spray angles should lie between A-2 and A-3 fuels
  - Viscosity at -40°C
    - 10.8* cSt for C-1
    - 10.5* cSt for C-2
    - 2.9* cSt for C-5



*Calculated from 25°C and 40°C viscosities

Spray Angle Dependent on Fuel Viscosity



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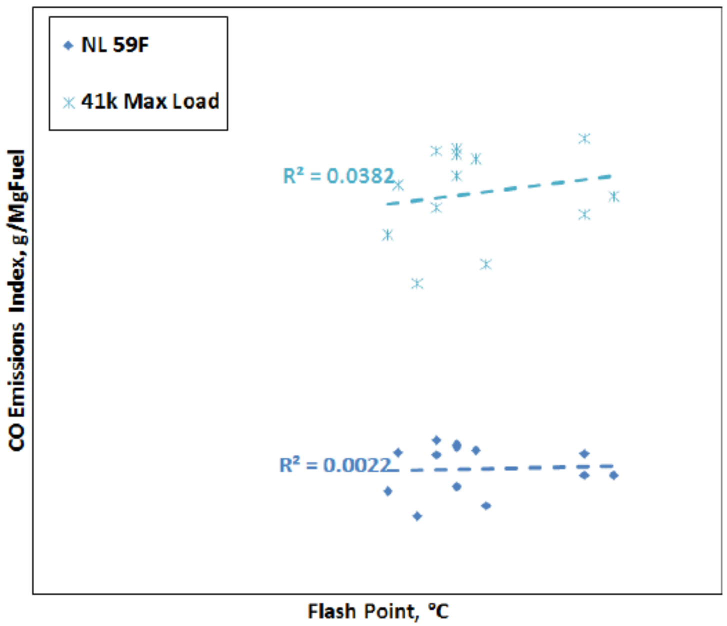
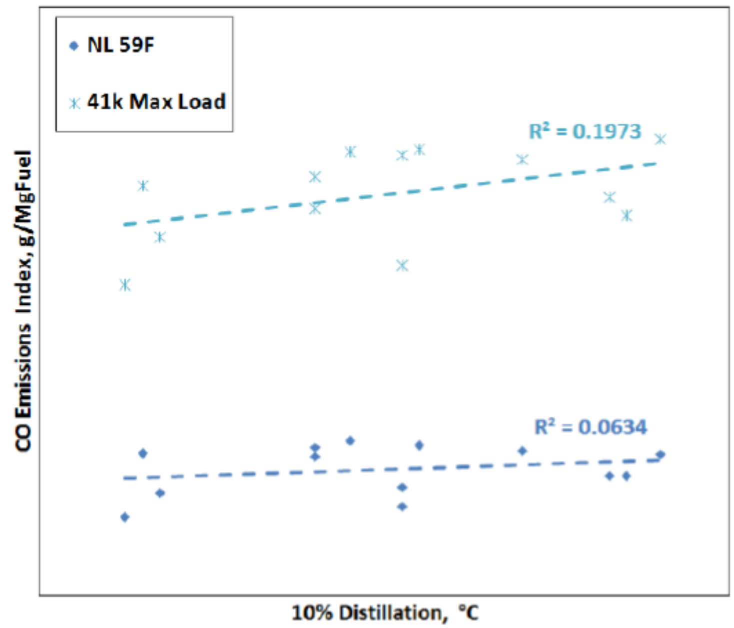
Smoke Correlations
SN vs Aromatic Content
ECS 59F
MES 103F
ECS 130F
R² = 0.3919
R² = 0.4343
R² = 0.4812
SAE Smoke Number
Aromatic Content, %
SN vs Smoke Point
ECS 59F
MES 103F
ECS 130F
R² = 0.7389
R² = 0.7426
R² = 0.7752
SAE Smoke Number
Smoke Point, mm
Better Correlation to Fuel Smoke Point than Aromatic Content

CO Correlations

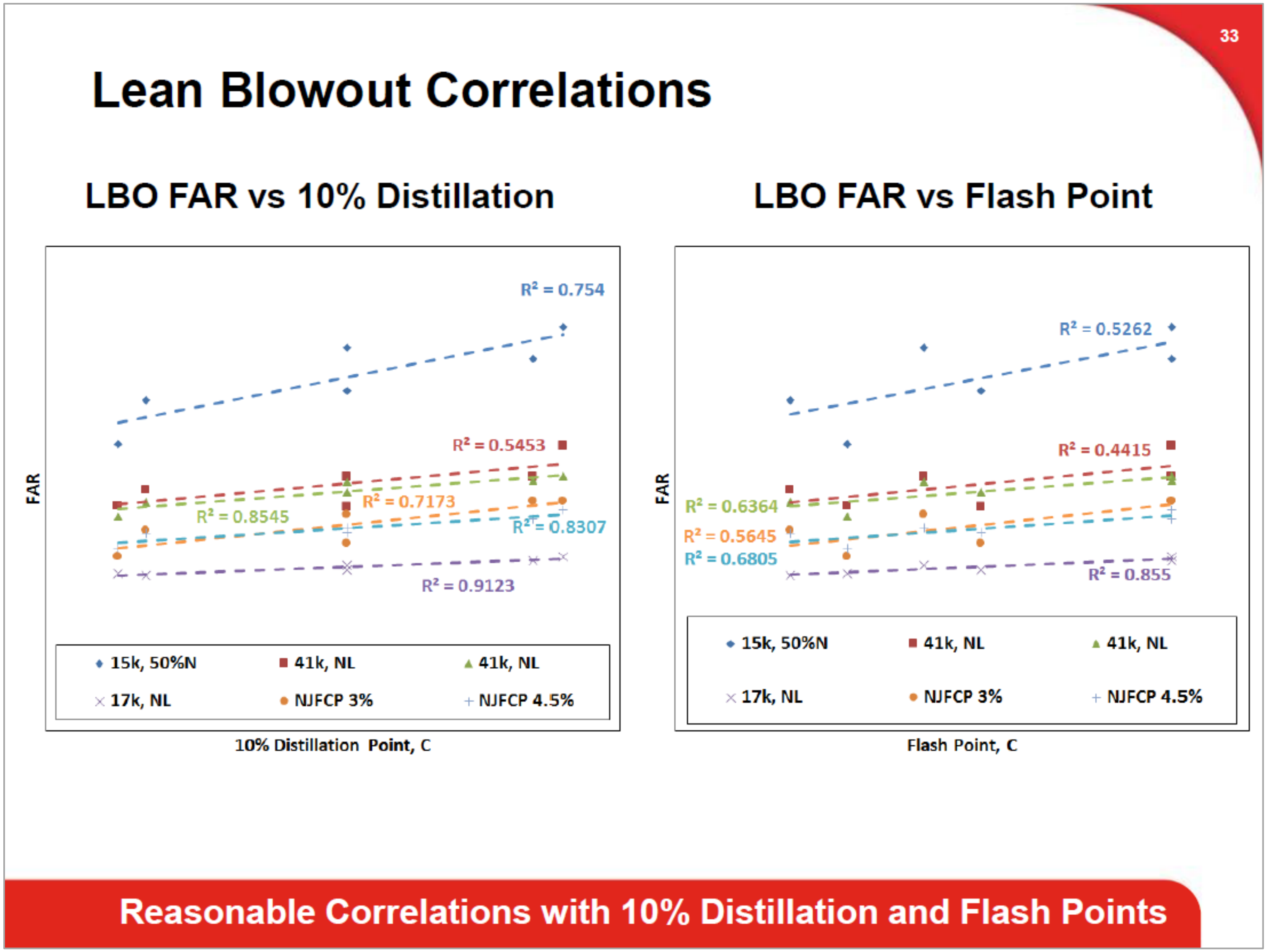
CO vs Flash Point



CO vs 10% Distillation Point

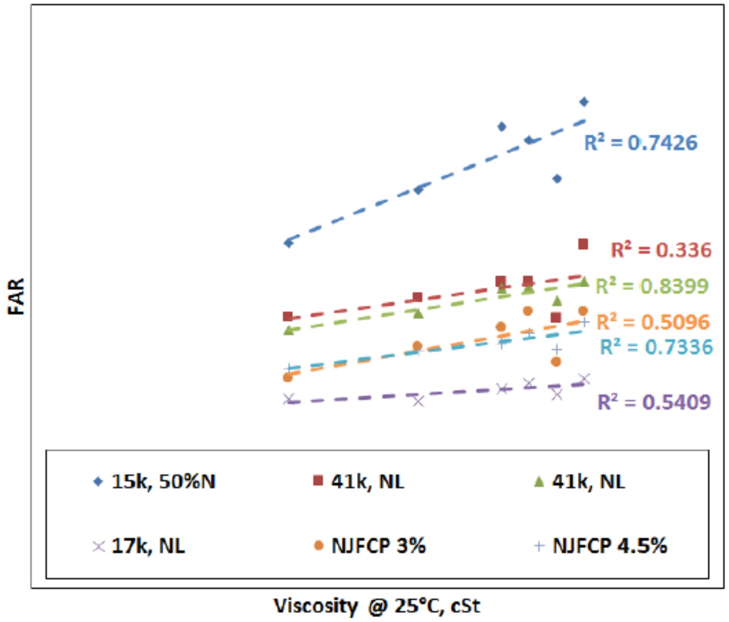


Poor Correlations with Flash and 10% Distillation Points

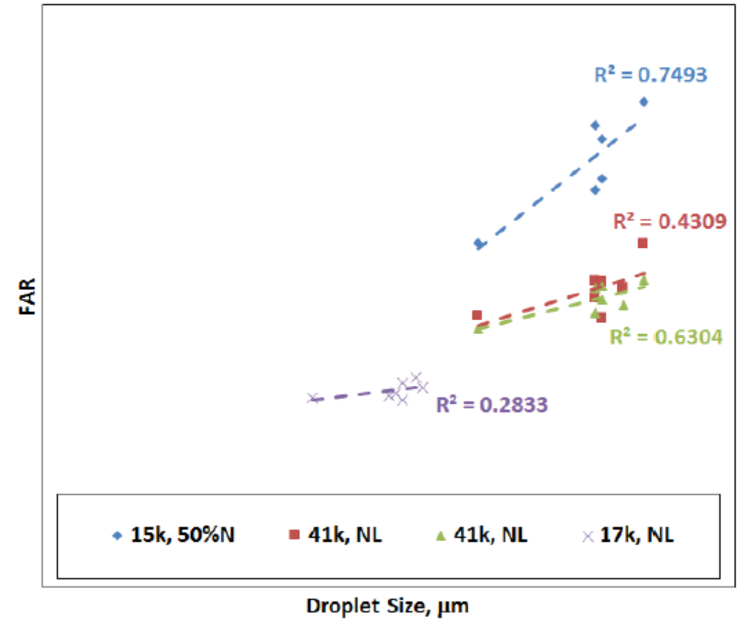

33
Lean Blowout Correlations
LBO FAR vs 10% Distillation
LBO FAR vs Flash Point
R² = 0.754
R² = 0.5453
R² = 0.7173
R² = 0.8545
R² = 0.8307
R² = 0.9123
FAR
15k, 50%N
41k, NL
41k, NL
17k, NL
NJFCP 3%
NJFCP 4.5%
10% Distillation Point, C
R² = 0.5262
R² = 0.4415
R² = 0.6364
R² = 0.5645
R² = 0.6805
R² = 0.855
FAR
15k, 50%N
41k, NL
41k, NL
17k, NL
NJFCP 3%
NJFCP 4.5%
Flash Point, C
Reasonable Correlations with 10% Distillation and Flash Points

Lean Blowout Correlations

LBO FAR vs Viscosity



LBO FAR vs Droplet Size

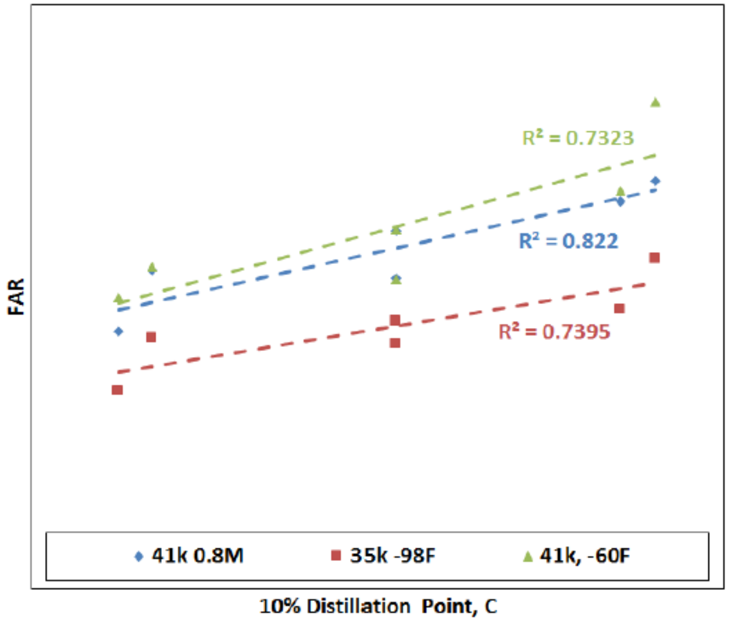


*droplets measured at different pressures

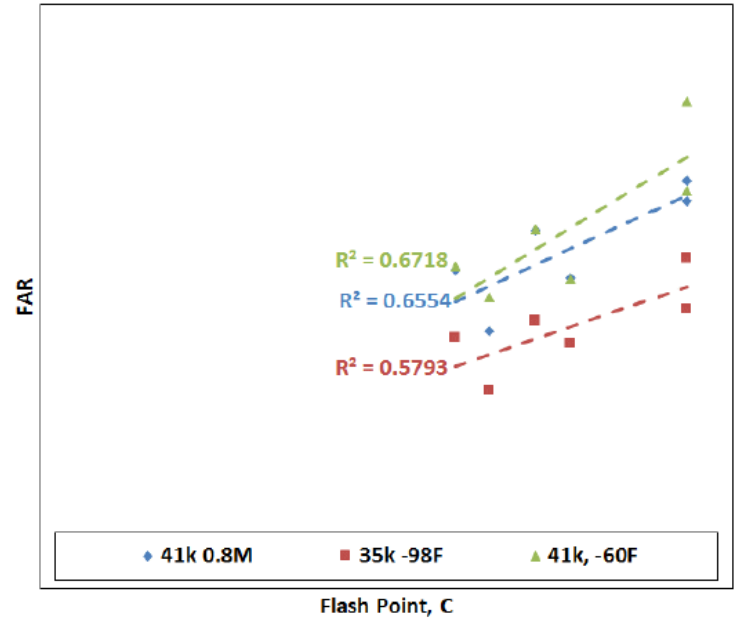
Reasonable Correlations with Viscosity and Droplet Size

Ignition Correlations

Ign. FAR vs 10% Distillation



Ign. FAR vs Flash Point



Reasonable Correlations with 10% Distillation and Flash Points

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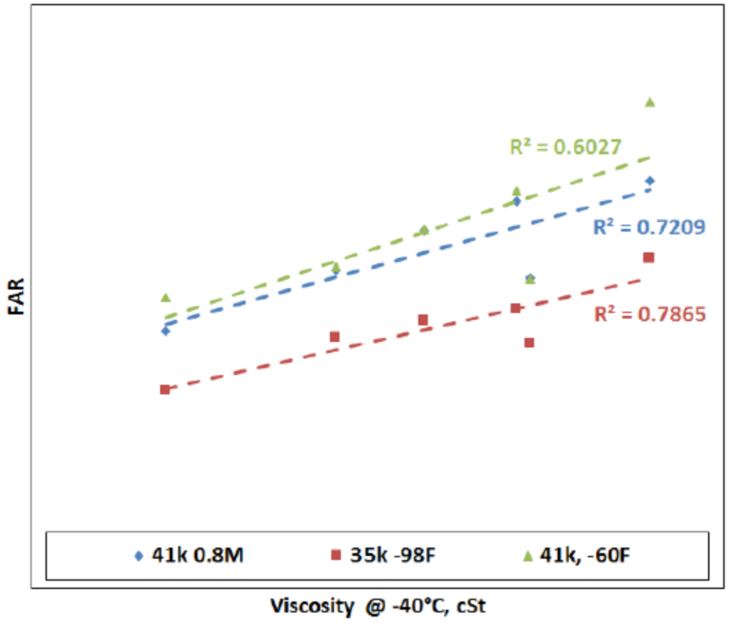
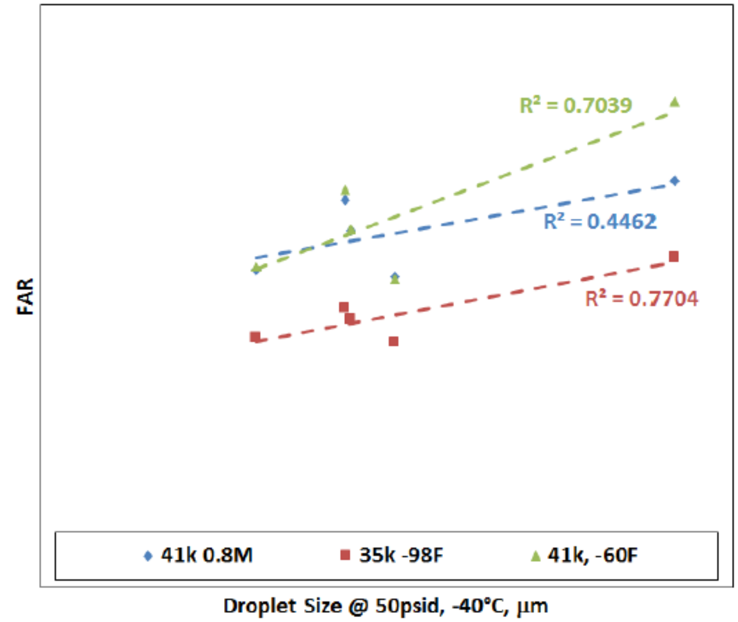
Ignition Correlations

Ign. FAR vs Viscosity



Ign. FAR vs Droplet Size



*droplets measured at different pressures

Reasonable Correlations with Viscosity and Droplet Size

APPENDIX 2. HONEYWELL RIG AND ENGINE TESTS USING GREEN DIESEL FUEL BLENDS

(16 pages)

Honeywell Rig and Engine Tests of Green Diesel Fuel Blends

Rig and engine testing of high freeze point hydroprocessed esters and fatty acids (HEFA) fuel blends, also called Green Diesel (GD) blends, was completed at the Honeywell Aerospace facility in Phoenix, Arizona. Funding for the testing was provided by the Federal Aviation Administration (FAA) and the Volpe National Transportation Systems Center under the Office of the Secretary of Transportation, FAA Continuous Lower Energy Emissions and Noise (CLEEN) I, and DLA Energy/Air Force Research Laboratory (AFRL). All findings and conclusions expressed are those of the authors (Honeywell) and do not necessarily reflect the views of the contracting agencies.

The purpose of the testing was to evaluate the effect of GD fuel blends on the performance, operability, and emissions of aircraft gas turbine engines. Blends from two different high freeze point HEFA synthetic paraffinic kerosene (SPK) blending components with conventional Jet A petroleum derived fuel were evaluated.

The following evaluation tests were completed using the two GD fuel blends:

- 131-9 auxiliary power unit (APU) combustor rig performance, emissions, lean blowout (LBO), and cold and altitude ignition tests
- Fuel atomizer cold plugging test
- Fuel atomizer cold spray test
- 131-9 APU cold and altitude starting test

Green Diesel Blending Components

The neat Diamond Green Diesel (DGD) SPK was provided by Valero's Diamond Green Diesel facility in Louisiana and produced from recycled animal fat and used cooking oil. The neat F-76 GD SPK provided by the U.S. Navy (HRD-76) was produced by a toll facility to MIL-DTL-16884 (Naval Distillate) requirements for Solazyme. Two 55-gallon drums of each GD SPK was provided. Selected properties of the neat GD SPKs are shown in Table 1. The GD SPK blending component freeze point (cloud point), distillation end point, and density were above the current HEFA SPK limits (D7566-16). However, if blended into Jet A fuel in a low enough concentration (depending on properties of the GD and petroleum derived fuel blending components) the final fuel blend could meet D7566 Table 1 requirements. Fuel for each test series was blended just prior to the test, so there were some test-to-test variations in both the Jet A and blend properties.

131-9 Combustor Rig Testing

131-9 combustor rig testing was completed to determine the effect of the GD fuel blends on combustion system performance. A full-scale 131-9 combustor rig was installed in the combustion test facility (Figure 1) in Phoenix, Arizona with ignition and blowout tests completed in July 2014 and performance and emissions tests in November 2015.

The GD SPKs were blended 5 percent by volume with Honeywell Jet A (D1655) for combustor rig testing at customer request. The test fuels for combustor rig testing consisted of a Jet A baseline, a 5 percent blend of DGD and Jet A, and a 5 percent blend of Navy F-76 GD and Jet A.

Table 1. Green Diesel SPK Properties.

Fuel Property	100% DGD	100% F-76 GD
Specific Gravity (D1298)	0.780	0.780
Temp, °C for 12 cSt viscosity (1)	-14	-13
Viscosity, cSt at +25°C (D445)	3.7	3.8
Dist IBP, °C (D86)	148	184
10% Dist Temp, °C (D86)	226	234
20% Dist Temp, °C (D86)	253	260
50% Dist Temp, °C (D86)	280	277
90% Dist Temp, °C (D86)	293	290
Dist FBP, °C (D86)	312	308
LHV, MJ/kg (D240)	43.92	43.99
Smoke Point, mm (D1322)	49.5	>50
Aromatics, %v (D1319)	0.0	0.0
Cloud Point, °C (D2500)	-4	-8
Water, ppmw (E1064)	25	31
(1) Calculated		

The 5 percent GD blends were supplied to the test cell from 55-gallon drums, while the Jet A was provided from the standard laboratory fuel supply. Table 2 provides properties of the Jet A and GD blends used for combustor rig ignition and LBO testing, while Table 3 provides properties used for combustor rig performance and emissions testing.

Figure 1. a) 131-9 Rig Installed in Test Cell, b) Mobile Emissions Truck, c) Fuel Drums.

Table 2. Fuel Properties for Combustor Rig Ignition and LBO Tests.

Fuel Property	Jet A	5% DGD Blend	5% F-76 GD Blend
Specific Gravity (D1298)	0.815	0.814	0.814
Viscosity, cSt at -20°C (D445) (1)	4.7	4.8	4.9
Viscosity, cSt at -37°C (D445) (1)	8.5	8.6	9.2
Dist IBP, °C (D86)	151	153	152
10% Dist Temp, °C (D86)	171	171	170
20% Dist Temp, °C (D86)	180	182	180
50% Dist Temp, °C (D86)	208	210	209
90% Dist Temp, °C (D86)	256	264	262
Dist FBP, °C (D86)	284	292	290
Flash Point, °C (D56)	41	42	42
LHV, MJ/kg (D240)	43.07	43.02	43.03
Freeze Point, °C (D2386)	-45	-38	-37
Water, ppmw (E1064)	37	34	45
(1) calculated			

Table 3. Fuel Properties for Combustor Rig Performance and Emission Tests.

Fuel Property	Jet A	5% DGD Blend	5% F-76 GD Blend
Specific Gravity (D1298)	0.810	0.806	0.806
Viscosity, cSt at -20°C (D445) (1)	4.5	4.6	4.6
Dist IBP, °C (D86)	158	154	157
10% Dist Temp, °C (D86)	173	173	173
20% Dist Temp, °C (D86)	181	180	181

Fuel Property	Jet A	5% DGD Blend	5% F-76 GD Blend
50% Dist Temp, °C (D86)	202	201	202
90% Dist Temp, °C (D86)	253	252	256
Dist FBP, °C (D86)	286	287	287
Flash Point, °C (D56)	43	43	43
LHV, MJ/kg (D240)	43.11	43.17	43.10
Smoke Point, mm (D1322)	24	25	25
Aromatics, %v (D1319)	17.0	16.0	16.5
Freeze Point, °C (D2386)	-46	-39	-38
Water, ppmw (E1064)	53	45	32
(1) Calculated			

Performance tests were completed over a range of operating conditions from idle to maximum power conditions including sea level standard (SLS) day No-Load (NL), SLS and hot day ECS (Environmental Control System), sea level hot day main engine start (MES) and 41,000 feet altitude hot day generator load. All tests were run at actual engine conditions (not scaled). Fuel flows were adjusted to provide a constant heat input (MJ/hr) to the combustor, to account for the varying fuel lower heating value (LHV).

There was no fuel effect on combustor pattern factor (PF) (Figure 2) or radial profile (Figure 3). PF and radial profile are measures of the temperature distribution at the turbine stator inlet plane (combustor exit). PF is the ratio of the difference between the maximum and average temperature at the turbine inlet plane to the combustor temperature rise, and affects turbine stator life. PF with the DGD and F-76 GD blends were similar to the baseline Jet A fuel at all high power load conditions, and slightly higher than the Jet A baseline at the sea level (SL) NL condition. PF at NL or idle conditions are not significant due to the low turbine inlet temperatures. All PFs were well below the design limit.

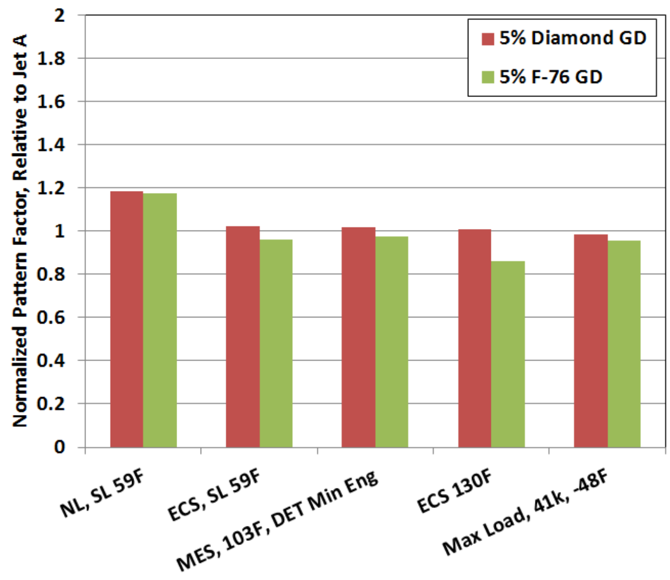


Figure 2. 131-9 Combustor Relative Pattern Factor.

Radial profile is the circumferential average temperature across the measurement plane (turbine stator inlet), and affects turbine rotor life. Radial profile was similar for the DGD and F-76 GD blends and the baseline Jet A fuel, as seen in Figure 3 for one of the ground high power load conditions. Results shown are within test-to-test variation. The maximum average exhaust gas temperatures (EGTs) at the 60 percent span location was just slightly higher with the GD blends than Jet A, but not considered significant. The GD blends had slightly higher temperatures at the blade tip location and slightly lower temperatures at the blade hub location, but these differences are also not considered significant. Similar results were obtained at other load conditions.

Gaseous and smoke emissions were measured during combustor performance testing using a fixed sampling rake in the rig tailpipe and a mobile emissions truck. Gaseous emissions were measured in accordance with SAE ARP1156 and reduced to Society of Automotive Engineers (SAE) aerospace recommended practices (ARP) 1533 requirements. Smoke emissions were measured with an optical smoke meter and converted to equivalent SAE smoke number (SN). Combustor nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbon (UHC), and SN emissions were measured at each test condition. The data reported were averages of the samples taken during the PF scan of the combustor exhaust. Test results with the 5 percent GD fuel blends are presented as relative emissions, which is the ratio of GD blend emissions index (g/kg fuel) or SN to the emissions with the baseline Jet A fuel.

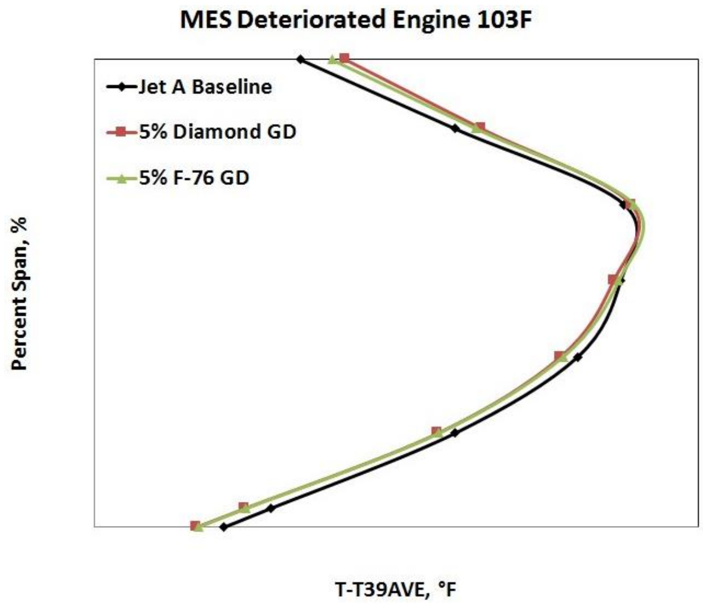


Figure 3. 131-9 Radial Profile at SL 39°C MES Load Condition.

The NOx, CO, and UHC emissions with the DGD and F-76 GD blends were comparable at all conditions to results with the baseline Jet A fuel. NOx emissions were similar for both fuels at all conditions (Figure 4). The UHC and CO emissions were also similar at all loaded conditions (Figure 5). UHC and CO emissions are significant only at the NL and altitude generator load condition. CO and UHC variations at the high power conditions [environmental control system (ECS) and MES] are not considered significant due to the very low emissions levels, and since small changes in measured values result in large percent changes. Smoke emissions with the GD blends were reduced approximately 20 percent at most higher power conditions (Figure 6), but fuel aromatic content which normally correlates well with SN decreased less than 6%v due to the low blend ratio. Smoke emissions were very low (SN < 10) at all conditions with all fuels, so small variation in SN with the GD blends can lead to large changes relative to the baseline. Smoke emissions at the altitude generator load condition (41K shp) were not reported as they were below the instrument detection limit.

Test results showed no adverse effect of the 5 percent GD fuel blends on engine gaseous emissions, with a slight reduction in smoke emissions at high power conditions which could improve local air quality near the airport.

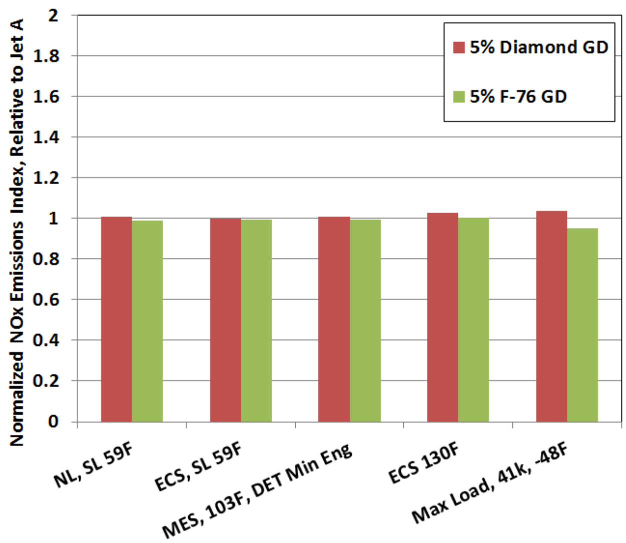


Figure 4. 131-9 Rig NOx Relative Emissions.

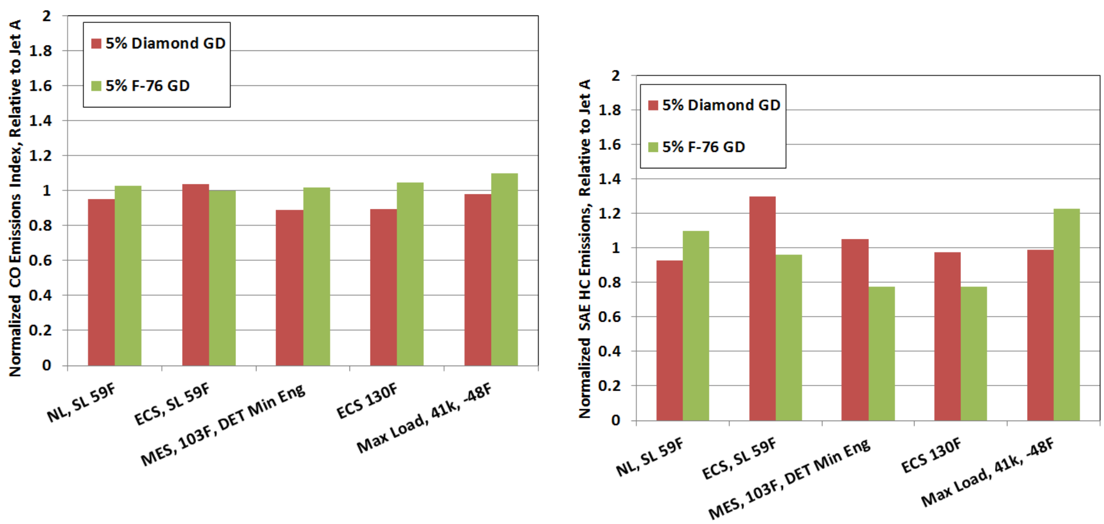


Figure 5. a) 131-9 Rig CO and b) UHC Relative Emissions.

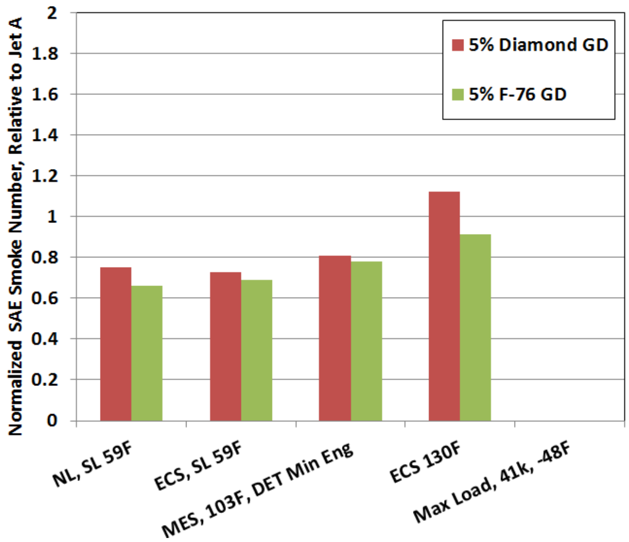


Figure 6. 131-9 Rig Relative Smoke Emissions.

LBO tests were run at simulated engine NL (idle) conditions over the operating envelope (SL up to 41,000 feet altitude). After stabilizing at each condition, the fuel flow rate was slowly decreased while holding combustor inlet conditions constant and continuously recording data. Blowout was detected when the measured combustor exit temperatures suddenly dropped. Blowout test results were correlated against a corrected reference velocity (corrected airflow). Test results (Figure 7) showed no significant difference in LBO fuel-air ratios (FARs) due to fuel type over the range of test conditions, and no loss in blowout margin (difference between NL fuel flows and the LBO line). LBO characteristics with both the baseline and 5 percent GD blends were consistent with expectations based on previous Honeywell rig testing.

Lean ignition tests were run at simulated APU ground and altitude start conditions from SL up to 41,000 feet altitude. Fuel temperatures varied at each test condition, and ranged from ambient to -37°C. After stabilizing at each condition, an ignition attempt was performed at varying fuel flows until the minimum fuel flow for acceptable ignition delay was found. Fuel temperatures and flows were preset in a bypass circuit, and then directed to the combustor through a three-way solenoid valve. Ignition delay is defined as the time from when the fuel is introduced and the igniter switched on until ignition was detected by a rise in combustor exit temperature. The lean ignition FAR is reported as a function of corrected reference velocity (corrected airflow). Test results (Figure 8) show lean ignition FARs with the 5 percent GD blends were the same or slightly lower than the baseline Jet A fuel, presumably due to the same front end distillation (from Jet A). Even though the 5 percent GD blend freeze points were above the D1655 specification maximum (-40°C), there were no difficulties is setting up and running the cold ignition tests at -37°C fuel temperature. Ignition characteristics with the baseline and GD blends were consistent with expectations based on previous Honeywell rig testing, which were run with slightly warmer fuel temperatures (ambient to -27°C).

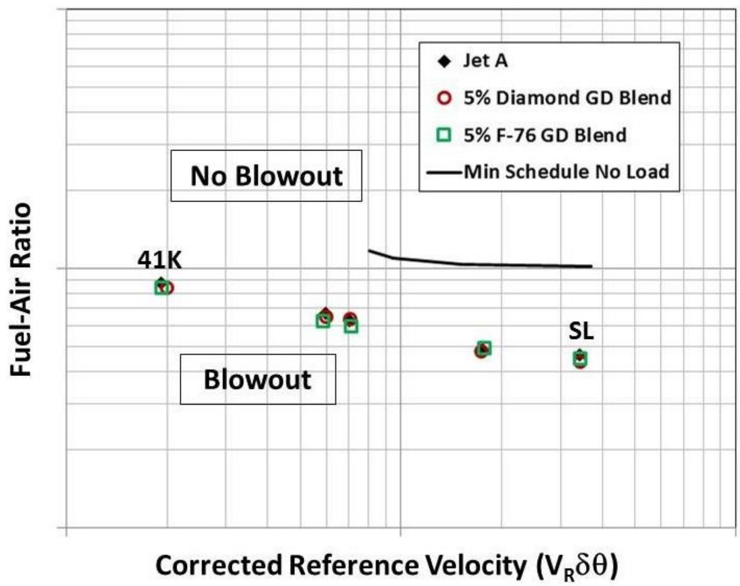


Figure 7. 131-9 Rig Lean Blowout Results.

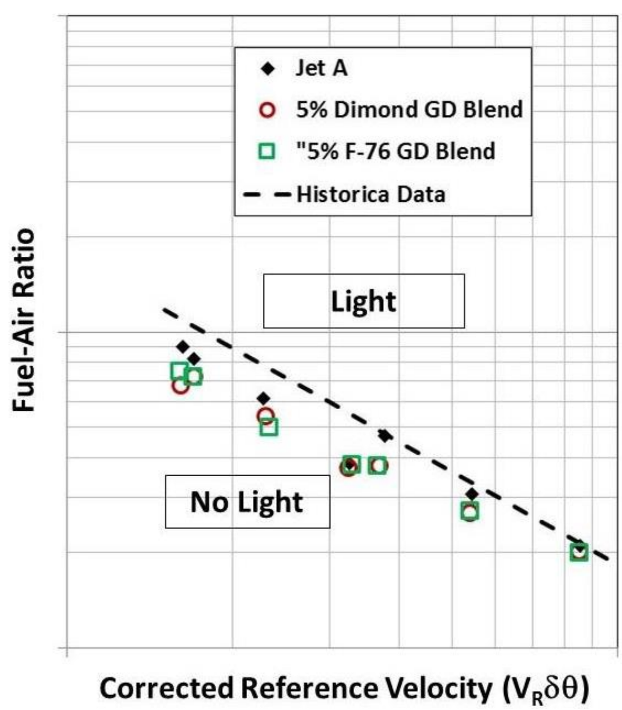


Figure 8. 131-9 Rig Lean Ignition Results.

Combustor rig test results showed there was no adverse effect of 5 percent GD blends on combustion performance, exhaust emissions, LBO, or lean ignition characteristics.

Atomizer Cold Plugging Test

Atomizer cold plugging tests were run in April 2014 to evaluate if high freeze point hydrocarbons or contaminants in the 5 percent GD blends would cause atomizer plugging when cold soaked at -40°C. This test was originally run in 2010 on a contaminated HEFA fuel that caused plugging during an ONERA cold ignition bench test. The ONERA plugging results were duplicated on the Honeywell test setup with the ONERA HEFA fuel blend, and showed no plugging after the high boiling contaminant was removed.

The test is run in a simple pipe rig installed in the C-100 combustor test facility, with a medium-sized pressure atomizer setup to spray horizontally. The fuel was pre-conditioned to -15°C in a bypass loop, with an APU fuel control providing a constant pre-set fuel flow. The rig air flowing past the atomizer was chilled to -40°C at half an atmosphere pressure and moderate velocity. The test is performed by directing the fuel flow to the atomizer for approximately 10 seconds, then diverting the fuel back to the bypass circuit for 10 minutes. The atomizer is cold soaked during the entire test period. The cycle was repeated six times to see if any atomizer plugging was observed. Plugging would be observed by an increase in fuel pressure at the atomizer inlet for a constant fuel flow.

Test fuels included baseline Jet A (D1655), 5 percent DGD blend, and 5 percent F-76 GD blend. Key fuel properties are shown in Table 4.

Table 4. Fuel Properties for Atomizer Plugging Test.

	Specific Gravity	Viscosity at 25° (cSt)	Freeze Point (°C)	Water Content (ppm)
Jet A Baseline	0.817	1.69	-45	39
5% Diamond GD	0.814	1.78	-39	36
5% Navy F-76 GD	0.815	1.77	-38	36
(1) Calculated				

Test results showed no indication of plugging with the Jet A or the two 5 percent GD blends, with fuel pressure constant for each fuel pulse.

Atomizer plugging was not observed with any of the test fuels, including the GD blends with freeze point (D2386) slightly above the cold soak temperatures.

Atomizer Cold Spray Testing

Onboard APUs are required to provide reliable cold and high altitude starting if there is a main engine generator failure or an in-flight shutdown of a main engine. Since the APU is normally off in-flight, the APU and its fuel supply can be cold-soaked which makes atomization of the fuel critical to reliable starting. In contrast, most main engines have a fuel-oil heat exchanger (HX) which warms the fuel prior to the inlet fuel filter. The APU and main engine have similar ground cold start requirements.

Honeywell completed atomizer cold bench spray tests to determine fuel effects on atomization and spray quality, and by inference, APU or engine cold ignition. Pressure atomizers typical of those used on APUs and small propulsion engines, or as start injectors for main propulsion engines were selected for testing. Atomizer performance parameters including fuel flow, spray droplet size, and spray characteristics were measured over a range of conditions.

Two pressure atomizers were used for testing. Atomizer A was a small flow number (FN) atomizer typical of those used on newer transport and military APUs. Atomizer B was a large FN atomizer typical of secondary atomizers used on older commercial and military transport APUs or on can-type combustion systems. FN is an indication of the atomizer size, and is the fuel flow (lb/hr) divided by the square root of the fuel pressure (psid). Small FN atomizers are normally the most sensitive to fuel property variations.

Four test fluids were used for testing including standard calibrating fluid (MIL-PRF-7024 Type II), Jet A (D1655), a 2 percent DGD fuel blend, and Viscor 12 cSt calibrating fluid. The Jet A provided by Honeywell was from the standard laboratory facility fuel supply.

Table 5 summarizes fuel properties important to atomization, including specific gravity (D1298) and viscosity (D445). Freeze point was measured by D2386. Spray tests were conducted with warm 2 percent F-76 GD blend, but cold spray tests were not conducted with this fluid due to budget limitations. Spray results with the warm 2 percent F-76 GD blend were similar to the results with warm 2 percent DGD, so are not shown.

Each atomizer was tested over a range of conditions representative of typical engine start conditions. For pressure atomizers, this required a range of inlet fuel pressures. The fuels were all run at ambient ~27°C (80°F) and -40°C (-40°F) fluid temperatures. The Viscor fluid was run at a temperature to provide 12 cSt viscosity (around 27°C). Sauter mean diameter (SMD) was used as a measure of atomization quality, which has been shown to correlate well with engine ignition and blowout characteristics. SMD measurements (microns) were obtained with a Malvern Spraytec particle analyzer. Test results are presented with spray SMD normalized to 7024 II calibrating fluid.

Table 5. Atomization Test Fluid Properties.

Fluid	Specific Gravity	Viscosity (cSt at 25°C)	Viscosity (cSt at -40°C) (1)	Freeze Point (°C)
7024 II	0.766	1.2	n/a	na
Jet A	0.814	1.7	9.5	-46
2% DGD Blend	0.817	1.8	11.2	-41

Fluid	Specific Gravity	Viscosity (cSt at 25°C)	Viscosity (cSt at -40°C) (1)	Freeze Point (°C)
Viscor	0.874	11.9	n/a	na
(1) calculated				

Figure 9(a) shows the warm 2 percent DGD blend had spray droplet size (SMD) for atomizer A (smallest FN) similar to that of Jet A, while cold 2 percent DGD had much larger (worse) SMD over the entire pressure range tested. SMDs with the 2 percent DGD blend were also much larger than the Viscor 12 cSt fluid. The reason the atomizer A spray droplet size increased so significantly with the cold 2 percent DGD blend is not known, as the fluid viscosity was calculated to be less than 12 cSt at the -40°C test temperature. There could have been an instrument calibration or measurement error, or small wax particles may have formed between the fuel chiller and the atomizer. Spray angles for atomizer A presented in Figure 9(b) show spray angles for both cold Jet A and 2 percent DGD similar to spray angles for the more viscous Viscor 12 cSt fluid at higher fuel pressures, but the 2 percent DGD spray angle drops below the Viscor values at low fuel pressures. Figure 10 shows photographs of the cold spray at 50 psid with Viscor, Jet A, and the 2 percent DGD, where the narrow angle for the DGD blend is clearly evident. Spray collapse with viscous fluids at low fuel pressures is normal, but the sharp drop in spray angle with cold 2 percent DGD fuel is a concern. Due to the irregularities in both droplet size and spray angle measurements with the 2 percent DGD blend, it is recommended that the cold spray tests with the 2 percent DGD blend be repeated with the small pressure atomizer, and cold spray tests run with the 2 percent F-76 GD blend.

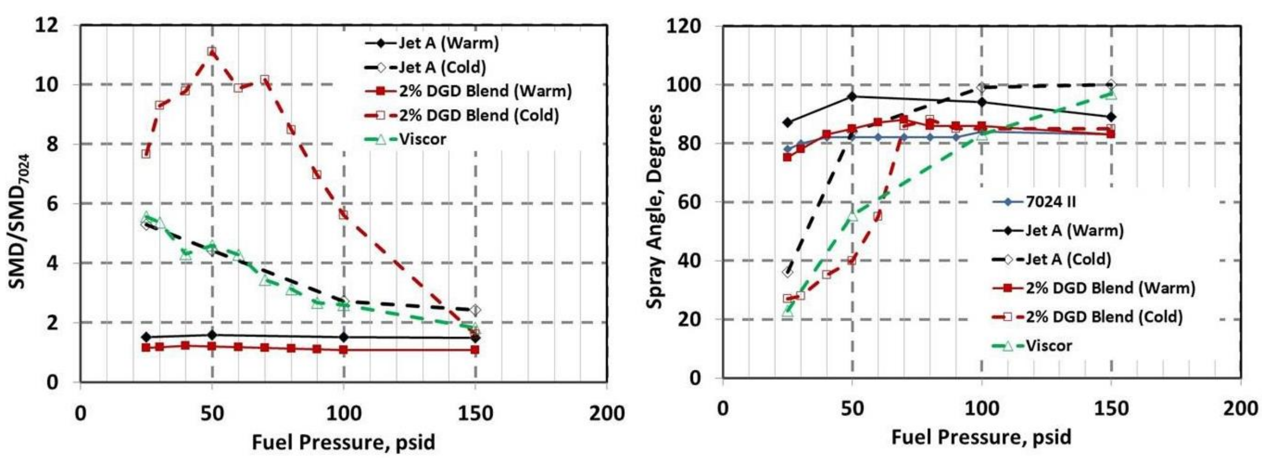


Figure 9. Comparison of Small Atomizer a) Droplet Size, b) Spray Angle.

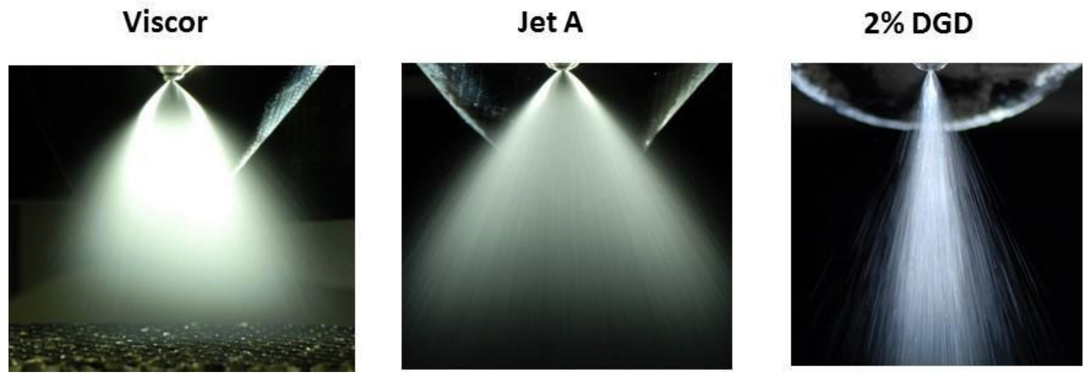


Figure 10. Cold Spray Photographs at 50 psid for a) Viscor, b) Jet A, c) 2% DGD.

SMD results for the larger pressure atomizers (atomizer B) presented in Figure 11(a) were similar for Jet A and the 2 percent DGD blend, and below values for the Viscor 12 cSt fluid. Spray angle with the larger atomizer B presented in Figure 11(b) shows a smaller spray angle for the 2 percent DGD blend at most fuel pressures, but all angles are acceptable with no sharp collapse in angle at lower fuel pressures.

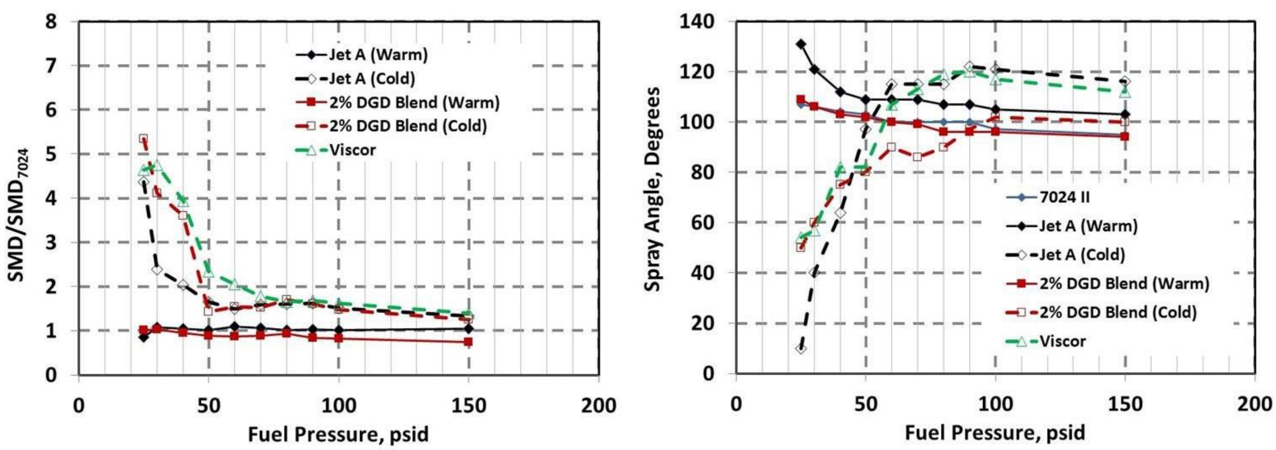


Figure 11. Comparison of Large Atomizer a) Droplet Size, b) Spray Angle.

Atomizer cold (-40°C) spray tests showed spray characteristics with the small pressure atomizer and 2 percent DGD blend were acceptable at higher pressure, but degraded below conventional Jet A fuel and the Viscor calibrating fluid at lower pressures. Cold spray tests with the larger pressure atomizer showed similar results for Jet A, the 2 percent DGD blend, and Viscor 12 cSt fluid. It is recommended that the cold spray tests with the 2 percent DGD blend be repeated with the small pressure atomizer, and tests run with the 2 percent F-76 GD blend.

131-9 APU Cold and Altitude Start Testing

The objectives of this test were to determine the effects of a 2percent DGD blend on the cold and altitude start capability of the 131-9 APU. The 131-9 APU is a small gas turbine engine used in a number of commercial (B737, A320) and military (C-40, P-8) applications. The 131-9 APU (Figure 12) is a constant speed, load compressor type engine with a pressure ratio (PR) of approximately 7, and a reverse flow annular combustion system with dual-orifice pressure type fuel atomizers. APUs are used to provide aircraft secondary power (bleed air for cabin conditioning and generator load for electrical power) and MES capability on the ground and in flight.

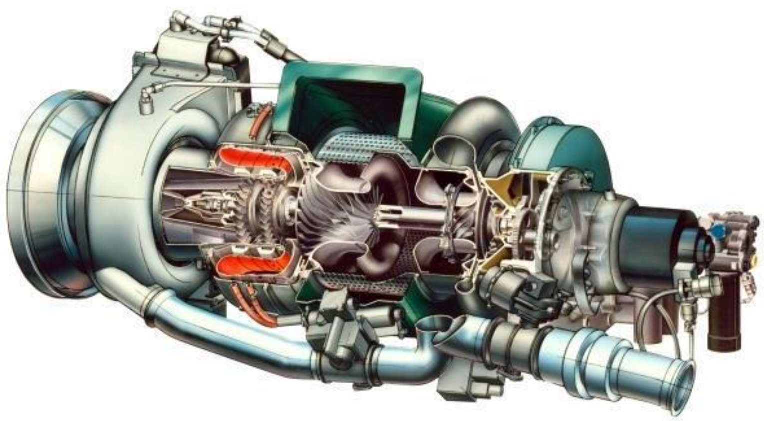


Figure 12. 131-9 APU.

A development 131-9A APU was installed in large altitude cold chamber No. 1 (LACC 1) test cell (Figure 13a). APU starts (Table 6) were run at base level cold day (-40°C), standard day (15°C), and hot day (55°C) conditions on the ground, and cold day (-70°C) and hot day (-14°C) at the 39,000 feet maximum start altitude. The engine was installed in a cold box inside the altitude chamber to simulate the APU compartment in the aircraft, and soaked at the start temperature as required (up to 6 hours) prior to initiating the start to allow the engine, oil, and fuel to stabilize at the desired temperatures. A fuel coil located inside the cold box provides enough conditioned fuel for the start transient and initial APU on-speed operation. The APU had a ducted inlet to match the aircraft installation, with APU inlet pressure, air temperature, and ram air pressure drop (airflow) adjusted to simulate the APU inlet conditions in flight. The 131-9A APU has an electric starter, with the battery power provided matching previous testing.

Tests with the 2 percent DGD fuel and the baseline Jet A fuels were conducted in December 2015. Tests with the 2 percent F-76 GD blend were not run due to funding limitations and the similarity to the 2 percent DGD blend.

Table 6. 131-9 APU Cold and Altitude Start Conditions.

Test Condition	Altitude, ft	Ambient Temp, °C	Fuel Temp, °C	APU Inlet Temp, °C
1	1100	15	15	15
2	1100	-40	-40	-40
3	1100	55	55	55
4	39000	-21	14	14
5	39000	-70	-40	-40

The Jet A was provided directly from the laboratory fuel supply, while the 2 percent DGD blend was supplied from a 55-gallon drum (Figure 13b). Fuel samples were taken from the drums to ensure proper fuel type, and at the APU inlet at the start of the test to verify proper flushing of fuel lines. Selected fuel properties of the two test fuels are shown in Table 7.

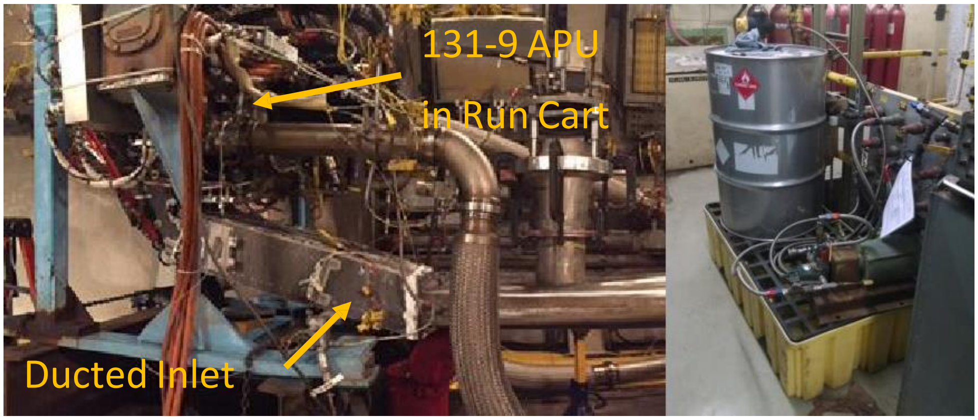


Figure 13. a) 131-9 APU Installed in Test Cell, b) Fuel Drum.

Table 7. Fuel Properties for APU Cold and Altitude Start Test.

Fuel Property	Jet A	2% DGD
Specific Gravity (D1298)	0.818	0.817
Viscosity, cSt at -40°C (D445) (1)	10.8	11.2
10% Dist Temp, °C (D86)	176	172
Freeze Point, °C (D2386)	-43	-41
Water, ppmw (E1064)	45	30
(1) calculated		

All starts from base level to 39,000 feet altitude and from hot to cold day with the 2 percent DGD fuel were successful, and similar to starts with the baseline Jet A fuel. Only normal start-to-start differences were seen between the Jet A and 2 percent DGD blend, with similar start times, combustor ignition delays, fuel flows (WF), primary fuel pressures (PFPRIM), and maximum EGTs (TTDEA). Figure 14 shows start traces for base level -40°C for Jet A, and Figure 15 for 39K feet altitude -40°C condition.

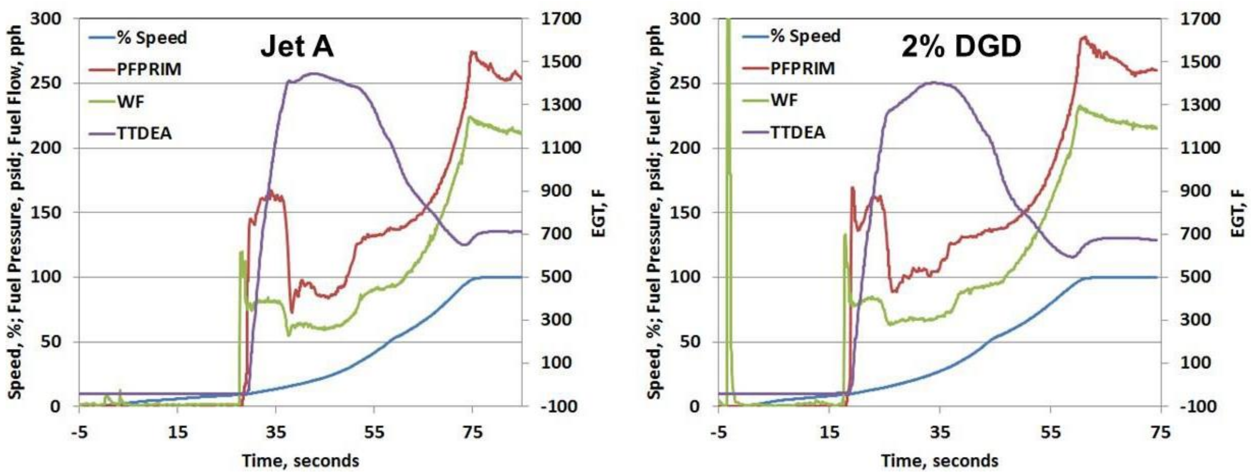


Figure 14. Start Traces for Base Level -40°C with a) Jet A, and b) 2% DGD.

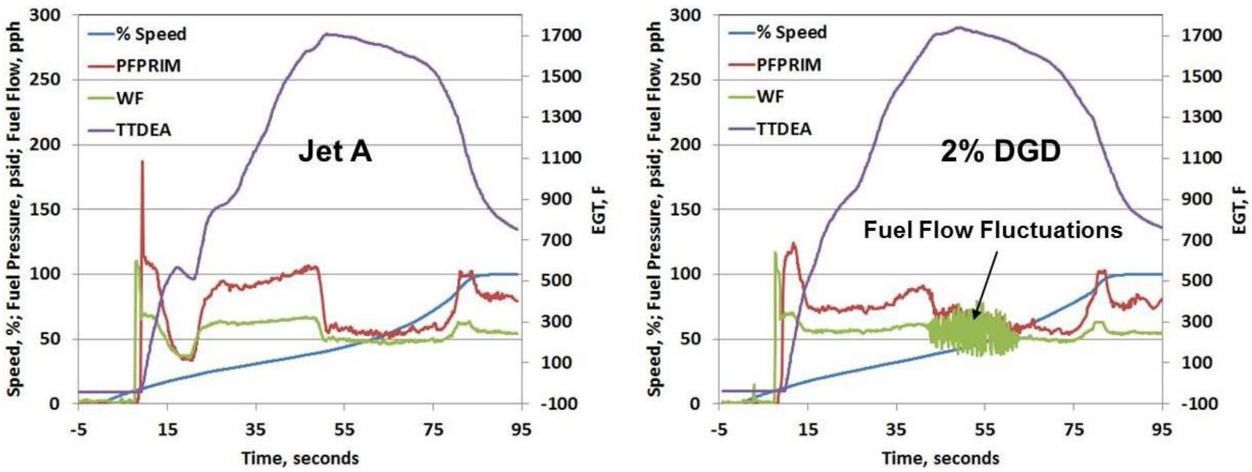


Figure 15. Start Traces for 39K Feet Altitude -40°C with a) Jet A, and b) 2% DGD.

There was a fluctuation in fuel flow at the 39K foot cold condition with the 2 percent DGD fuel when the fuel flow was trimmed to the minimum fuel schedule, which may be an indication of marginal atomization or the combustor near blowout.

APU cold and altitude starts tests were successful with a 2 percent DGD fuel blend over a range of ground and altitude start conditions. Start times, combustor ignition delay times, and EGTs during the start were similar for the 2 percent DGD blend and the Jet A baseline fuel at all test conditions. Test results show there would be no adverse effect of a 2 percent DGD fuel blend on APU cold or altitude start reliability, but there were fuel flow fluctuations with the DGD blend at maximum altitude cold start conditions that may be due to marginal atomization. It is recommended that the viscosity of GD fuel blends be limited to 12 cSt maximum at -40°C for Jet A fuel in the D7566 specification to ensure there is no increase in viscosity relative the current jet fuel pool.

The viscosity of Jet A-1 blends should be limited to 10 cSt maximum at -40°C. This corresponds to 12 cSt maximum at -44°C, which is the low temperature operating limit for Jet A-1 fuel in most aircraft. The freeze point of GD blends should be well below the specification minimum (-40°C for Jet A, -47°C for Jet A-1) to provide margin for long flights where fuel in the APU compartment can be cold soaked.

Summary

Combustor rig tests completed with 5 percent GD blends showed there was no adverse impact on combustor performance (PF or profile), exhaust emissions, LBO, or lean ignition. Atomizer cold plugging tests with 5 percent GD blends showed no plugging from high boiling hydrocarbons or contaminants.

APU cold and altitude start tests completed with a 2 percent DGD blend showed successful starting over the start envelope, but did have fuel flow fluctuations at high altitude cold start conditions that may be due to marginal atomization. Cold spray tests with a 2 percent DGD blend showed droplet size much larger than cold Jet A and the Viscor 12 cSt calibrating fluid, possibly due to wax formation in the upstream fuel chiller. It is recommended that the cold spray tests with the 2 percent DGD blend be repeated, and cold spray tests run with the 2 percent F-76 blend.

It is recommended that the viscosity of the GD blends be limited in the D7566 specification to 12 cSt maximum at -40°C for Jet A and 10 cSt maximum for Jet A-1 to ensure there is no increase in viscosity relative to the current jet fuel pool. The freeze point of GD blends should be well below the D7566 specification minimum (-40°C for Jet A, -47°C for Jet A-1) to provide margin for long flights where fuel in the APU compartment can be cold soaked.

APPENDIX 3. HONEYWELL TESTS TO EVALUATE A LOW FREEZE POINT GREEN DIESEL FUEL BLEND

(13 pages)

Honeywell Tests to Evaluate a Low Freeze Point Green Diesel Fuel Blend

Component and combustor rig tests of a low freeze point hydroprocessed esters and fatty acids (HEFA) fuel blend, also called Green Diesel (GD) blend, was completed at the Honeywell Aerospace facility in Phoenix, Arizona. Funding for the testing was provided by the Air Force Research Laboratory (AFRL). All findings and conclusions expressed are those of the authors (Honeywell) and do not necessarily reflect the views of the contracting agency.

The purpose of the testing was to evaluate the effect of GD fuel blends on the performance, operability, and emissions of aircraft gas turbine engines. Blends of a low freeze point HEFA synthetic paraffinic kerosene (SPK) in the diesel fuel boiling range with conventional petroleum derived jet fuel were evaluated.

The following evaluation tests were completed using the GD fuel blend and a baseline fuel:

- 131-9 APU combustor rig performance, emissions, lean blowout (LBO), and lean ignition tests
- Fuel atomizer cold spray test

Green Diesel Blending Component

The low freeze point GD SPK was provided by Neste Corporation in Finland. Two 55-gallon drums of the Neste GD SPK were provided, with select properties shown in Table 1. The density, freeze point, distillation 10 percent point, and distillation end point of the GD SPK blending component were above the current HEFA SPK specification limits (D7566-16). A GCxGC gas chromatography analysis of the neat GD SPK was performed by AFRL, with the chromatogram shown in Figure 1.

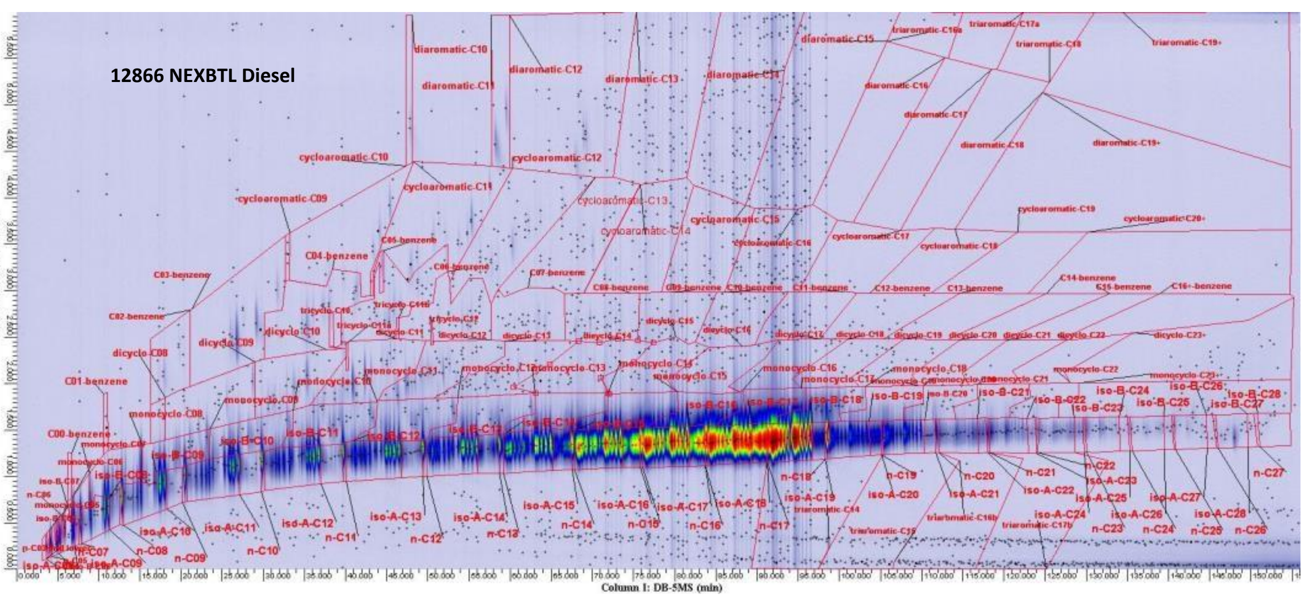


Figure 1. Neste Green Diesel Synthetic Paraffinic Kerosene GCxGC Chromatogram.

The Neste GD SPK is primarily (>92 percent by weight) iso-paraffins with carbon numbers up to 27 (small quantities), with higher concentrations up to a carbon number of 20.

When a low freeze point GD SPK is blended into jet fuel in varying concentrations depending on the properties of the petroleum derived jet fuel blending component, the final blended fuel can meet all D7566 Table 1 requirements.

Fuel for each Honeywell test series was blended just prior to the test, so there were some test to test variations in both the baseline fuel and GD blend properties. The 30 percent Neste GD blends tested met specification requirements for all properties tested. The low freeze point Neste GD SPK was blended with a light JP-8 fuel to maximize the amount of GD SPK in the blend. The final blend ratio was 30 percent by volume GD SPK, which was set by viscosity limitations (12 cSt maximum at -40°C).

Table 1. Green Diesel SPK Properties

Fuel Property	100% Neste Green Diesel	D7566 Annex A2 (HEFA SPK) Spec Limits	D7566 Table 1 (HEFA Blend) Spec Limits
Density (D1298)	781	730 to 770	775 to 840
Temp, °C for 12 cSt viscosity (1)	-10		
Viscosity, cSt at -20°C (D445) (1)	18.7		8 max
Viscosity, cSt at -20°C (D445)	19.2		8 max
Dist IBP, °C (D86)	158		
10% Dist Temp, °C (D86)	260	205 max	205 max
20% Dist Temp, °C (D86)	271		
50% Dist Temp, °C (D86)	281	report	report
90% Dist Temp, °C (D86)	291	report	report
Dist FBP, °C (D86)	306	300 max	300 max
Dist T50-T10, °C (D86)	21		15
Dist T90-T10, °C (D86) (1)	31	20	40
Flash Point, °C (D56) (1)	64	38 min	38 min
LHV, MJ/kg (D240)	43.97		42.8 min
Smoke Point, mm (D1322)	>50		25.0 min
Aromatics, %v (D1319)	0.0	0.5 max	8 to 25
Freeze Point, °C (D2386)	-30	-40 max	-40 max

Fuel Property	100% Neste Green Diesel	D7566 Annex A2 (HEFA SPK) Spec Limits	D7566 Table 1 (HEFA Blend) Spec Limits
Freeze Point, °C (D5972)	-29	-40 max	-40 max
(1) Calculated			

131-9 Combustor Rig Testing

131-9 combustor rig testing was completed to determine the effect of the GD fuel blend on combustion system performance. A full scale 131-9 combustor rig was installed in the combustion test facility (Figure 2) in Phoenix, Arizona with tests completed in August of 2016.

The test fuels for combustor rig testing consisted of a Jet A baseline, the JP-8 blending component, and the 30 percent GD blend.

The 30 percent GD blend was supplied to the test cell from a 55-gallon drum, while the Jet A and JP-8 were provided from the standard laboratory fuel supply. Jet A is the normal baseline fuel and was run for all tests, while JP-8 was run for performance and emissions tests since it was the major blending component in the 30 percent GD blend. Table 2 provides properties of the Jet A and GD blend used for combustor rig ignition testing, while Table 3 provides Jet A, JP-8, and GD blend properties used for combustor rig performance, lean blowout, and emissions testing.

The 30 percent GD blend met all specification properties tested, except for aromatics which was slightly below the current D7566 specification limit due to the relatively low aromatics of the JP-8 blending component.

Figure 2. a) 131-9 Rig Installed in Test Cell, b) Mobile Emissions Truck, c) Fuel Drums.

Table 2. Fuel Properties for Combustor Rig Ignition Tests.

Fuel Property	Jet A	30 percent GD Blend
Specific Gravity (D1298)	0.811	0.781
Viscosity, cSt at -20°C (D445)	4.9	5.5
Viscosity, cSt at -40°C (D445)	10.5	11.9
LHV, MJ/kg (D240)	43.14	43.67
Flash Point, °C (D56)	45	47
Dist IBP, °C (D86)	154	160
10% Dist Temp, °C (D86)	171	176
20% Dist Temp, °C (D86)	182	182
Freeze Point, °C (D2386)	-44	-45
Freeze Point, °C (D5972)	-45	-50
Water, ppmw (E1064)	46	44

Table 3. Fuel Properties for Combustor Rig Performance and Emission Tests.

Fuel Property	Jet A	JP-8	30 percent GD Blend
Specific Gravity (D1298)	0.811	0.780	0.780
Viscosity, cSt at -20°C (D445)	4.9	3.6	5.5
Dist IBP, °C (D86)	160	160	160
10% Dist Temp, °C (D86)	172	170	177
20% Dist Temp, °C (D86)	182	177	183
50% Dist Temp, °C (D86)	204	188	209
90% Dist Temp, °C (D86)	249	216	284
Dist FBP, °C (D86)	282	242	298
Flash Point, °C (D56)	46	47	49
LHV, MJ/kg (D240)	43.11	43.51	43.71
Smoke Point, mm (D1322)	23	30	32
Aromatics, %v (D1319)	18.0	11.5	7.0
Naphthalenes, %v (D1840)	0.15	- -	0.03
Freeze Point, °C (D2386)	-48	-55	-44
Freeze Point, °C (D5972)	-47	-55	-48
Water, ppmw (E1064)	68	71	104

GCxGC chromatograms for the Jet A and 30 percent GD blend are shown in Figures 3 and 4 respectively.

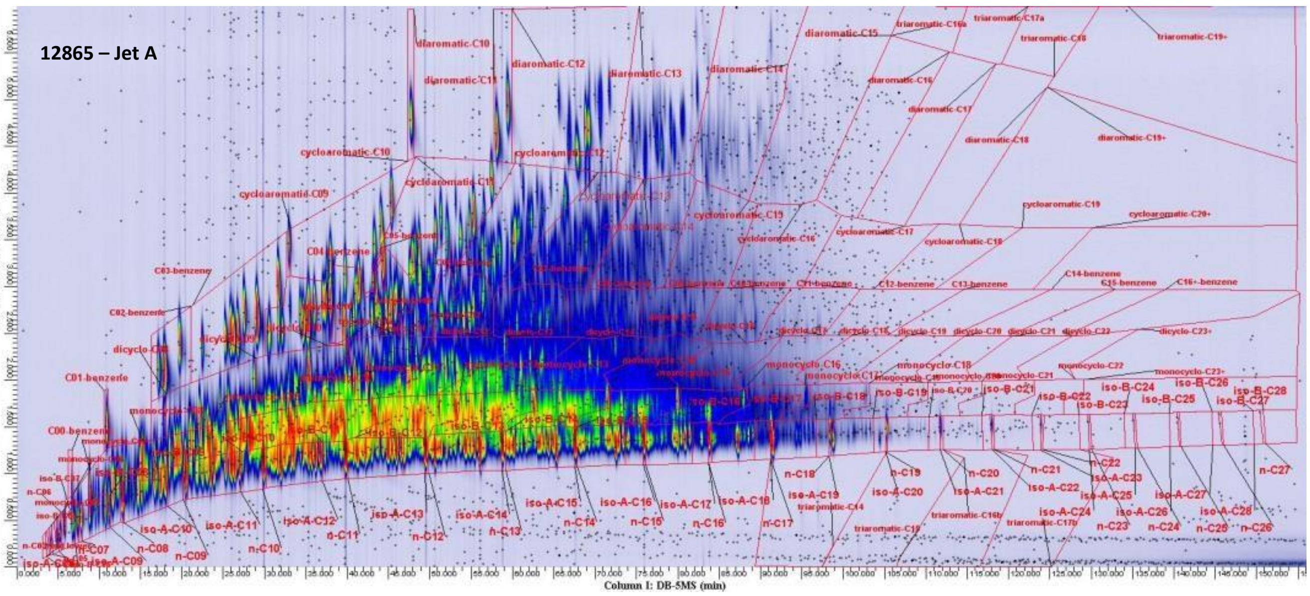


Figure 3. Jet A GCxGC Chromatogram.

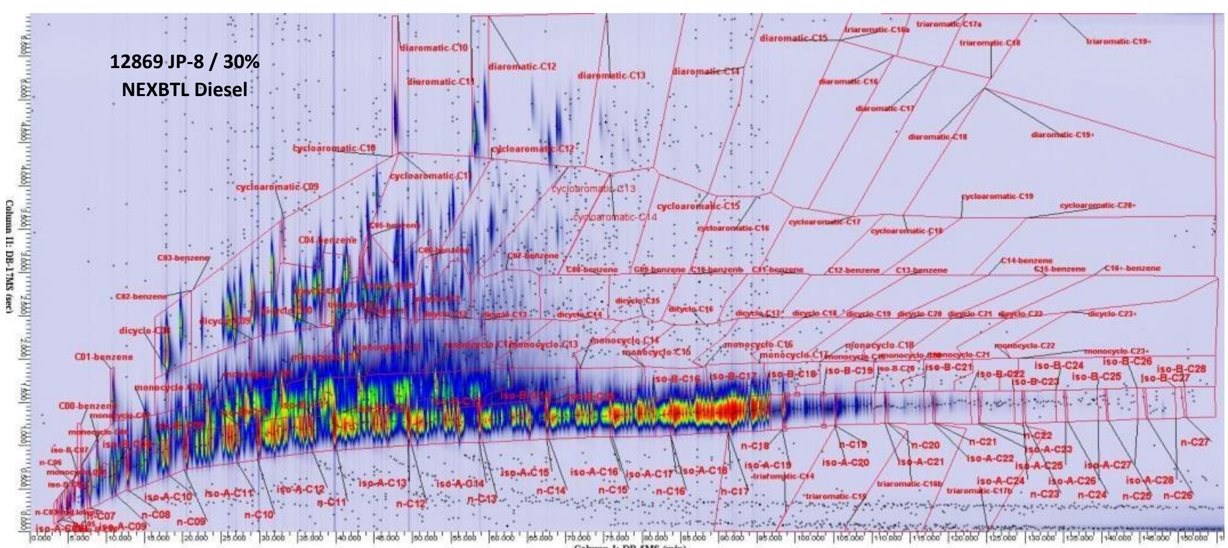


Figure 4. 30 Percent Low Freeze Point Green Diesel Blend Chromatogram.

Performance tests were completed over a range of operating conditions from idle to maximum power conditions including sea level standard day No-Load (NL), sea level standard and hot day ECS (Environmental Control System), sea level hot day MES (Main Engine Start) and 41,000 feet altitude hot day generator load. All tests were run at actual engine conditions (not scaled). Fuel flows were adjusted to provide a constant heat input (MJ/hr) to the combustor, to account for the varying fuel lower heating value (LHV).

There was no fuel effect on combustor pattern factor (Figure 5) or radial profile (Figure 6). Pattern factor (PF) and radial profile are measures of the temperature distribution at the turbine stator inlet plane (combustor exit). PF is the ratio of the difference between the maximum and average temperature at the turbine inlet plane to the combustor temperature rise, and affects turbine stator life. Pattern factor with the 30 percent GD blend was similar to the baseline Jet A and JP-8 fuels at all high power load conditions, within normal test to test variation. All pattern factors were well below the design limit.

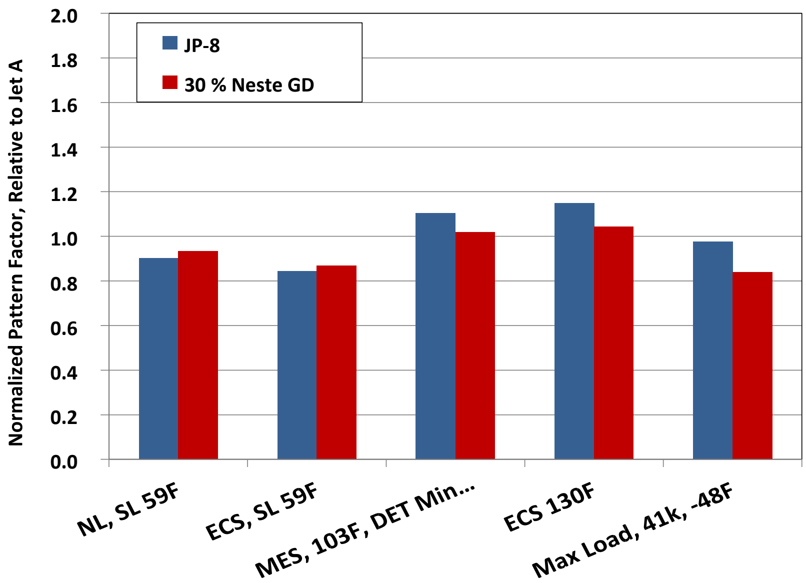


Figure 5. 131-9 Combustor Relative Pattern Factor.

Radial profile is the circumferential average temperature across the measurement plane (turbine stator inlet), and affects turbine rotor life. Radial profile was similar for the 30 percent GD blend and the baseline Jet A and JP-8 fuels, as seen in Figure 6 for one of the ground high power load conditions. Results shown are within test to test variation. The GD blend had slightly higher temperatures at the blade tip location and slightly lower temperatures at the blade hub location, but these differences are not considered significant. Similar results were obtained at other load conditions.

MES Deteriorated Engine 103°F

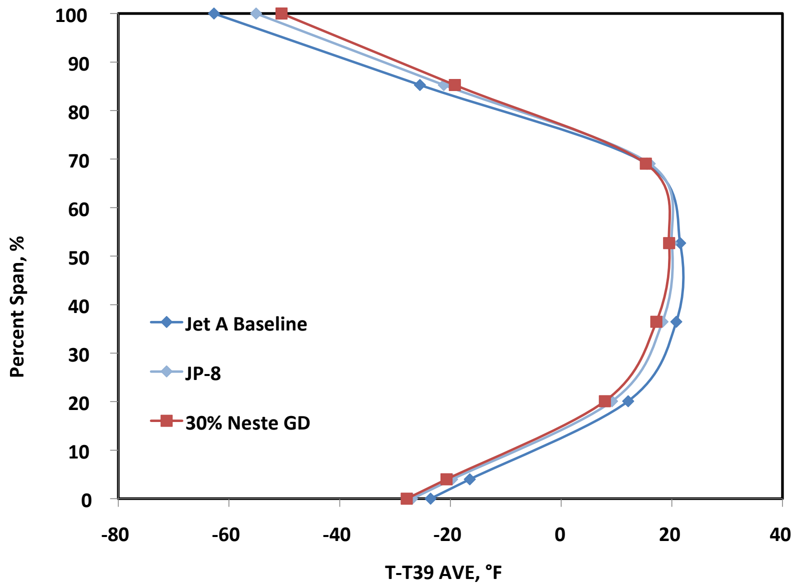


Figure 6. 131-9 Radial Profile at SL 39°C MES Load Condition.

Gaseous and smoke emissions were measured during combustor performance testing using a fixed sampling rake in the rig tailpipe and a mobile emissions truck. Gaseous emissions were measured in accordance with SAE ARP1156 and reduced to SAE ARP 1533 requirements. Smoke number (SN) emissions were measured with an optical smoke meter and converted to equivalent SAE smoke number. Combustor nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbon (UHC), and SN emissions were measured at each test condition. Test results with the JP-8 and 30 percent GD blend are presented as relative emissions, which is the ratio of emissions index (g/kg fuel) or smoke number to emissions with the baseline Jet A fuel.

NOx emissions with the 30 percent GD blend were the same as JP-8 and the baseline Jet A fuel at all conditions (Figure 7). The UHC and CO emissions of the 30 percent GD blend and JP-8 were similar at all conditions (Figure 8), with both slightly lower than the baseline Jet A. The CO emissions for the GD blend were slightly higher than JP-8 at all conditions, but both were below Jet A values. CO and UHC variations at the high power conditions (ECS and MES) are not considered significant due to the very low emissions levels, and since small changes in measured values results in large percent changes. UHC and CO emissions are significant only at the No-Load and altitude generator load conditions.

Smoke emissions with JP-8 and the GD blend were reduced over 55 and 70 percent respectively from the baseline Jet A fuel at all higher power conditions (Figure 9) due to the lower fuel aromatic content (Jet A 18.0 percent v, JP-8 11.5 percent v, GD blend 8.0 percent v). SN emissions were very low (SN < 10) at all conditions with all fuels, so small changes in measured smoke emission values result in large percentage changes. SN emissions at the altitude generator load condition (41K shp) were not reported as they were below the instrument detection limit.

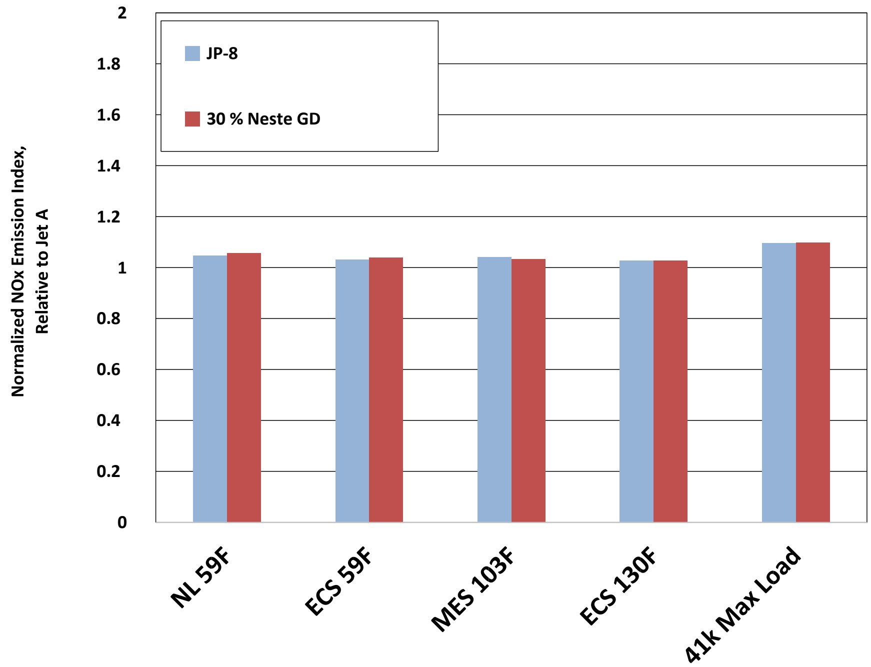


Figure 7. 131-9 Rig NOx Relative Emissions.

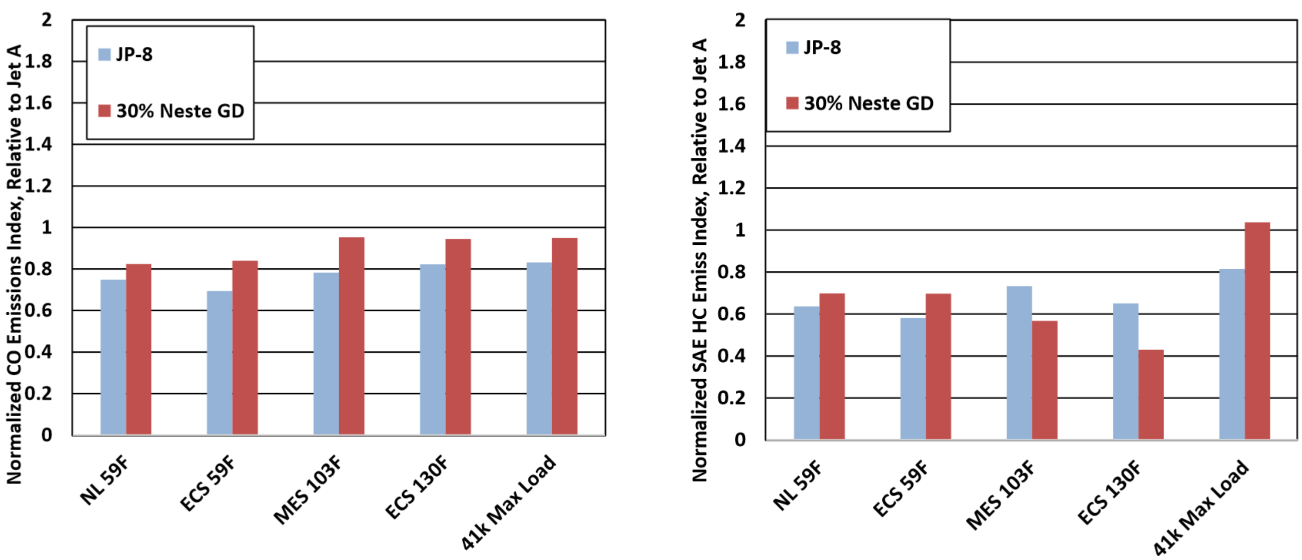


Figure 8. 131-9 Rig a) CO and b) UHC Relative Emissions.

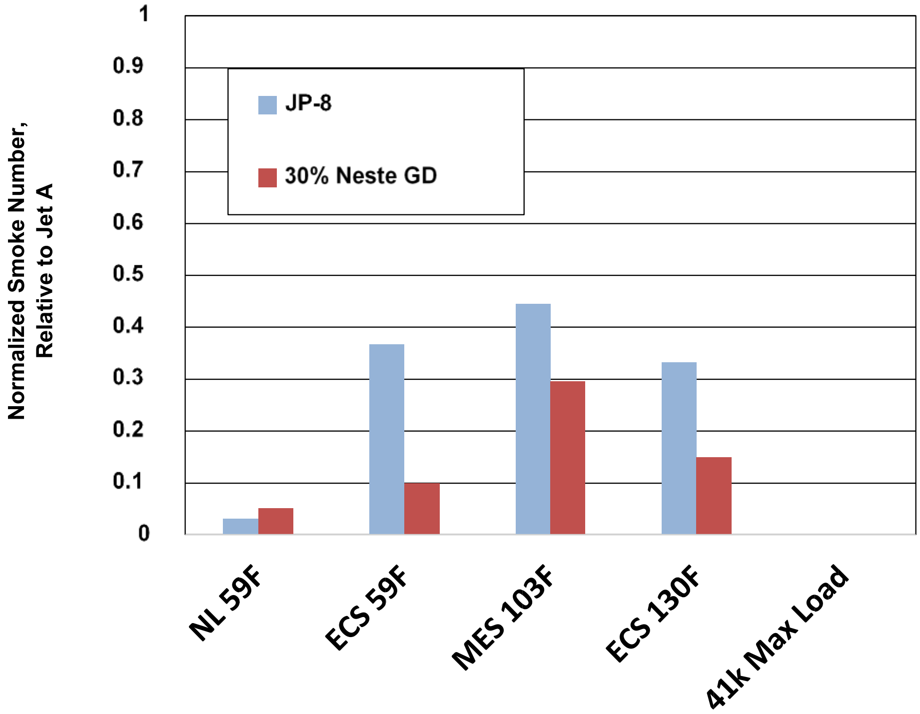


Figure 9. 131-9 Rig Relative Smoke Emissions.

Emission test results showed no adverse effect of the 30 percent GD fuel blend on engine gaseous emissions, with a reduction in smoke emissions which could improve local air quality near the airport.

Lean blowout tests were run at simulated engine No-Load (idle) conditions or part speed conditions over the operating envelope (sea level up to 41,000 feet altitude). After stabilizing at each condition, the fuel flow rate was slowly decreased while holding combustor inlet conditions constant and continuously recording data. Blowout was detected when the measured combustor exit temperatures suddenly dropped. Ambient fuel temperatures were used for blowout testing. Blowout test results were correlated against a corrected reference velocity (corrected airflow). Test results (Figure 10) showed a small increase in lean blowout fuel-air ratio with the 30 percent GD blend at the two high altitude conditions, which is a small loss of blowout margin.

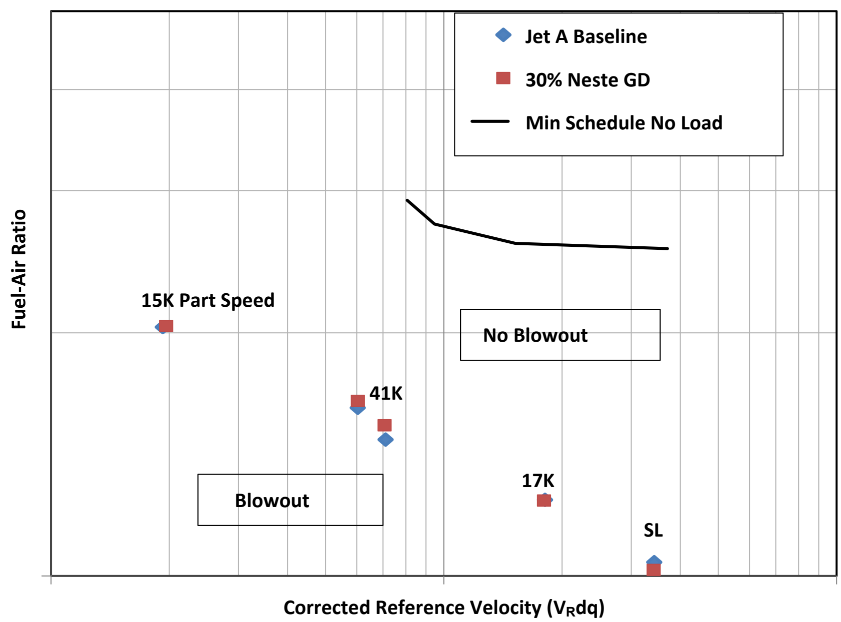


Figure 10. 131-9 Rig Lean Blowout Results.

Lean ignition tests were run at simulated APU ground and altitude start conditions from sea level up to 41,000 feet altitude. Fuel temperatures varied at each test condition, and ranged from ambient to -37°C. After stabilizing at each condition, an ignition attempt was performed at varying fuel flows until the minimum fuel flow for acceptable ignition delay was found. Fuel temperatures and flows were preset in a bypass circuit, and then directed to the combustor through a three-way solenoid valve. Ignition delay is defined as the time from when the fuel is introduced and the igniter switched on until ignition was detected by a rise in combustor exit temperature. The lean ignition fuel-air ratio is reported as a function of corrected reference velocity (corrected airflow). Test results (Figure 11) show lean ignition fuel-air ratios with the 30 percent GD blends were similar to the baseline Jet A fuel, presumably due to the similar front end distillations Results with both the Jet A and 30 percent GD blend were lower (better) than historical values for high flash point fuels such as JP-5 (not shown).

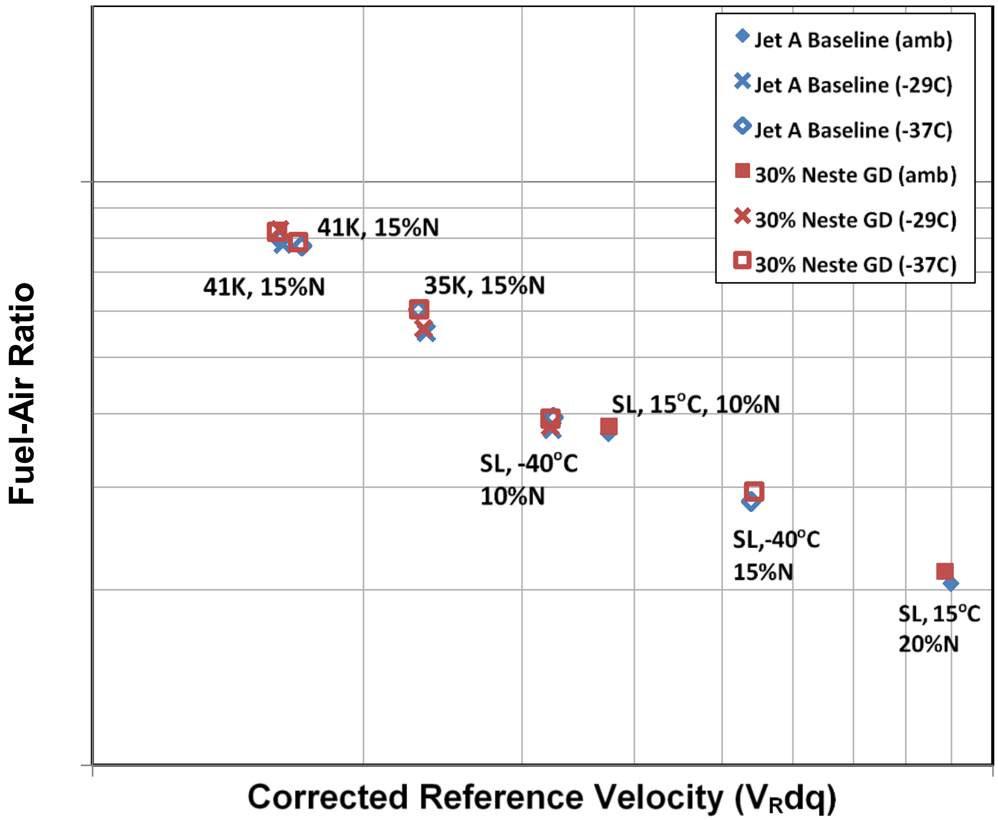


Figure 11. 131-9 Rig Lean Ignition Results.

Combustor rig test results showed there was no adverse effect of a 30 percent blend of low freeze point GD SPK and conventional petroleum derived jet fuel on combustion performance (pattern factor and profile), ignition characteristics, and exhaust gaseous emissions, with a significant reduction in exhaust smoke emissions. There was a small degradation in lean blowout at several high altitude conditions.

Atomizer Cold Spray Testing

Onboard APUs are required to provide reliable cold and high altitude starting if there is a main engine generator failure or an in-flight shutdown of a main engine. Since the APU is normally off in-flight, the APU and its fuel supply can be cold-soaked which makes atomization of the fuel critical to reliable starting. In contrast, most main engines have a fuel-oil heat exchanger which warms the fuel prior to the inlet fuel filter. The APU and main engine have similar ground cold start requirements.

Honeywell completed atomizer cold bench spray tests to determine fuel effects on atomization and spray quality, and by inference, APU or engine cold ignition. Pressure atomizers typical of those used on APUs and small propulsion engines, or as start injectors for main propulsion engines were selected for testing. Atomizer performance parameters including fuel flow, spay droplet size, and spray characteristics were measured over a range of conditions.

Three pressure atomizers were used for testing. Atomizer A was a small FN atomizer typical of those used on newer transport and military APUs. Atomizer B was a mid-sized FN atomizer typical of primary atomizers used on older commercial and military transport APUs, and smaller APUs used on regional aircraft. Atomizer C was a large FN atomizer typical of secondary atomizers used on older commercial and military transport APUs or on can-type combustion systems. FN is an indication of the atomizer size, and is the fuel flow (lb/hr) divided by the square root of the fuel pressure (psid).

Small FN atomizers are normally the most sensitive to fuel property variations.

Four test fluids were used for testing including standard calibrating fluid (MIL-PRF-7024 Type II), Jet A (D1655), the 30 percent GD fuel blend, and Viscor 12 cSt calibrating fluid. The Jet A provided by Honeywell was from the standard laboratory facility fuel supply. Table 4 summarizes fuel properties important to atomization, including specific gravity (D1298) and viscosity (D445).

Each atomizer was tested over a range of conditions representative of typical engine start conditions. For pressure atomizers, this required a range of inlet fuel pressures. The fuels were all run at ambient ~27°C (80°F) and -40°C (-40°F) fluid temperatures. The Viscor fluid was run at a temperature to provide 12 cSt viscosity (around 27°C). Sauter mean diameter (SMD) was used as a measure of atomization quality, which has been shown to correlate well with engine ignition and blowout characteristics. SMD measurements (microns) were obtained with a Malvern Spraytec particle analyzer. Test results are presented with spray SMD normalized to 7024 II calibrating fluid.

Table 4. Atomization Test Fluid Properties.

Fluid	Specific Gravity	Viscosity (cSt at 25°C)	Viscosity (cSt at -40°C)	Freeze Point (°C)	Freeze Point (°C)
	D1298	D445	D445	D2386	D5972
7024 II	0.766	1.2	n/a	n/a	n/a
Jet A	0.803	1.7	9.5	-50	-50
30% GD Blend	0.781	1.9	12.0	-44	-48
Viscor	0.874	11.9	n/a	n/a	n/a

Figure 12(a) shows the cold 30 percent GD blend had spray droplet size (SMD) for atomizer A (smallest FN) similar to that of the Viscor 12 cSt fluid for higher pressures tested, but slightly higher (worse) at lower fuel pressures. SMDs with Jet A were significantly lower than the 30 percent GD blend or Viscor due to the lower viscosity. Spray angles for atomizer A presented in Figure 12(b) show spray angles for the 30 percent GD blend were wider (better) than the spray angles for the Viscor 12 cSt fluid above 60 psid, then the spray collapses quickly (Viscor spray collapses below 50 psid). Spray collapse with viscous fluids at low fuel pressures is normal, but early collapse leads to cold starting concerns. Figure 13 shows photographs of the cold spray at 50 psid with Viscor, Jet A, and the 30 percent GD blend, where the narrow angle for the GD blend is clearly evident.

Results for the other two pressure atomizers (atomizers B and C) showed spray droplet size (SMD) and spray angle for the 30 percent GD blend were the same or better than values for the Viscor 12 cSt fluid.

Atomizer cold (-40°C) spray tests showed spray characteristics with the small pressure atomizer and 30 percent GD blend were acceptable at higher pressure, but degraded below conventional Jet A fuel and the Viscor 12 cSt calibrating fluid at lower pressures.

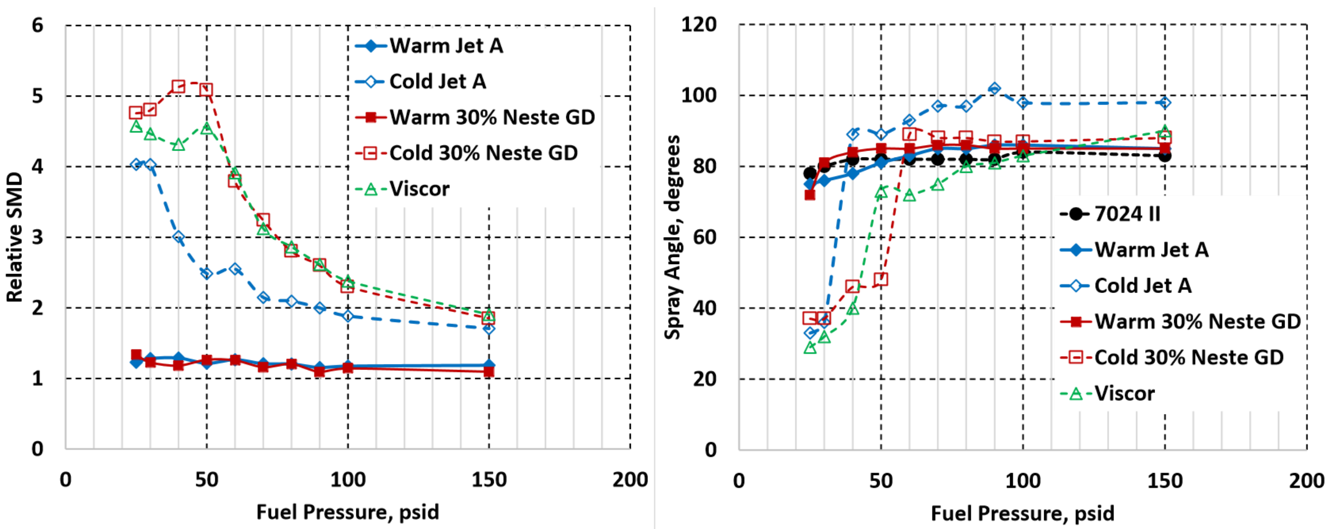


Figure 12. a) Comparison of Small Atomizer Droplet Size, b) Spray Angle.

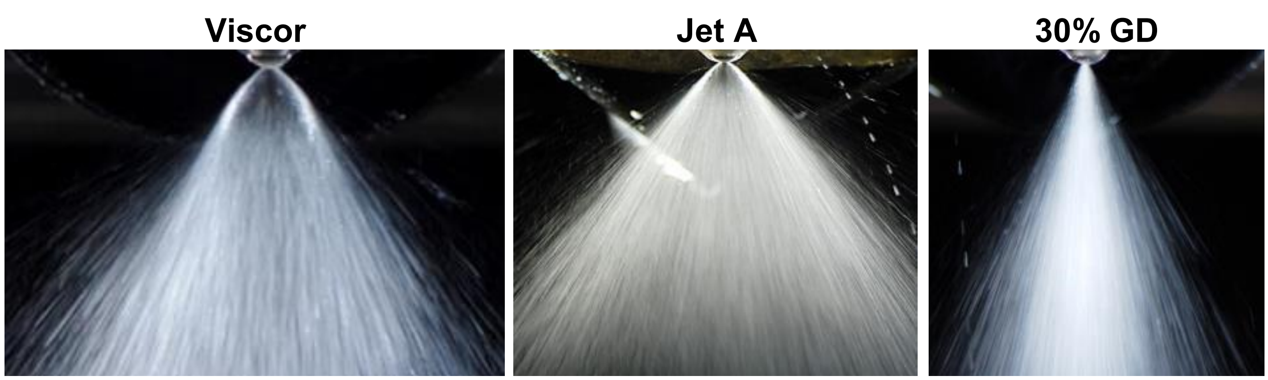


Figure 13. a) Cold Spray Photographs at 50 psid for Viscor, b) Jet A, c) 30 percent GD Blend.

Summary

Combustor rig tests completed with 30 percent low freeze point GD blend showed there was no adverse impact on combustor performance (pattern factor or profile), ignition characteristics or exhaust emissions, but there was a small degradation in lean blowout characteristics at some test conditions. Cold spray tests with the medium and large atomizer showed no adverse effect with the 30 percent GD blend, but with the smallest atomizer both droplet size and spray angle were degraded at low fuel pressures.

Based on the degradation in lean stability (lean blowout) at high altitude conditions and in spray characteristics at low fuel pressures for the smallest atomizer, it is recommended that APU system level start tests be conducted with the 30 percent Neste GD blend to verify there is no adverse effect on APU cold and altitude start reliability.

Another issue is the 4^{o} to 5^{o}C difference in freeze point between D2386 (manual method) and D5972 (Phase Technology) methods, with D5972 the lower value. Additional laboratory testing is recommended to determine freeze point with Green Diesel blends with all approved freeze point instruments.

It is recommended that the viscosity of Green Diesel blends be limited in the D7566 specification to 12 cSt maximum at -40^{o}C for Jet A, to ensure there is no increase in viscosity relative the current jet fuel pool. A 10 cSt maximum viscosity at -40^{o}C (corresponds to 12 cSt at -44^{o}C) should be imposed for Jet A-1. This would limit the blend viscosity to the maximum viscosity for reliable engine and APU cold starting (12 cSt) 3^{o}C below the -47^{o}C freeze point for Jet A-1. The freeze point of GD blends should be well below the D7566 specification maximum (-40^{o}C for Jet A, -47^{o}C for Jet A-1) to account for uncertainty in freeze point measurements and to provide margin for long flights where fuel in the APU compartment can be cold soaked.

LIST OF ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
AO	anti-oxidant
APU	auxiliary power unit
ARA	Applied Research Associates
ARP	Aerospace Recommended Practices
CHCJ-5	Catalytic Hydrothermolysis Jet Made to JP-5 Specifications
CI/LI	Inhibitor/Lubricity Improver
CLEEN	Continuous Lower Energy Emissions and Noise
CO_2	carbon dioxide
CO	carbon monoxide
DGD	Diamond Green Diesel
DLA	Defense Logistics Agency
DOD	Department of Defense
ECS	environmental control system
EGT	exhaust gas temperature
FAA	Federal Aviation Administration
FID	flame ionization detector
FN	flow number
FSII	fuel system icing inhibitor
GD	Green Diesel
HC	hydrocarbons
HEFA	hydroprocessed esters and fatty acids
HX	heat exchanger
ICAO	International Civil Aviation Organization

LACC	large altitude cold chamber
lb/hr	pounds per hour
LBO	lean blowout
LHV	lower heating value
LN2	liquid nitrogen
MES	main engine start
NDIR	non-dispersive infra-red
NIST	National Institute of Standards and Technology
NJFCP	National Jet Fuel Combustion Program
NL	no-load
NO_x	oxides of nitrogen
OEM	original equipment manufacturer
O_2	oxygen
PF	pattern factor
PR	pressure ratio
psid	pound(s) per square inch, differential
SAE	Society of Automotive Engineers
SDA	static dissipator additive
shp	shaft horsepower
SL	sea level
SLS	sea level standard
SMD	Sauter mean diameter
SN	smoke number
SPK	synthetic paraffinic kerosene
TC	thermocouple

TSO	Technical Standard Order
UHC	unburned hydrocarbon
USAF	United States Air Force