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CONTINUOUS LOWER ENERGY, EMISSIONS AND NOISE (CLEEN) TECHNOLOGIES DEVELOPMENT PROGRAM FINAL REPORT

PUBLIC RELEASE

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LIST OF ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
APU	Auxiliary Power Unit
ASTM	American Society for Testing and Materials
BOCLE	Ball on Cylinder Lubricity Evaluator
CFD	Computation Fluid Dynamics
CLEEN	Continuous Lower Energy Emissions and Noise
CMAS	Calcia-Magnesia-Alumina-Silica
DARPA	Defense Advanced Research Projects Agency
DDR	Detail Design Review
DOE	Design of Experiment
EVA	Ethylene Vinyl Acetate
FAA	Federal Aviation Administration
FRL	Fuel Readiness Level
GHG	Green House Gas
HDCJ	Hydrotreated Depolymerized Cellulosic Jet
HIPed	Hot Isostatic Pressed
HPT	High-Pressure Turbine
ILUC	Indirect Land Use Changes
IPPS	Integrated Power Plant System
LCA	Life Cycle Analysis
LCF	Low-Cycle Fatigue
MIT	Massachusetts Institute of Technology
MSMLII	Multi-Stiffness-Multi-Laminate II
OPR	Overall Pressure Ratio
OSU	Ohio State University
PBA	Petroleum-Based Aromatics
PDR	Preliminary Design Review
PVD	Plain View Display
SFC	Specific Fuel Consumption
Si-C	Silicon Carbide
SLBOCLE	Scuffing Load BOCLE
SOA	State-of-the-Art
SOW	Statement of Work
SwRI	Southwest Research Institute
TBC	Thermal Barrier Coating
TMF	Thermal Mechanical Fatigue
TRL	Technology Readiness Level
TSFC	Thrust Specific Fuel Consumption
UOP	Universal Oil Products
YSZ	Yttria-Stabilized Zirconia

CONTINUOUS LOWER ENERGY, EMISSIONS AND NOISE (CLEEN)
FINAL REPORT (PUBLIC)

1.0 INTRODUCTION

This document, prepared by Honeywell Aerospace, Phoenix, Arizona, presents a Final public releasable report for the Continuous Lower Energy Emissions and Noise (CLEEN) effort against contract DTFAWA-10-C-00040. This report is submitted to satisfy Deliverable Data Requirements List for Final Reports (C.4.3/E.3-d,e,f).

The objective of this effort is to mature fuel burn reduction technologies for gas turbine engines. In addition, alternate fuel bio-based fuels were tested and evaluated.

The fuel burn effort will focus on advanced turbine cooling and materials. These technologies will enable operating at higher turbine inlet temperatures with similar or improved durability.

The alternate fuel effort focuses on testing and evaluation of bio-based fuels.

The ultimate program goal is to mature the technologies to technology readiness level (TRL) 6 within the 5-year CLEEN program.

This report includes public releasable data. Sections in this document include compliance to the Statement of Work (SOW) and releasable data where not limited by ITAR, EAR or Proprietary restrictions. A separate “Government Only” document has been prepared that includes the ITAR, EAR and Proprietary restricted CLEEN program data.

2.0 PROGRAM SUMMARY

2.1 Program Management

Honeywell conducted the program management activities to supervise, direct and manage the demonstration of technologies. The company employed project management and planning tools necessary to ensure the accomplishment of each work element in a timely manner and within budget constraints. This work element included the planning, monitoring, analysis and reporting of company cost, schedule and technical performance.

2.2 Technology Maturation

2.2.1 Fuel Burn

2.2.1.1 High T3 Compressor

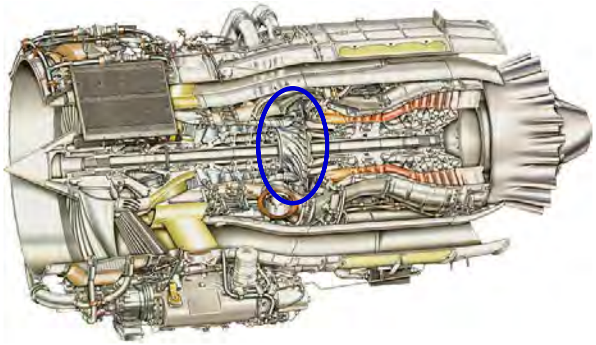
Honeywell designed, fabricated and tested a proprietary configuration to operate in a high T3 (compressor discharge temperature) impeller. A higher T3 capability enables the gas turbine engine to operate at a high overall pressure ratio which results in improved cycle efficiency. The mechanical configuration of the impeller will be designed to be inserted into a gas turbine core demonstrator and an engine demonstrator.

As part of the design process, Honeywell completed aero-mechanical iterations to define blade thickness distribution, blade angle distribution, blade vibrations and rotating group rotor dynamics.

Forced-response analysis was used to assess vibration, and plastic instability based analysis was used for burst speed determination. Design of Experiment (DOE) techniques were employed to explore design space for sensitivities to various design variables. Creep deflection mission analysis was also included in the design process.

Spinpit tests were conducted, using mini disks, to assess low-cycle fatigue (LCF) life. The mini disks and required spinpit tooling assembly was configured to simulate the operating multi-axial stress conditions of the high T3 impeller. Three mini disks were subjected to cyclic testing in a heated spinpit chamber to failure. A full-size impeller was subjected to a spinpit test to validate the burst capability of the impeller design.

The gas turbine core demonstrator validated thermal, mechanical, and aerodynamic performance of the high T3 impeller component. No detrimental impacts to performance were found, and the component was cleared for engine endurance testing. The gas turbine engine demonstrator tested the high T3 impeller in a relevant environment. The Honeywell CLEEN high T3 impeller successfully completed testing for TRL 6 maturation. The impeller met the performance objectives with the exception of weight, which was slightly higher than the goal.



2.2.1.2 Turbine

2.2.1.2.1 Advanced Turbine Cooling

2.2.1.2.1.1 Mechanical Low-Leakage Air-to-Air Finger Seal

Honeywell designed a low leakage air-to-air seal for gas turbine demonstrator engine using Honeywell's Multi-Stiffness-Multi-Laminate II (MSMLII) design patented Finger Seal technology. Honeywell fabricated MSMLII finger seals for rig and engine testing; the location in the engine is shown in Figure 1.

The low leakage air-to-air seal design was tested in an existing high temperature and high pressure air-to-air seal test rig. The seal was tested for different combinations of temperature, pressure differential, eccentricity, and speed. Seals were subjected to cyclic testing to assess sustainability of sealing over time. Testing included comparative tests of other air-to-air seal designs in the rig. The data showed that the MSMLII finger seals had an effective clearance 35 percent lower than an equivalent metal brush seal.

The gas turbine engine demonstrator ran the MSMLII finger seals in a relevant environment and successfully completed testing for TRL 6 maturation. The MSMLII finger seals met the performance objective of reducing the leakage flow relative to a labyrinth seal by greater than 50 percent within the same design space envelope (see Figure 2).

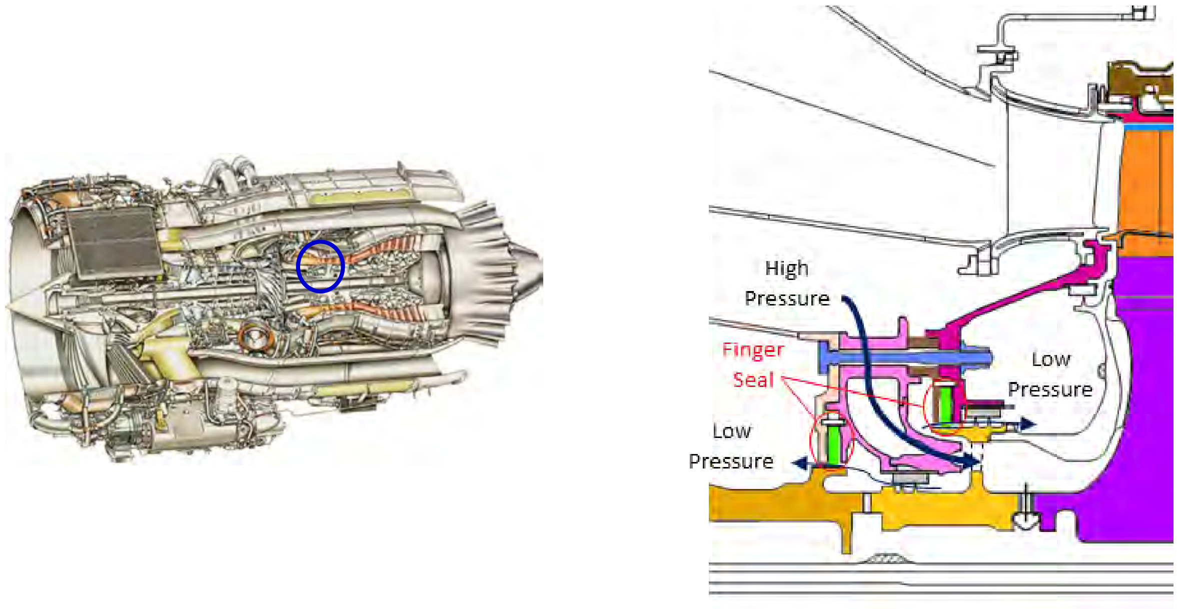


Figure 1. Location of MSMLII Finger Seals in Gas Turbine Engine.

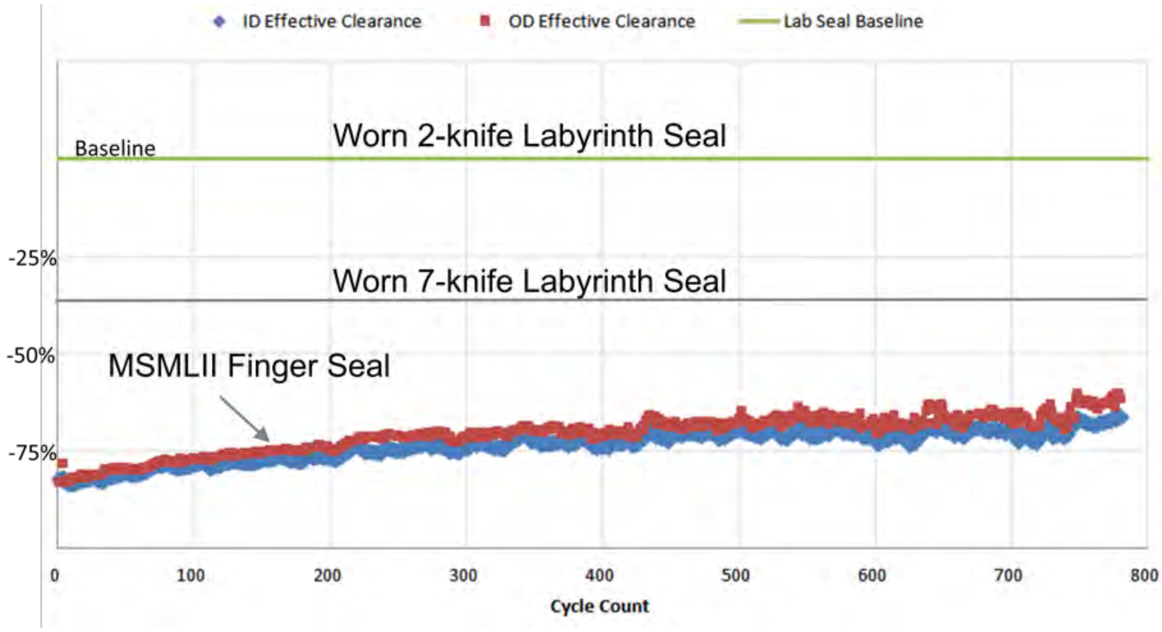


Figure 2. MSMLII Finger Seals in Gas Turbine Engine Over 800 Endurance Cycle Testing.

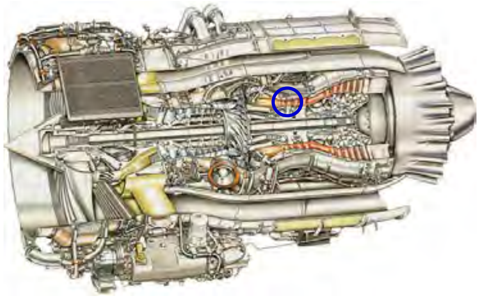
2.2.1.2.1.2 Shaped Film-Cooling Holes

Honeywell analyzed advanced shaped film cooling geometries using Computation Fluid Dynamics (CFD) computer codes. Candidate shaped cooling holes were selected for further study.

Turbine blades were procured; selected candidate shaped cooling hole configurations were fabricated into the turbine blades. These blades were instrumented and installed in a turbine rotor for testing in full stage rotating turbine rig at Ohio State University (OSU). Data from this test was used to assess film cooling effectiveness of the selected candidate shaped cooling hole configurations. Results indicated that the advance shaped film cooling holes improved the cooling effectiveness of the blades as expected.

Advanced shaped film cooling holes were fabricated into high pressure turbine (HPT) blade hardware. Under Honeywell private expense, selected blades were instrumented with surface silicon carbide (Si-C) chips and tested in an engine demonstrator to assess temperature impact resulting from the advance shaped film cooling holes. Results indicated that the advanced shaped film cooling holes reduced the surface temperature of the blades as expected.

The gas turbine engine demonstrator ran the Honeywell shaped film-cooling holes in a relevant environment and successfully completed testing for TRL 6 maturation.



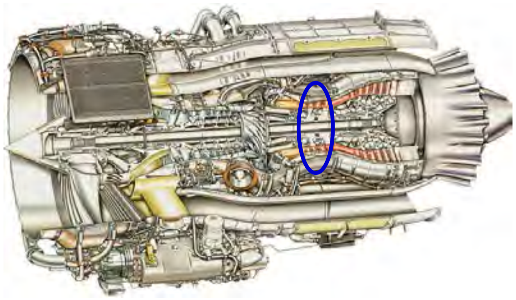
2.2.1.2.2 Advanced Turbine Materials

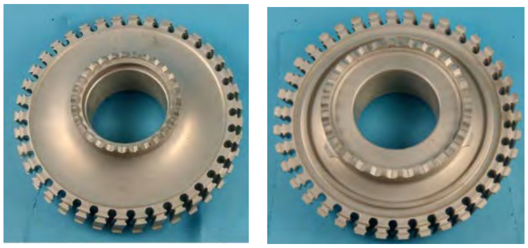
2.2.1.2.2.1 Alloy10 Turbine Disk

Prior to the CLEEN program, Alloy10 powder was developed by Honeywell to operate at higher temperatures than state-of-the-art (SOA) rotor materials. Under the CLEEN program, Honeywell procured Hot Isostatic Pressed (HIPed) compacts made of Alloy10 powder. Test specimens were machined from Alloy10 compacts. Mechanical property tests were conducted to measure mechanical properties such as tensile, LCF, fatigue crack growth, notched LCF (for the disk curvic), notched LCF (for the disk attachment), fir tree configured specimens (including dwell) and curvic configured specimens. A limited number of multi-axial specimens were tested to assess the biaxial stress conditions that are typical in a turbine disk during engine operation. Representative specimens from each type of test had the fracture surface evaluated and metallographically examined to evaluate the fracture growth potential. Alloy10 turbine disks were machined to a configuration suitable for insertion into Honeywell’s demonstrator engine.

An Alloy10 turbine disk was evaluated in a spinpit test to ensure safe operation in Honeywell's demonstrator engine.

The gas turbine engine demonstrator ran the Honeywell Alloy10 turbine disks in a relevant environment and successfully completed testing for TRL 6 maturation.

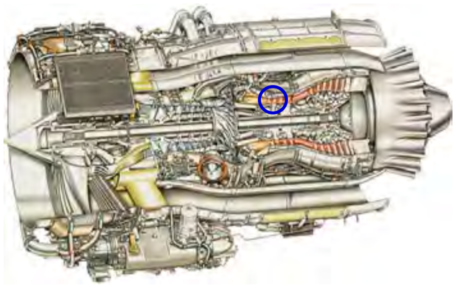


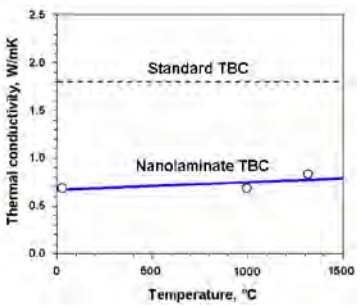


2.2.1.2.2.2 Low-Conductivity Thermal Barrier Coating (TBC) for Vanes and Blades Material

Honeywell procured tooling, coating materials, burner rig bars, turbine blades, and buttons substrates. Coating trials were conducted to refine deposition parameters and composition based on evaluation of low-k TBC's microstructure, composition, and physical properties. Selected compositions were coated on burner rig bars, airfoils and buttons substrates, and testing will be conducted. Physical properties were measured on selected compositions. Measured properties included composition, thermal conductivity, cyclic burner rig life, high temperature phase stability, density, and the evolution of these properties after high temperature exposure. The results from burner rig cyclic testing showed that the Low-k TBC demonstrated substantially higher spallation life compared to standard k TBC (by at least 2X).

The gas turbine engine demonstrator ran the Honeywell low K TBC blades in a relevant environment and successfully completed testing for TRL 6 maturation. The tested rotor also included turbine blades with standard k TBC as a control. The turbine blades with Low-K TBC met the performance objectives of reducing the thermal conductivity while maintaining equivalent durability as the blades coated with standard k TBC.





2.2.1.2.2.3 Type V TBC for Turbine Shrouds

As turbine inlet temperatures continue to rise, the turbine shroud TBC surface temperatures increase and result in sintering, oxidation, and spallation distress. These mechanisms in turn, increase turbine rotor tip clearance, reduce turbine efficiency, and increase engine fuel burn. Current Yttria-Stabilized Zirconia (YSZ) compositions change phase above 2300°F and are not suitable for long life application.

The purpose of this investigation is to determine a viable composition and spray parameters that will allow for increased phase stability at higher temperatures (>2300°F), decreased thermal conductivity (<1.8 W/m•K), and increased coating durability as compared to current YSZ compositions.

Honeywell procured tooling, burner rig bars, shrouds, and button substrates. Coating trials were conducted to evaluate deposition parameters and composition based on evaluation of Type V TBC's microstructure, composition, and physical properties. Selected compositions were coated on burner rig bars, shrouds and substrates, and testing was completed. Various properties were measured for select coating options. Measured properties included composition, thermal conductivity, cyclic life, wear, and the evolution of these properties after high temperature exposure (sintering resistance and phase stability).

This task was designed to systematically examine the effect of impurities on TBC's thermal phase stability and compare 7YSZs with 20YSZ and NASA YSZ-Gd-Yb. Other variables taken into consideration are aging temperature, aging time and cooling rate. Standard and high purity 7YSZ coatings used spray dried powder in order to generate low density TBCs.

Three major evaluations were completed: thermal conductivity, phase stability, and coating durability.

Thermal conductivity evaluation verified that both NASA YSZ-Gd-Yb and 20YSZ to be lower than baseline 7YSZ with the NASA composition being the lowest. High purity 7YSZ appeared to be marginally better than standard purity, but it was not a statistically significant difference. NASA's YSZ-Gd-Yb composition and 20YSZ has much better phase stability than baseline 7YSZ; high purity 7YSZ was marginally better than baseline.

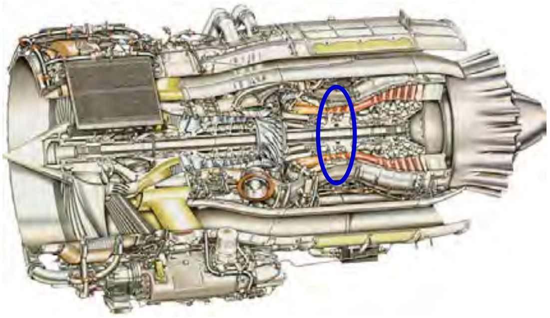
Durability evaluations showed that only high purity 7YSZ showed better results than baseline. All other coating systems performed worse in burner rig shroud testing, machinability, furnace cyclic testing and thermal shock testing. The final qualification was an engine test which involved high thermal strains, calcia-magnesia-alumina-silica (CMAS) exposure, and physical interactions with blades. High purity 7YSZ was the only coating to perform better than the baseline consistently throughout all of the variation of engine tests.

Also completed was a cost analysis based on the powder chemistry and formation. Standard purity 7YSZ was the least expensive, with high purity 7YSZ being slightly more expensive than standard purity 7YSZ.

Taking into consideration all of the individual testing methodologies and results, high purity 7YSZ is the most successful improvement over standard purity 7YSZ. By decreasing the oxides and organics it was possible to increase the thermal stability and decrease thermal conductivity. High purity 7YSZ also had better burner rig results, furnace cyclic testing and thermal shock resistance than the baseline, and much better as compared to the other chemistries evaluated.

Another substantial benefit of high purity 7YSZ is industry knowledge related to 7YSZ-based coatings. This yields benefit to using the high purity form as its spray parameters and processing do not cause an increase in cost or processing since it is already a generationally mature coating chemistry.

The gas turbine engine demonstrator ran the Honeywell Type V TBC coated HPT blades in a relevant environment and successfully completed testing for TRL 6 maturation. The high purity 7YSZ Type V turbine shroud TBC met the performance objectives of higher temperature operation but did not reduce the thermal conductivity.



2.2.1.2.2.4 Advanced Turbine Blade Tip

In the pursuit of more efficient engine operation, increasing combustion temperature clearly provides improvements. Higher temperatures can mean engine components contacted by combustion gases must be capable of withstanding higher material temperatures. Generally, as metal temperatures increase, the mechanical and physical capabilities can degrade. With first stage blades, the blade tip can often be hotter than the bulk temperature and can approach the melting point of the metal, a single crystal nickel based superalloy. This extreme condition on blade tip can lead to damage such as metal recession and cracking.

The oxidation resistance of nickel based superalloys is temperature dependent and for most alloys can be severe above certain critical temperature ranges. Blade tips that operate in engine combustion gases at or above the metal alloy critical temperature range can suffer rapid metal loss from oxidation, thereby increasing the tip to shroud clearance. This condition can result in excessive flow over the tip, decreasing engine efficiency, defeating the benefits of increased combustion temperatures.

Since the blade tip can operate at a higher temperature than the bulk of the blade airfoil, a temperature gradient results, inducing a compressive strain at the tip. This changing condition of strain with engine operation can lead to thermal mechanical fatigue (TMF) cracking at the tip. This type of cracking is first initiated by deformation at the tip during high temperature exposure and compressive strain followed by resultant residual tensile stress. Multiple cycles ultimately result in a fatigue crack initiation which grows with additional cycles and is aided by oxidation at the crack tip root. Crack growth in combination with oxidation can result in a V shape groove resulting in excessive flow through the parapet, reducing efficiency. In addition, crack growth can extend past the tip cap allowing leakage of blade cooling gas, possibly resulting in overheating and failure of the blade.

The goal of this task was to apply a metal alloy to the tip of a nickel based superalloy blade that would enable higher temperature exposure than the base alloy without excessive oxidation recession or TMF cracking.

An additive manufacturing (AM) process was used to laser clad an oxidation resistant material to the tip of single crystal turbine blades. A DOE approach was used to study the effect of welding parameters on weld deposit metrics of cracking, penetration and fusion.

Welding trials were conducted on flat single crystal plates with the crystal orientation such that weld deposit would be onto the (001) direction as it would be for weld cladding the single crystal blade tips. The weld beads were patterned as a loop with a crossover to simulate the conditions on the trailing edge of a turbine blade. Post weld inspection consisted of visual observation and cross sections in two locations as shown in Figure 3.

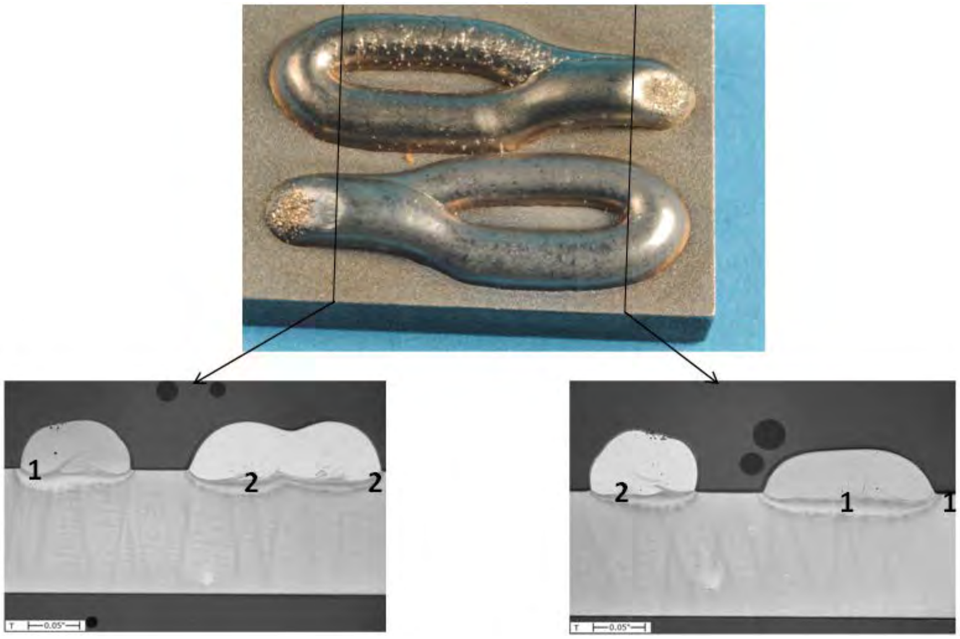


Figure 3. Example Laser Clad Trial.

The application of the laser clad process on actual turbine blades produced acceptable weld deposition geometry and fusion. No cracking or porosity was observed. Photos of a tip welded blade are shown in Figure 4 with a buildup bulge at the trailing edge on the weld crossover. The weld deposit was sufficient to allow cleanup to the final dimension of the airfoil with machining.

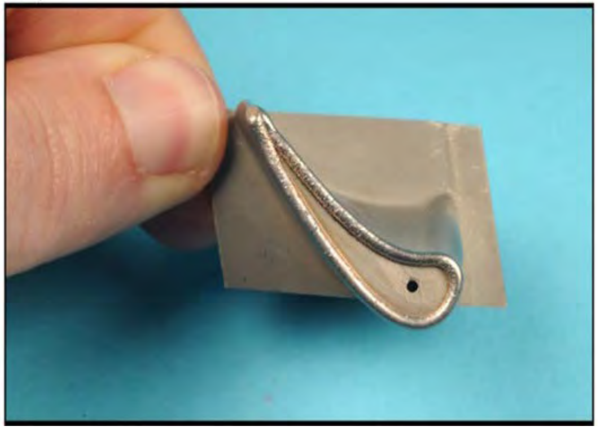


Figure 4. Macro Photo of Tip Buildup With the Advance Turbine Blade Tip Material.

Cyclic oxidation rig testing showed that the advanced turbine blade tip material had significantly less weight change than the baseline single crystal alloy, making it suitable for engine testing.

Testing of TMF was conducted on a Honeywell test rig. The TMF test rig (Figure 5) was designed as an automated test intended to heat a blade-like laboratory specimen in a manner that would produce a large thermal gradient, producing a strain and stress equivalent to calculated conditions on a first stage blade tip. These compressive tip stresses are high enough to cause yielding or creep and when cooled the plastic strains reverse to tension. Repeated thermal cycles result in an out of phase TMF test simulating blade tip engine conditions that was used to compare alloy compositions for cracking resistance. Composition A (Figure 6) performed the best, with no evidence of cracking after 1200 cycles, and it was significantly better than the baseline single crystal material (Composition D).

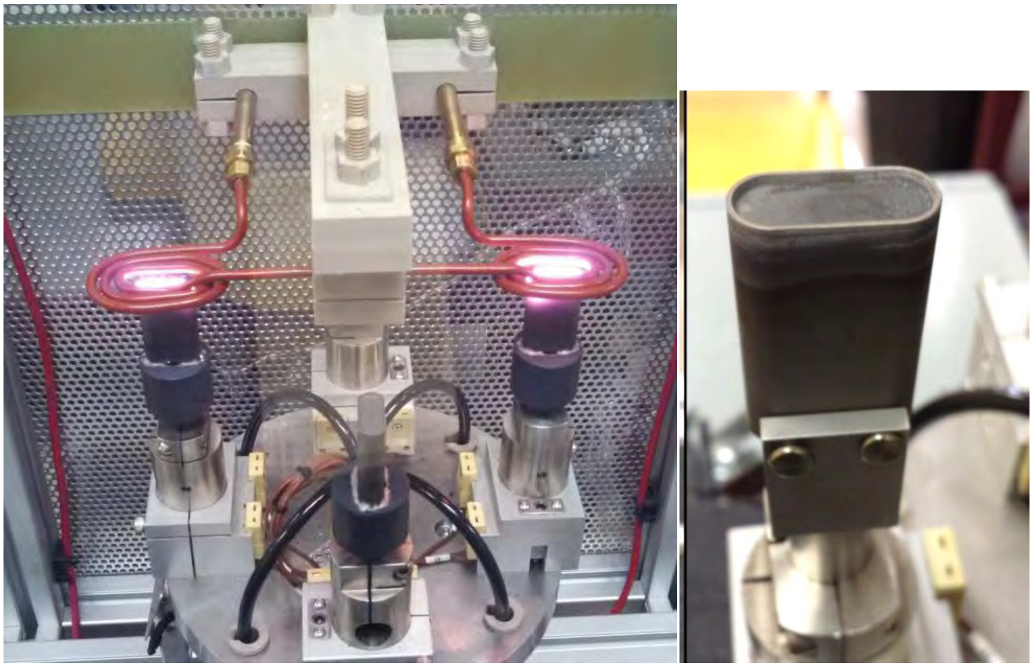


Figure 5. Test Specimens for TMF.

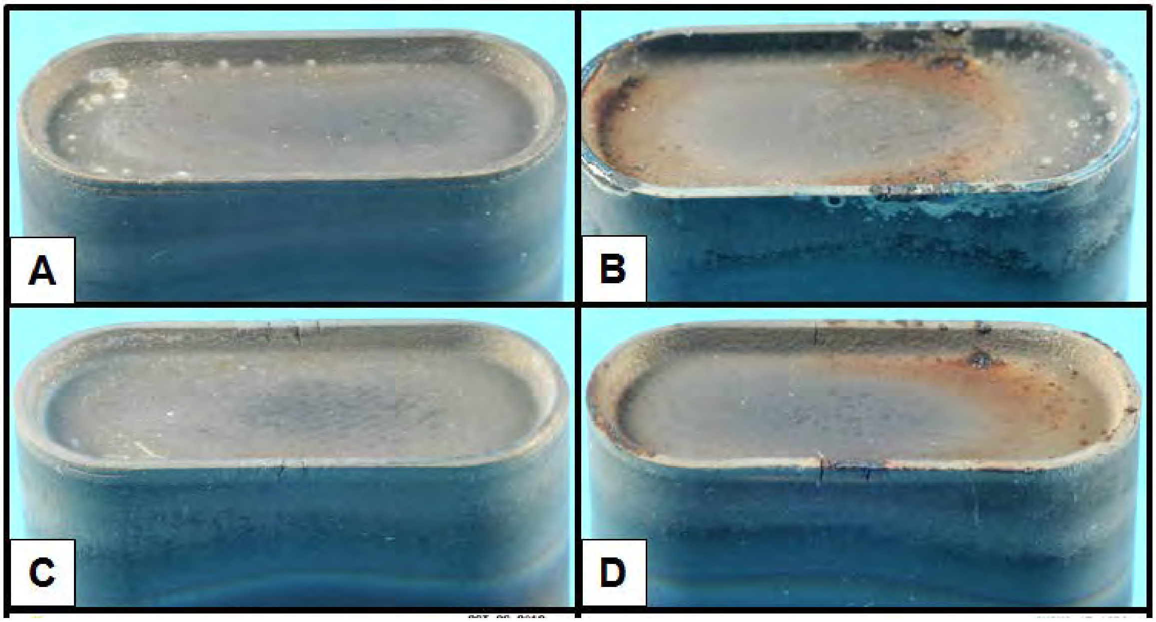


Figure 6. Specimen Appearance After 1200 Cycles.

Engine endurance testing of the three laser clad compositions showed improved performance in oxidation resistance compared with the baseline single crystal material. Composition A provided the best improvement in oxidation resistance and TMF crack resistance when compared with the baseline single crystal blade material.

2.2.2 Alternative Fuels

Honeywell procured petroleum based aromatics (with similar properties as the bio-aromatics) for initial testing.

Honeywell conduced bearing wear tests, seal swell tests, and limited fit-for-purpose chemical analyses tests with petroleum based aromatics at different concentration levels of lubricity and aromatics to determine the minimum level of lubricity and aromatics required for jet fuel.

Honeywell conducted 50/50 blend cold fuel testing of government supplied fuel in support of 50/50 blend American Society for Testing and Materials (ASTM) certification.

Honeywell completed a life cycle analysis (LCA) for the fully synthetic jet fuel compared to petroleum based jet fuel. Massachusetts Institute of Technology (MIT) was subcontracted by Honeywell to support preparation of the LCA.

The approach for assessment of alternative fuel technology maturation is defined in Figure 7, with Fuel Readiness Levels (FRL) associated with each step in the evaluation process.

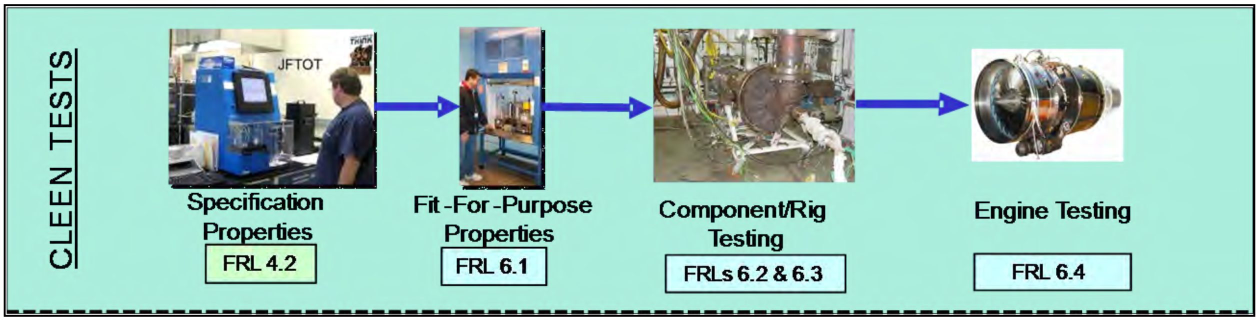


Figure 7. Specification Analysis Fuel Properties.

Initial steps by the alternative fuels team included a literature search for available synthetic aromatics to be blended with the HRJ-SPK Biofuel. In addition to the literature search, Honeywell Universal Oil Products (UOP) worked to establish a plan for creating or selecting a surrogate petroleum based aromatic that will be similar to the final renewable aromatic.

Aromatic compatibility research was conducted through the Honeywell UOP facility. Alternative fuel maturation activities included completion of analyses to evaluate the aromatic composition in jet fuel, a commercially available aromatic, and two renewable alternatives.

The objective of these analyses was to determine if HiSol would be a suitable alternative for the renewable py-oil aromatic or an alternative process currently in development by Honeywell UOP. The HiSol aromatic, the hydrotreated pyrolysis-oil, and the alternative renewable aromatic, were analyzed for their aromatic content and distribution and compared to petroleum jet. Three samples of petroleum jet fuels were evaluated from different Honeywell sites. The results illustrated the broad range of aromatics from C3 to C13 (which include alkylbenzenes, indanes, tetralins, and napthalenes) and the variability in the mass distribution from site to site (Figure 8). HiSol, which was used to produce a semi-synthetic JP-8 for Defense Advanced Research Projects Agency (DARPA) fuels, which has a narrow range of alkylbenzenes in the C3 to C5 range (Figure 9). The hydrogenated pyrolysis-oil aromatics has similar distributions to petroleum jet but lacks napthalenes (Figure 10). While the alternative, for the py-oil renewable aromatic, has similar aromatics to petroleum jet with a different distribution (Figure 11).

The percent relative aromatic composition of HiSol is closer to the aromatic distribution for the alternative renewable aromatic under development by UOP. The distributions are slightly different than the py-oil and the petroleum jet aromatics but are acceptable for use in early program evaluations. Since the HiSol analytical results were slightly different than py-oil and petroleum jet, the program evaluated another commercially available aromatic before making a decision to move forward with early program component testing.

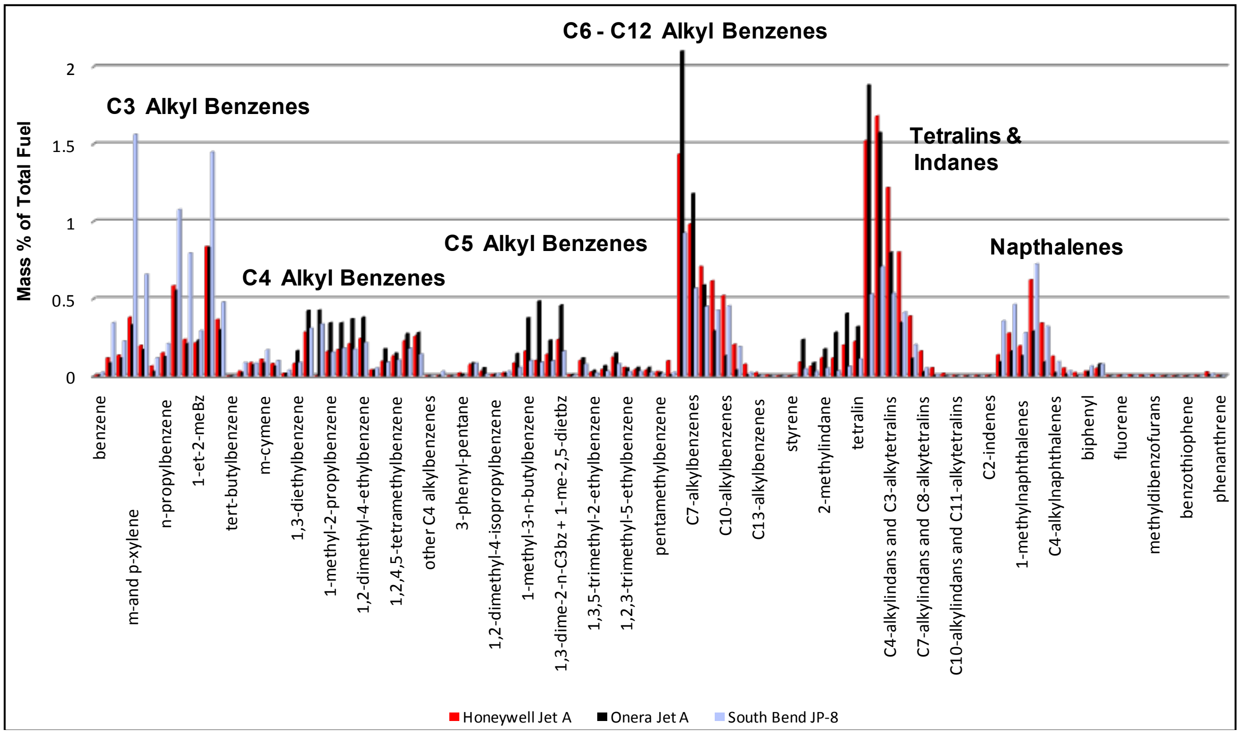


Figure 8. Total Aromatics in Petroleum Jet.

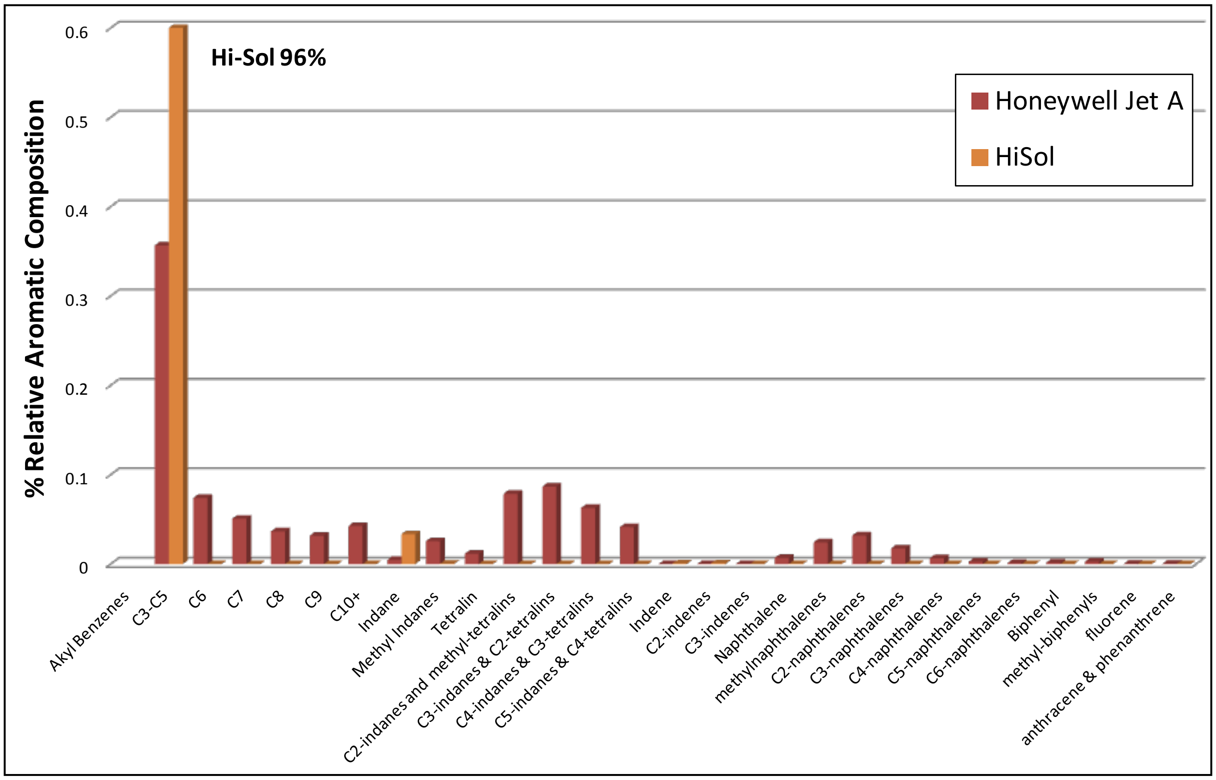


Figure 9. Comparison of Aromatic in Jet Fuel and Hi-Sol.

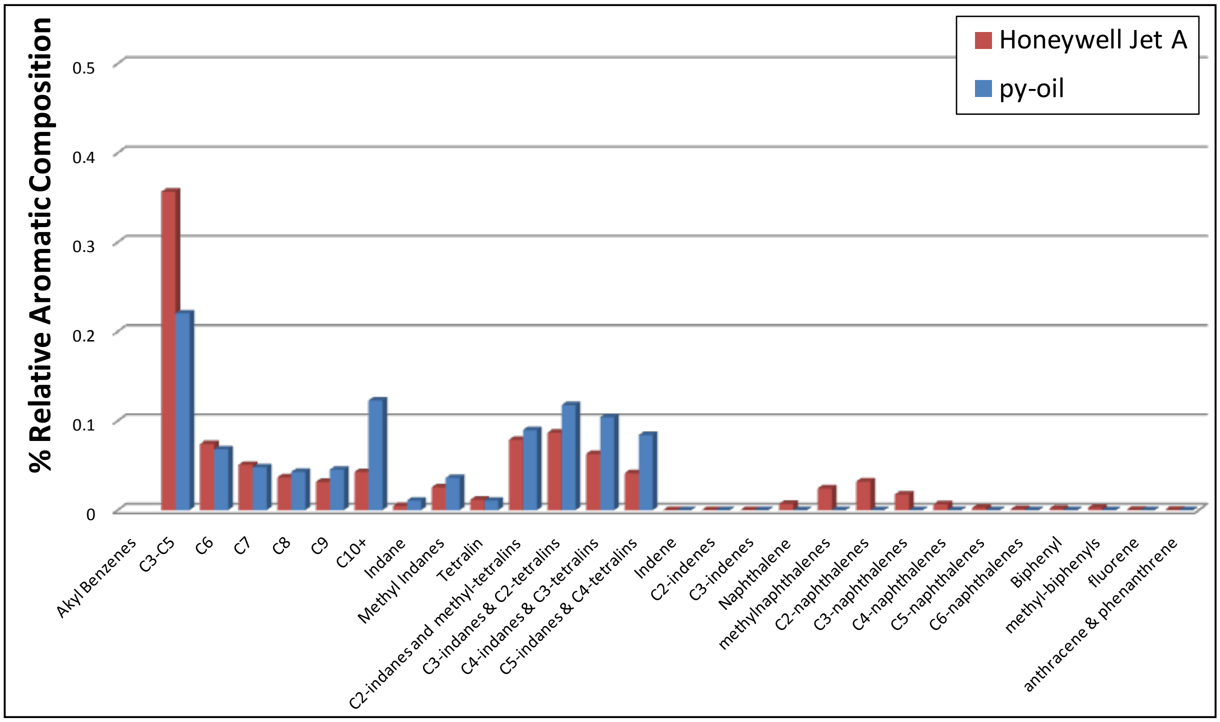


Figure 10. Comparison of Aromatic in Jet Fuel and Py-Oil.

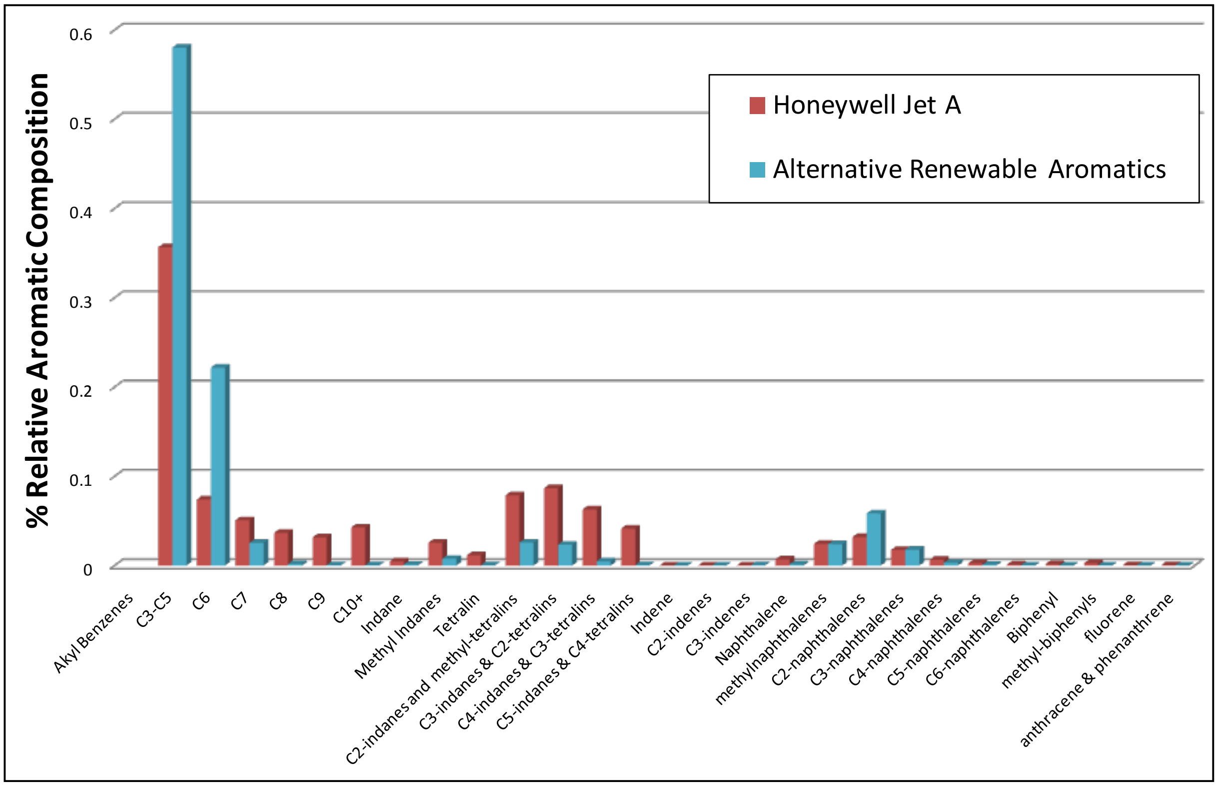


Figure 11. Comparison of Aromatic Jet Fuel and Alternative Renewable.

For early test evaluation Honeywell used petroleum-based aromatics (PBAs) blended with HRJ-SPK. Specification properties (FRL 4.2) for the fuels used for testing are shown in Table 1, and include the fuel aromatic content.

HEFA-SPK (tallow feedstock) was blended with petroleum-derived aromatic. The aromatic blend is based on Air Force Research Laboratory (AFRL) Jet Reference 3 formula, 2:1 blend of Aromatic 150 and Aromatic 100. The mix primarily contained C9 and C10 aromatics. C9 benzenes (trimethyl, ethyl-methyl, propyl, etc.). C10 benzenes (tetramethyl, dimethyl-ethyl, butyl, etc., and some naphthalene). Aromatic blend was then mixed with Neat SPK at 4, 6, 8, and 10 percent concentrations, and also evaluated at 0 percent and 100 percent aromatic content. Under this study, only aromatic quantity was varied, not type of aromatics. Test fuel properties are summarized in Table 2. Aromatic blends evaluated were within and below the Jet-Spec range.

A blending procedure was developed to replicate the AFRL fully renewable fuel blend. The blended fuel was sent to Southwest Research Institute (SwRI) for lubricity and seal volume swell evaluations. The test plan defined the aromatic concentrations to be tested for evaluating the impact of aromatic content on fuel lubricity and elastomeric seal volume swell. The test plan identified the Scuffing Load Ball-on-Cylinder Lubricity Evaluator as the test for identifying the aromatic effect on fuel lubricity. A Caterpillar seal compatibility procedure was used to evaluate the impact of fuel aromatic content on elastomeric seal volume swell.

Table 1. Specification Analysis Fuel Properties.

		Jet A Spec (D1655)	Neat SPK	Aromatic Blend (150:100 = 2:1)	Honeywell Jet A
LHV	MJ/kg	≥ 42.8	43.9	41.0	43.0
Density	kg/L	0.775-0.840	0.7559	0.8893	0.8132
Viscosity @ 25°C	cSt		1.64	1.12	1.73
Viscosity @ -20°C	cSt	≤ 8.0	4.53	2.42	4.80
Aromatics	%	8.0-25.0	0	100	19
Freeze Point	°C	≤ -40	-57	-38.5	-45.5
Flash Point	°C	≥ 38	39.4	54.26	41.67
Water Content	ppm		20.75	71.81	33.6

Table 2. Test Fuel Properties.

	Specific Gravity	Viscosity @ 25°C	Aromatics	Sulfur	Mercaptan Sulfur
Units		mm^2/s	Vol %	ppmw	mass %
Jet A Spec (D7566)	0.775 to 0.840		8 to 25	< 3,000	< 0.003
100% SPK	0.756	1.64	0.2	0.5	< 0.0003
4% Aromatics	0.762	1.60	3.9	0.3	< 0.0003
6% Aromatics	0.764	1.58	5.9	0.4	< 0.0003
8% Aromatics	0.767	1.56	8.4	0.2	< 0.0003
10% Aromatics	0.769	1.54	10.0	0.2	< 0.0003
100% Aromatics	0.890	1.10	100*	0.0	< 0.0003
Jet A	0.814	1.68	19.5	971	0.0015

* Test method (D1319) did not run properly but no saturates were detected

Evaluation of Aromatic Content on Lubricity and Elastomer Seal Swell

Fit-for-purpose testing was conducted using the PBAs blended with HRJ-SPK to evaluate the impact on lubricity and seal swell for; Nitrille (Buna-N, NBR), Fluorosilicone (FVMQ), and Fluorocarbon (Viton, FKM) seal elastomer materials.

The impact of aromatic content on lubricity was tested by two methods; D5001 Ball on Cylinder Lubricity Evaluator (BOCLE), and D6078 Scuffing Load BOCLE (SLBOCLE). Test results are shown in Figure 12. Results indicate that aromatic content does influence lubricity, but there may be other important factors as well such as sulfur content and viscosity.

Elastomer material compatibility was also assessed to evaluate the impact of aromatic content on seal swell (% volume change). Test results for these elastomer materials are shown in Figure 13, and indicate that aromatic content does influence seal volume swell with significant impact seen to nitrile o-rings. This Honeywell data is compared with Boeing data (Figure 14, open symbols) from FAA-CLEEN report OTA DTFAWA-10-C-0030, and correlates well. Boeing evaluated reference Jet fuels, 100 percent SPKs, and 50/50 blends.

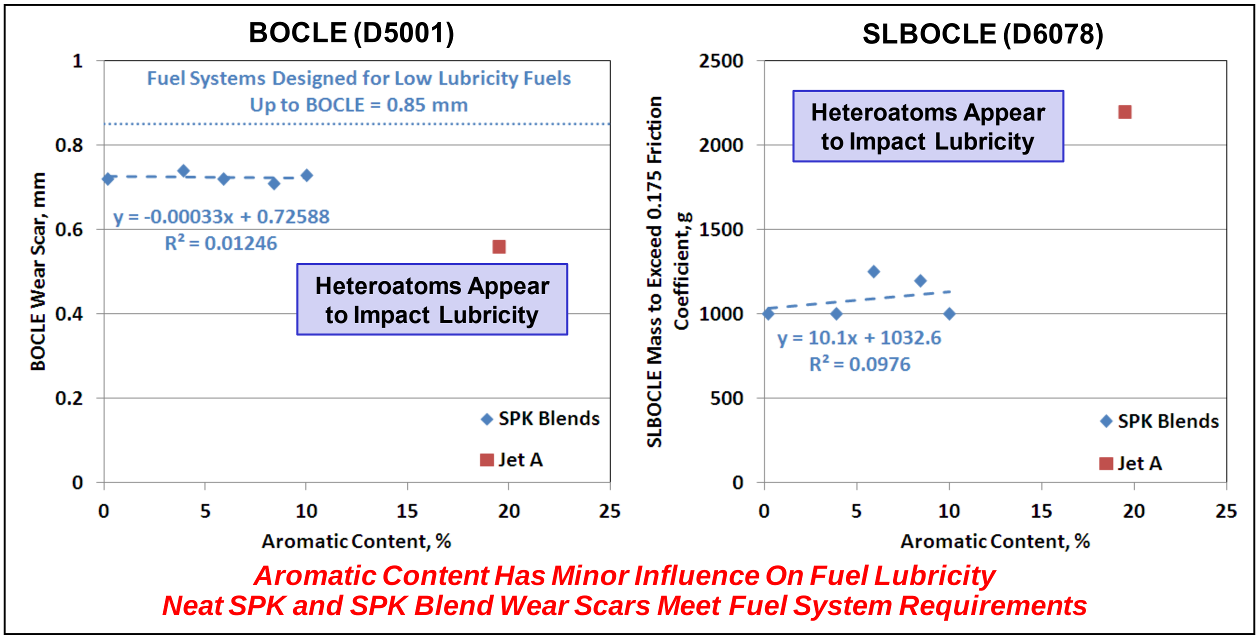
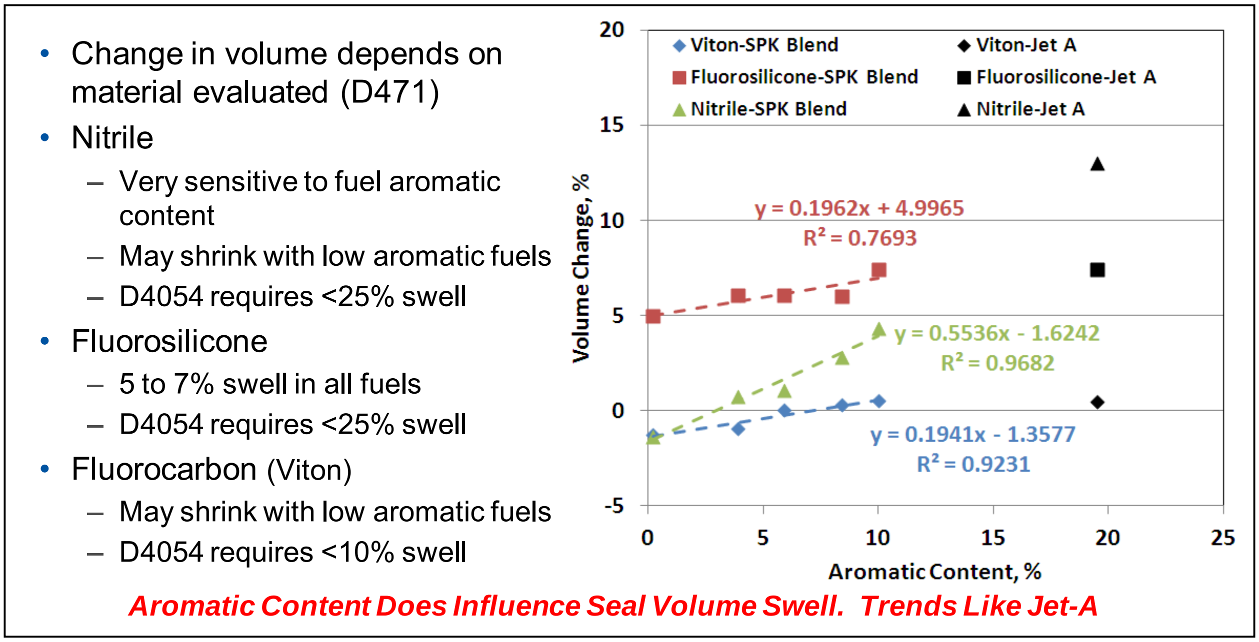


Figure 12. Fluid Lubricity Test Results (D5001 and D6078).

Percent volume seal swell results are compared for these three types of elastomer seal materials over a range of 0 percent to 25 percent aromatic content. Comparison of Honeywell and Boeing data shows good correlation (Figures 14 through 16).

Results indicate that Nitrile seals are significantly impacted by aromatic content, and that the volume doubles with pure aromatic fluid (Figure 14). Fluorosilicone seals were largely unaffected by aromatic content, with approximately 6 percent swell in Jet fuel (Figure 15). Fluorocarbon (Viton) seals were also nearly unaffected by jet fuels, with slight shrinkage in low aromatic fuels (Figure 16). In Figure 12, Heteroatoms are any atoms not carbon or hydrogen, and higher SLBOCLE numbers indicate more lubricating quality.

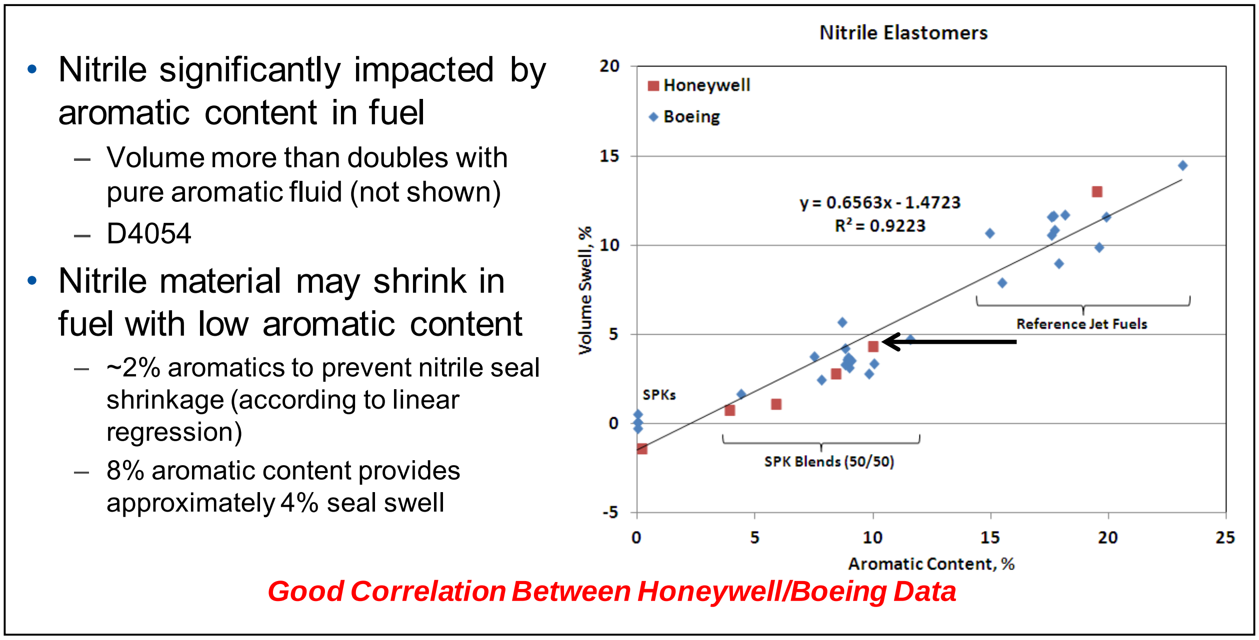
Testing was also performed to check the impact of aromatic content on tensile strength, hardness and seal swell. Past evaluations have shown significant impact on volume swell in nitrile seals. It was found that aromatic content has only a minor influence on o-ring durometer. Both Neat SPK and SPK-Aromatic blends meet o-ring hardness requirements (Figure 17). Also, aromatic content (less than 25 percent) had only a minor impact on tensile strength. Both Neat SPK and SPK-Aromatic blends meet o-ring tensile strength requirements (Figure 18). Tests also showed that aromatic content does influence seal volume swell, and available data trends similar to that of Jet-A fuel (Figure 13).



- Change in volume depends on material evaluated (D471)
- Nitrile
  - Very sensitive to fuel aromatic content
  - May shrink with low aromatic fuels
  - D4054 requires <25% swell
- Fluorosilicone
  - 5 to 7% swell in all fuels
  - D4054 requires <25% swell
- Fluorocarbon (Viton)
  - May shrink with low aromatic fuels
  - D4054 requires <10% swell

Aromatic Content Does Influence Seal Volume Swell. Trends Like Jet-A

Figure 13. Seal Swell Results for SPK Blend and Jet-A Fuels.

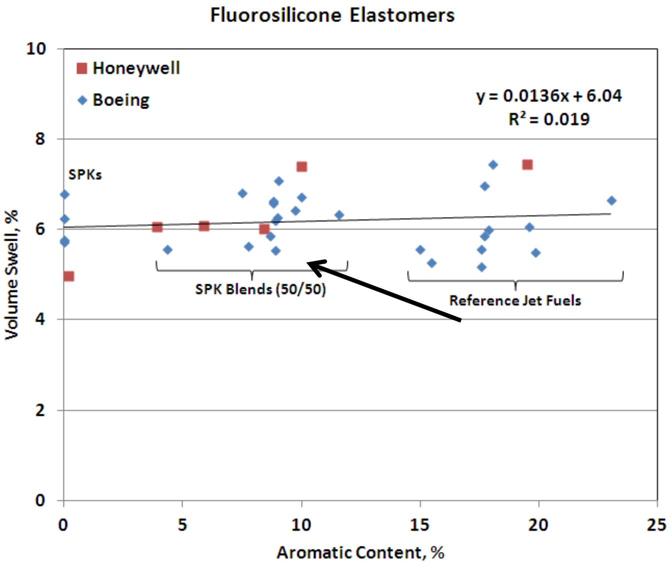


- Nitrile significantly impacted by aromatic content in fuel
  - Volume more than doubles with pure aromatic fluid (not shown)
  - D4054
- Nitrile material may shrink in fuel with low aromatic content
  - ~2% aromatics to prevent nitrile seal shrinkage (according to linear regression)
  - 8% aromatic content provides approximately 4% seal swell

Good Correlation Between Honeywell/Boeing Data

Figure 14. Aromatic Impact on Nitrile Elastomer Seals.

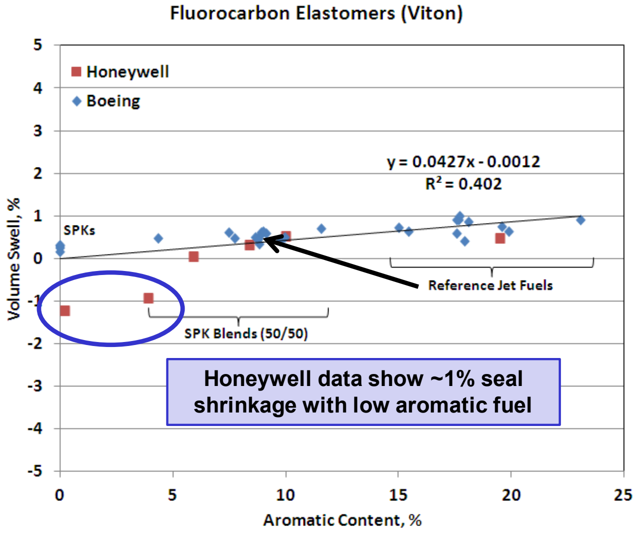
- Data shows minimal impact by fuel aromatic content
  - Both data sets display similar data scattering
- 5-7% swell in all fuels regardless of aromatic content
  - Small correlation to aromatic content
  - Approximately 6% swell in fluids with less than 25% aromatics



Good Correlation Between Honeywell / Boeing Data

Figure 15. Aromatic Impact on Fluorosilicone Elastomer Seals.

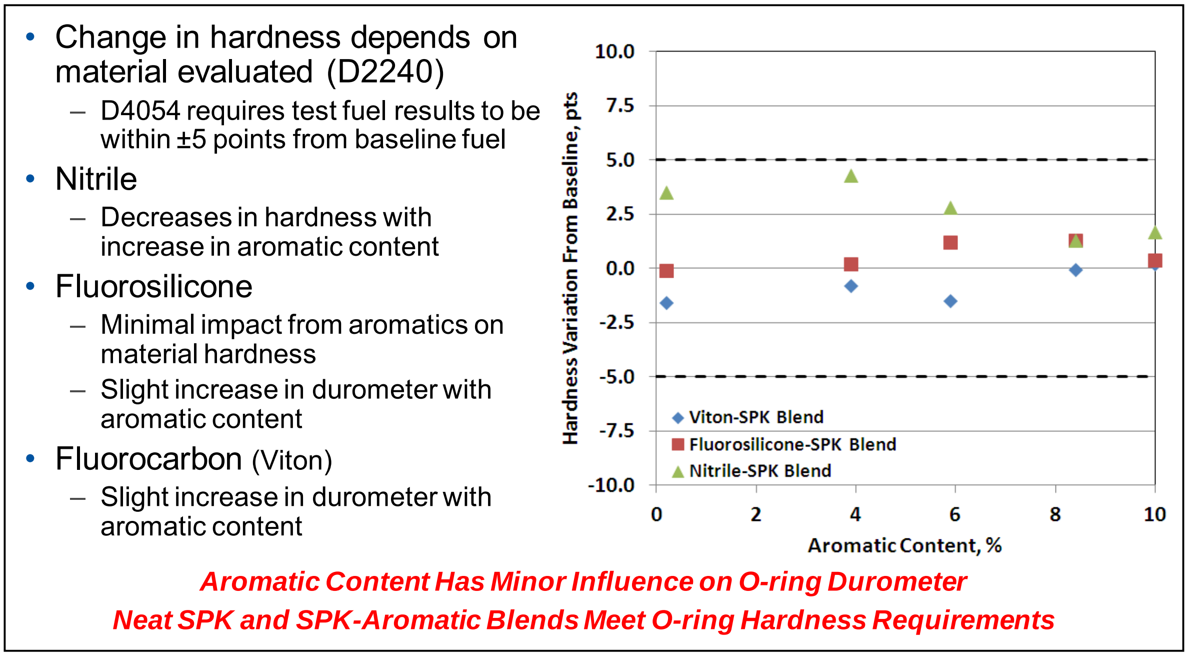
- Data indicates slight impact of aromatic content to seal swell
  - 0-1% swell
  - Less than 1% swell in fluids with less than 25% aromatics
- Fluorocarbon material may shrink slightly in low aromatic fuels
  - Linear regression of complete data set indicate no seal shrinkage



Honeywell data show ~1% seal shrinkage with low aromatic fuel

Good Correlation Above 5% Between Honeywell / Boeing Data

Figure 16. Aromatic Impact on Fluorocarbon (Viton) Elastomer Seals.

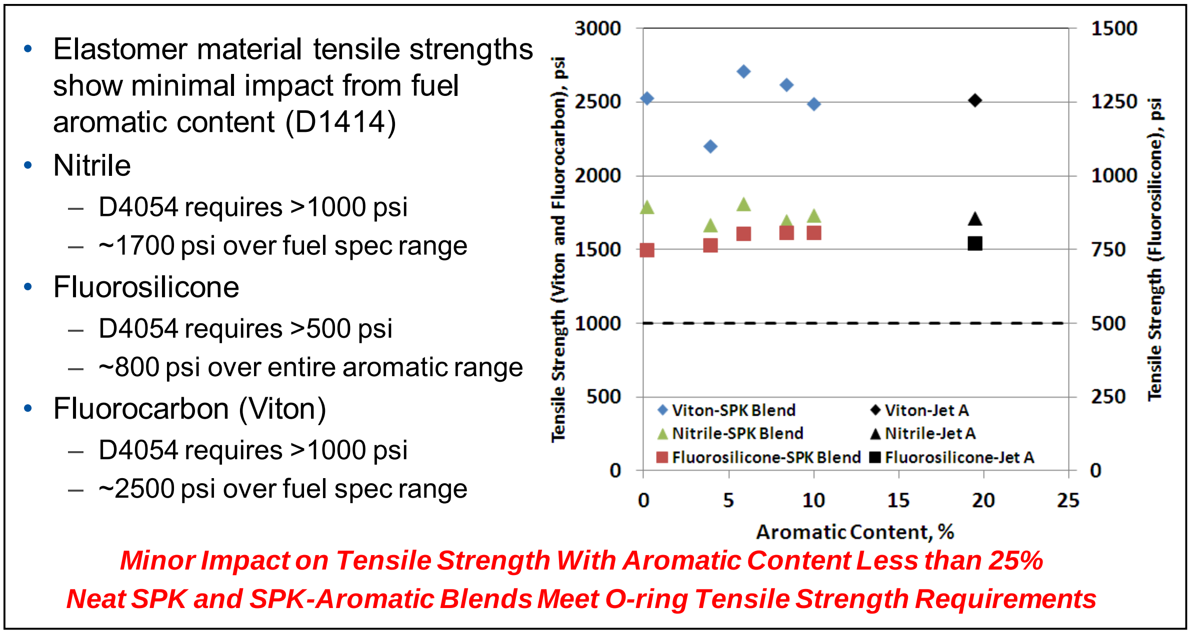


- Change in hardness depends on material evaluated (D2240)
  - D4054 requires test fuel results to be within ±5 points from baseline fuel
- Nitrile
  - Decreases in hardness with increase in aromatic content
- Fluorosilicone
  - Minimal impact from aromatics on material hardness
  - Slight increase in durometer with aromatic content
- Fluorocarbon (Viton)
  - Slight increase in durometer with aromatic content

Aromatic Content Has Minor Influence on O-ring Durometer

Neat SPK and SPK-Aromatic Blends Meet O-ring Hardness Requirements

Figure 17. Impact of Aromatic Content on Change in Material Hardness.



- Elastomer material tensile strengths show minimal impact from fuel aromatic content (D1414)
- Nitrile
  - D4054 requires >1000 psi
  - ~1700 psi over fuel spec range
- Fluorosilicone
  - D4054 requires >500 psi
  - ~800 psi over entire aromatic range
- Fluorocarbon (Viton)
  - D4054 requires >1000 psi
  - ~2500 psi over fuel spec range

Minor Impact on Tensile Strength With Aromatic Content Less than 25%

Neat SPK and SPK-Aromatic Blends Meet O-ring Tensile Strength Requirements

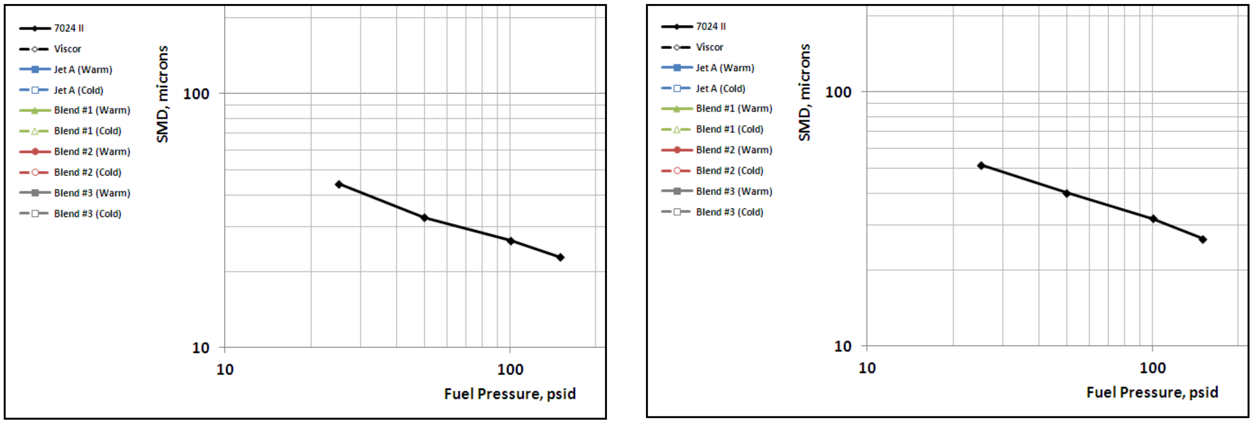
Figure 18. Impact of Aromatic Content on Tensile Strength.

Alternative Fuel Rig Testing

Cold Fuel Testing

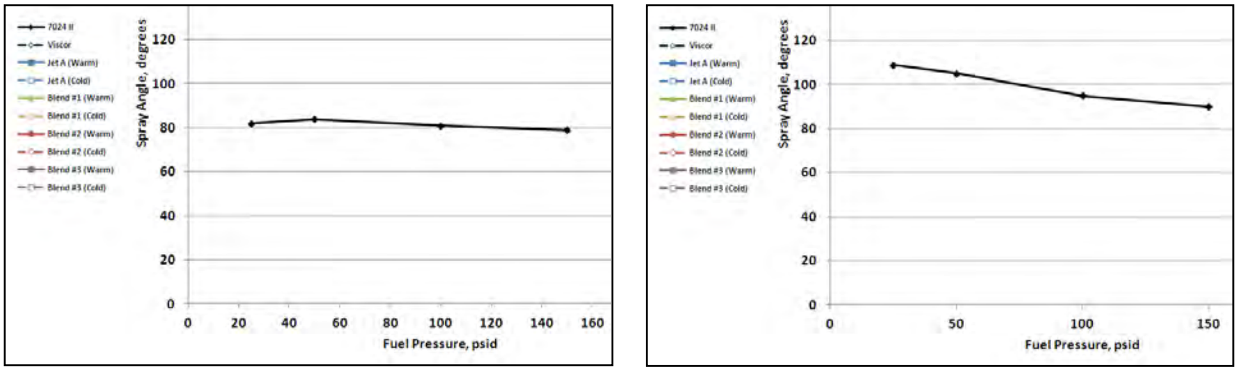
Cold fuel testing was initiated to evaluate Biofuel blended equally with Jet A. This effort was added to the CLEEN program as a vehicle to quickly collect cold fuel data to support approving and including HRJ-SPK fuels in the ASTM D7566 fuel specification. The scope of this effort includes cold atomization testing of a baseline Jet A fuel, a neat HRJ-SPK fuel, and a re-distilled HRJ-SPK fuel blended in equal parts (50/50) with Jet A. Testing will be conducted in a Honeywell combustor pipe rig with -40°F air temperature and -5°F fuel temperature.

Initial atomizer spray testing was conducted using a calibration fluid, MIL-PRF-7024E-II. The calibration fluid was tested with a low flow number atomizer (FN = 0.6) and a high flow number atomizer (FN = 2.0). Fuel flow, spray droplet size (SMD), spray angle, and spray quality were recorded with SMD and spray angle shown for the two atomizers in Figure 19.



(a) – SMD for 0.6 FN Atomizer

(b) – SMD for 2.0 FN Atomizer

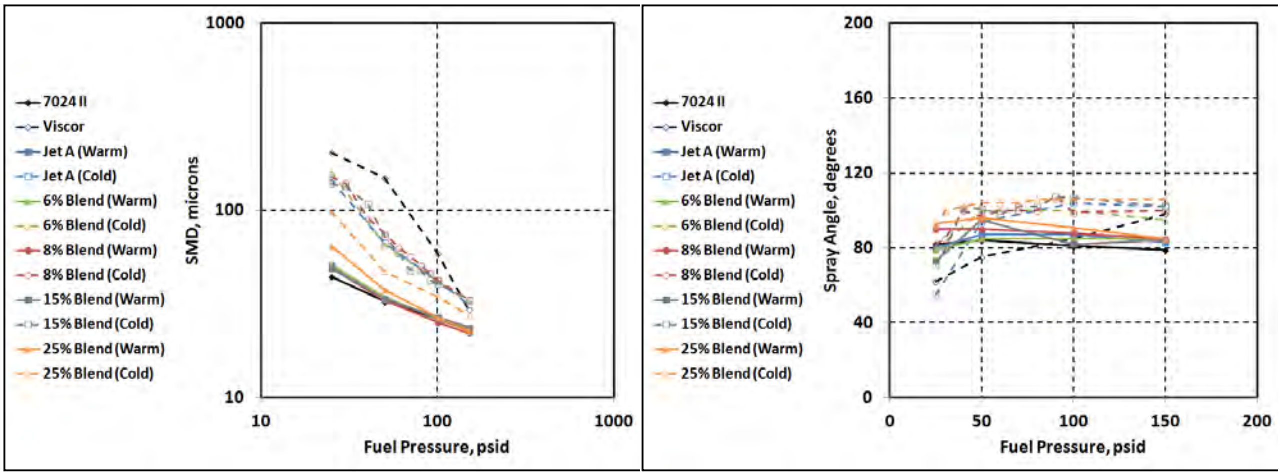


(c) – Spray Angle for 0.6 FN Atomizer

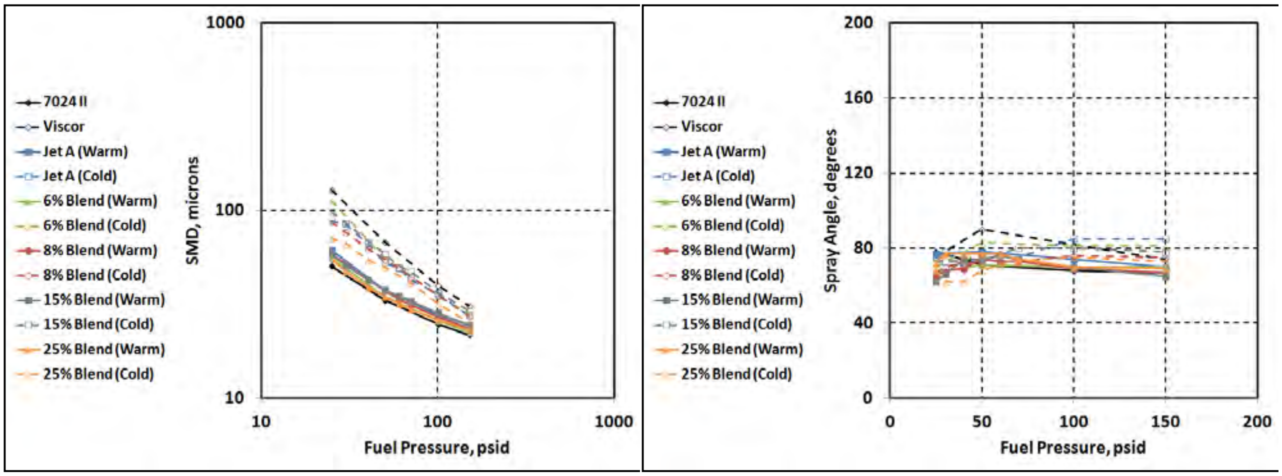
(d) – Spray Angle for 2.0 FN Atomizer

Figure 19. Atomizer Spray Data (a, b) Droplet Sizes With MIL-PRF-7024-II Calibration Fluid (c, d) Spray Angle With Calibration Fluid.

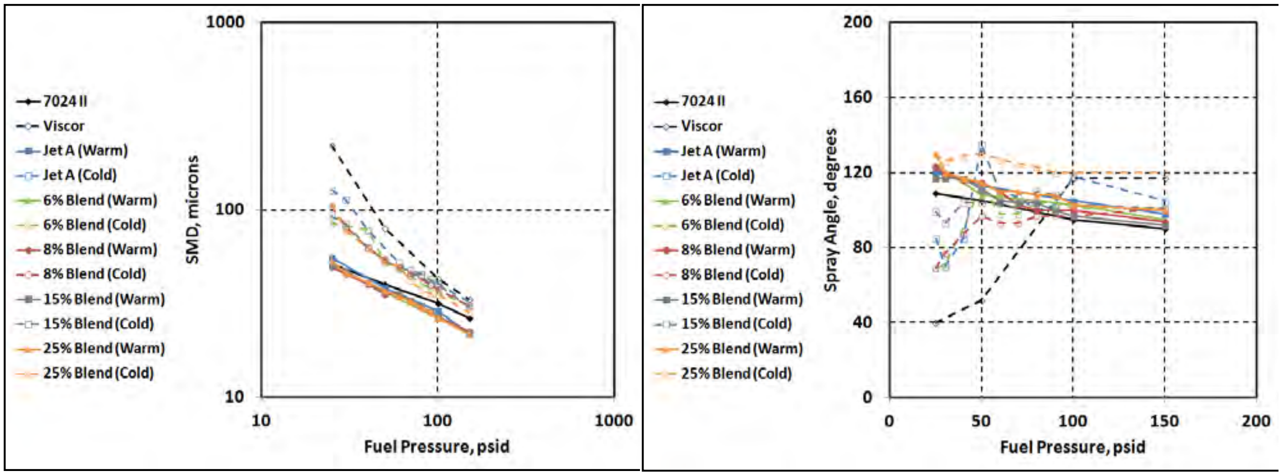
Cold fuel testing was conducted in the Honeywell Phoenix large altitude test chamber using a atomizer pipe rig to evaluate a re-distilled HRJ/Jet A fuel blend that exhibited plugging at cold temperatures prior to distillation. The results of the tests were positive and the re-distilled fuel did not exhibit plugging at cold temperatures. Atomization spray quality was evaluated with HEFA-SPK fuel blended with various aromatic concentrations. Spray evaluations were also performed with calibration fluids, MIL-PRF-7024E-II and Viscor, as well as warm Jet A baseline fuel. The three fluids were tested with all three test assets; a low flow number atomizer (FN = 0.6), a medium flow number atomizer (FN = 1.3), and a high flow number atomizer (FN = 2.0). Fuel flow, spray droplet size (SMD), spray angle, and spray quality were recorded with SMD and spray angle. This data is included in the plots shown in Figure 20 (a,b,c,d,e,f).



(a) – SMD for 0.6 FN Atomizer (b) – Spray Angle for 0.6 FN Atomizer



(c) – SMD for 1.3 FN Atomizer (d) – Spray Angle for 1.3 FN Atomizer



(e) – SMD for 2.0 FN Atomizer (f) – Spray Angle for 2.0 FN Atomizer

Figure 20. Atomizer Spray Data (a, c, e) Droplet Sizes and (b, d, f) Spray Angles With Test Fluids.

Following completion of the tests, the fuel system was drained and solid wax material was observed in the 2-micron filter. Upon flushing the system with the subsequent 25 percent aromatic blend, additional wax material was captured and filtered out. The material was collected and sent to UOP for analysis. Analysis indicated that the contaminant material is ethylene vinyl acetate (EVA) containing some vinyl acetate (Figure 21). Results show that the contaminant was not from any fuel source or a remnant of unprocessed fuel feedstock but rather the contaminant was traced to the plastic seal material used to seal the drum bungholes. The plastic seals were sent to UOP for analysis which showed a good match with EVA with 7-13 percent vinyl acetate.

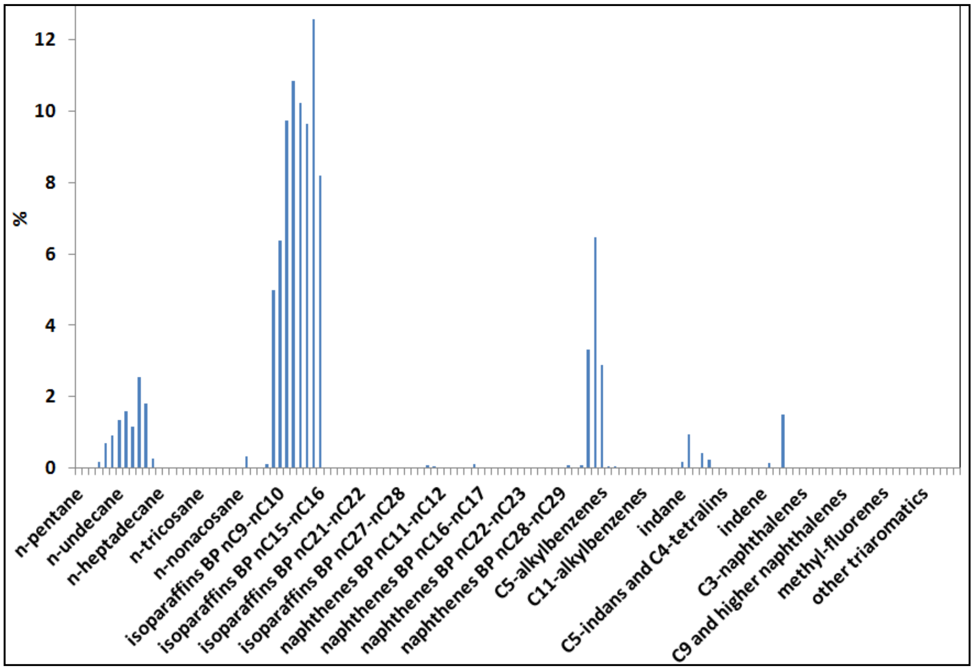


Figure 21. GC x GC Analysis of Fuel Entrapped in Wax Material.

Procurement of Renewable Aromatics

Due to technical issues it was not possible to obtain sufficient quantities of fully renewable aromatics from UOP to run engine testing. The team investigated the procurement of renewable aromatics from alternate sources, including KiOR's Hydrotreated Depolymerized Cellulosic Jet (HDCJ). The CLEEN program pursued discussions with KiOR to permit use of the KiOR HDCJ as the renewable aromatic content for the fully renewable fuel.

As a potential replacement for UOP's Upgraded Py-Oil as the aromatic material for CLEEN program testing, the team compared KiOR HDCJ to UOP Upgraded Py-Oil. KiOR submitted at least two batches (POSF 7602 and 8076) of HDCJ to USAF for evaluation. Analysis results of the two KiOR samples were very similar. Also evaluated JP-8 and Jet A, POSF 4751 and 8077, respectively (Figures 22 through 24).

Summarizing these results: Upgraded Py-Oil contains a higher percentage of single-ring aromatics than KiOR HDCJ. Most UOP aromatic content is alkylbenzenes. Most KiOR aromatic content is indanes and tetralins (two ring molecules), one aromatic ring and one cycloparaffin ring. Alternative fuel approvals of similar processes do not require fuels to be identical. Concentrations of particular components can differ as long as no new molecules are added from conventional petroleum derived baseline fuels. Both UOP Py-Oil and KiOR HDCJ appear to meet this requirement.

- UOP Upgraded Py-Oil contains ~40% single-ring aromatics
  - KiOR HDCJ ~13%
- UOP ~36% cycloparaffins
  - KiOR HDCJ ~52%
- UOP ~20% indanes and tetralins
  - KiOR HDCJ ~31%
- Upgraded Py-Oil contains significantly more single-ring aromatics than KiOR HDCJ

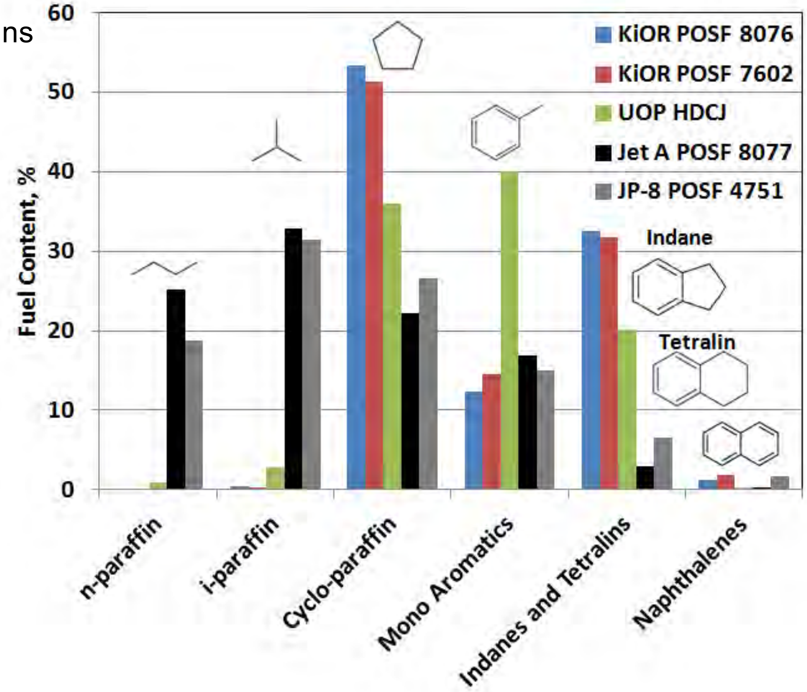


Figure 22. Comparison of KiOR HDCJ to UOP Upgraded Py-Oil.

- Cycloparaffins:
  - UOP 23% single-ring
    13% multi-ring
  - KiOR 17% single-ring
    35% multi-ring
  - Similar single-ring cycloparaffin content
  - Significantly more multi-ring in KiOR HDCJ
- Aromatics:
  - UOP - Most aromatic content is alkylbenzenes
  - KiOR - Most aromatic content is indanes and tetralins (two ring molecules)

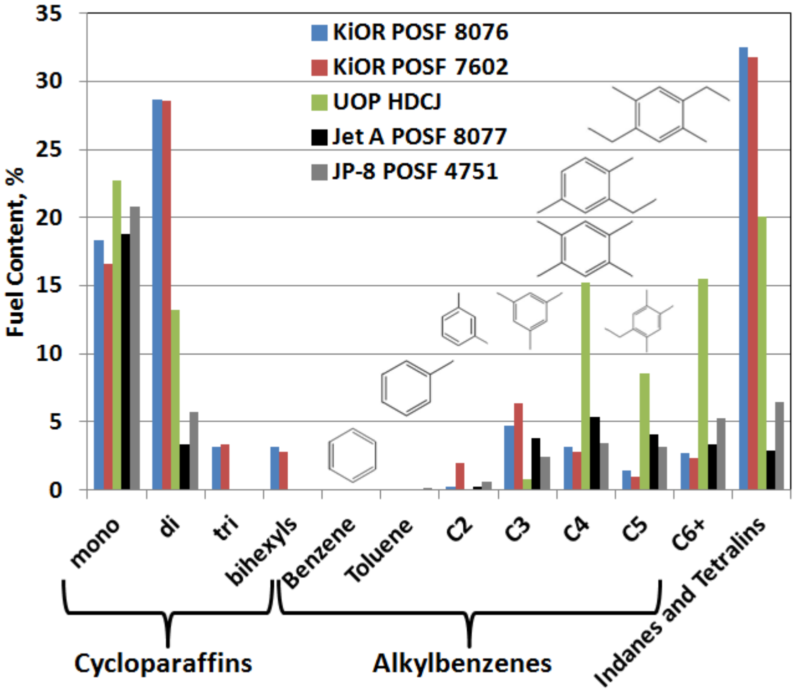


Figure 23. Main HDCJ Content Comparison.

- Alkylbenzenes:
  - UOP 41% C3-C5
    26% C6+
  - KiOR 21% C3-C5
    5% C6+
  - UOP aromatics similar to Honeywell Jet A aromatic content
- Larger Aromatics:
  - UOP 33%
    No naphthalenes
  - KiOR 69%
    4% naphthalenes
- UOP aromatics similar to Honeywell Jet A

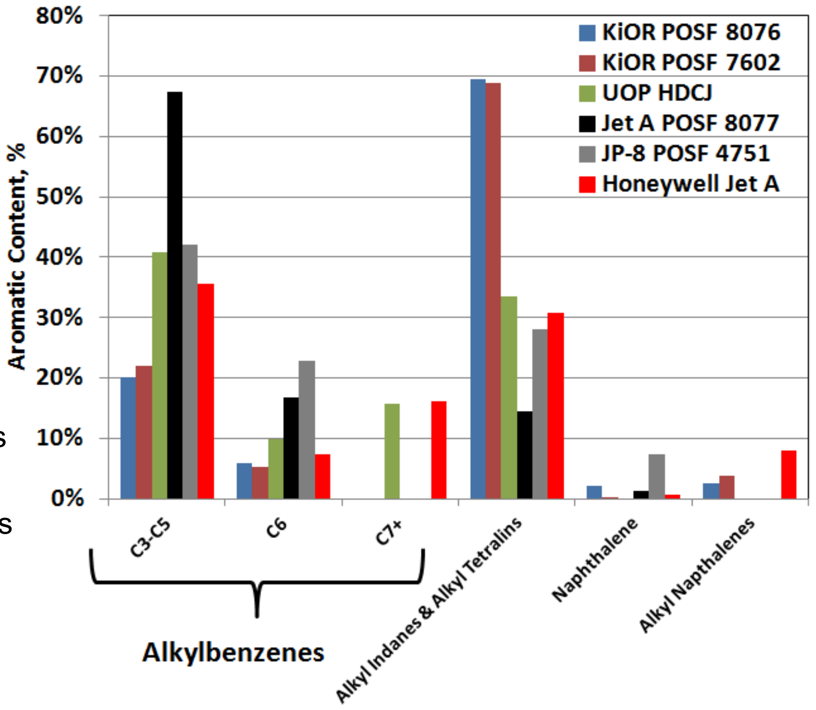


Figure 24. HDCJ Aromatic Comparison.

To support planned testing Honeywell estimated it would require 2000 to 4000 gallons of fuel. No supplier could provide these quantities of fully renewable aromatics within the time frame of the CLEEN program.

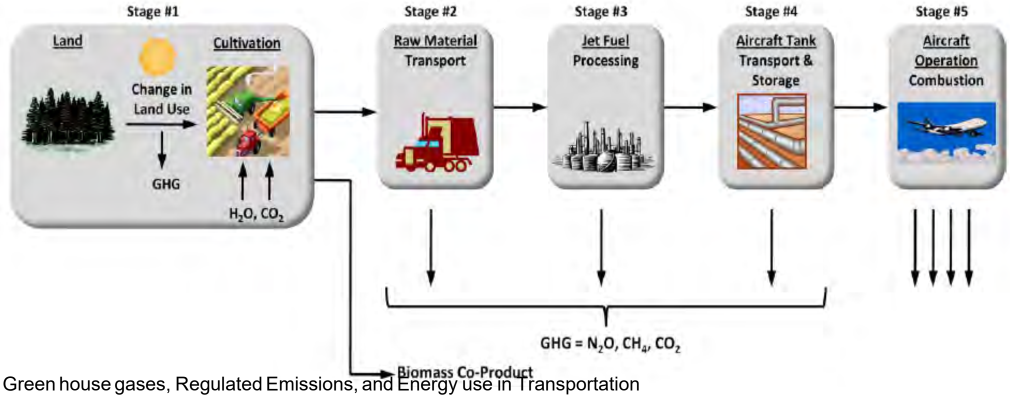
The unavailability of the bio based aromatic in the quantity required to conduct the planned rig and engine testing, and these tasks were deleted from the program. The program was rescoped to conduct testing on blended fuels. Results are included in Appendix 2.

Alternative Fuels Lifecycle Cost Analysis (LCA)

MIT and UOP combined their expertise to calculate the lifecycle cost and impact of using fully synthetic jet fuel. UOP contributed their experience in the creation of biofuel from source material, through delivery to business aviation (Figure 25). MIT conducted lifecycle analysis and examined a wide range of feedstocks, for their Green House Gas (GHG) emissions, economics, water usage, and assessment of production potential, to support Honeywell UOP assessment of options for production of this fuel. This analysis included an examination of the life cycle GHG emissions and economics of synthetic jet fuel and synthetic aromatics from pyrolysis.

This was completed in two phases. In Phase I MIT conducted detailed LCA and economic analysis (Figure 26). Fifty-one different feedstocks were investigated for paraffinic fuel production through direct feedstock hydrotreatment and aromatic fuel production based on UOP data on pyrolysis routes. Alternative processing techniques were compared for converting bio-oils, once produced by fast pyrolysis, to aromatics taking into account environmental and economic concerns. Co-product allocation for fast pyrolysis routes were also considered since these processes yield gasoline- and diesel fuel-range hydrocarbons. Three sources of H2 supply were investigated: (1) H2 from steam reforming of natural gas; (2) H2 produced as a co-product from catalytic reforming of naphtha to gasoline with the catalytic reformer operating as a stand-alone facility and not as part of an integrated refinery; and (3) H2 from steam reforming of low MW renewable co-products of HRJ and FSJ production processes. UOP assisted MIT with defining the LCA inputs and recommended parameters to MIT. Only mono-aromatics were considered to be blended with HRJ to keep the combustion emissions low. The final composition of the aromatics in FSJF (nominally around 10 percent) were defined by UOP. The life-cycle GHG assessment included a few specific scenarios for direct land use changes. Indirect land use changes (ILUC) were not investigated. MIT also assessed the current level of uncertainty associated with ILUC analysis for a few of the most studied biofuels.

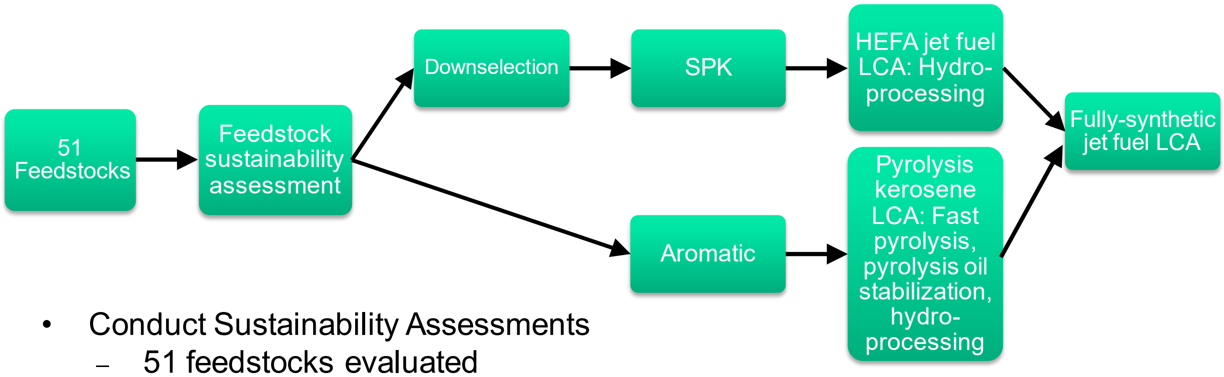
- ‘Well-to-wake’ analysis of greenhouse gas emissions over the entire life cycle from biomass cultivation through fuel combustion
- Material data inputs and outputs for HEFA-SPK were taken from open literature. Proprietary material inputs and outputs were used for the modeling of renewable aromatic production.
- GHG Modeling performed using GREET* software
- Considers all stages of the life cycle including LUC impacts



***GREET =** Green house gases, Regulated Emissions, and Energy use in Transportation

Figure from: http://www.netl.doe.gov/energy-analyses/pubs/EstGHGFtprntsAvFuels2009.pdf

Figure 25. Lifecycle GHG Emissions From Renewable Fuels.



51 Feedstocks

Feedstock sustainability assessment

Downselection

SPK

HEFA jet fuel LCA: Hydro-processing

Aromatic

Pyrolysis kerosene LCA: Fast pyrolysis, pyrolysis oil stabilization, hydro-processing

Fully-synthetic jet fuel LCA

- Conduct Sustainability Assessments
  - 51 feedstocks evaluated
  - Included environment, economic, societal perspectives, and feedstock ‘readiness’
- Down-select Feedstock
- Conduct LCAs for SPK & Aromatic

Figure 26. Phase I Lifecycle Cost Analysis (LCA) Approach.

Results from the MIT study are shown in Appendix 1.

2.3 System Engineering

2.3.1 Preliminary Design Review (PDR)

Honeywell conducted an initial preliminary design - a future gas turbine engine with the proposed technologies fully integrated (this work consisted of the conceptual engine envisioned to assess the benefits of technologies imbedded into the engine).

Honeywell conducted a preliminary design of the gas turbine engine with the proposed technologies as they will be tested and integrated into the demonstrator engine.

Thermodynamic engine performance parameters were predicted for each of the PD engine cycles including: operating temperatures, pressures, rotor speeds, flow and thrust, required turbine nozzle areas, exhaust nozzle areas, necessary bleeds, and operability margins. A preliminary design layout was created.

Honeywell utilized its conceptual design software for system preliminary design. It fully integrates traditional thermodynamic modeling with flow path generation, component efficiency prediction, disk sizing, bearing compartment sizing and weight trends in a single mathematical solution. The analysis formerly performed during the detailed design is moved forward in the design process. Results from this analysis can range from design space viability to a single optimized configuration. New component designs were evaluated throughout the engine using this software. Furthermore, value equations were utilized to drive the engine cycle to realize the maximum aircraft mission range with minimum aircraft mission fuel burn.

Honeywell's conceptual design software manages multiple design requirements like thrust at various flight conditions, mission values [specific fuel consumption (SFC), weight, length], mechanical viability (LCF, stress), noise and emission requirements. The model is subsequently made up of many engines that work together in a single mathematical solution that consists of: a flow path engine; "N" engines that reflect the design requirements (maximum shaft speeds for stress, combustion sizing conditions, etc.). Results from design process are 1) traditional performance data 2) a cross section and quality measures, and 3) data that is exported for rotor dynamics analysis, CAD and other related analysis (See Figure 27).

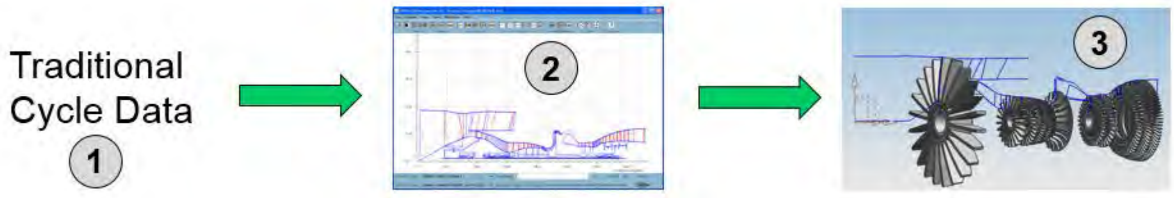


Figure 27. Honeywell's Conceptual Design Software.

Parametric studies were performed to define the design space for viable engine solutions relative to CLEEN goals. Traditional results such as thrust specific fuel consumption (TSFC) were captured along with other important design features. Engine geometries, lengths, weights and quality measures such as loadings and predicted stresses were evaluated throughout the optimization. Honeywell's conceptual design software provided a holistic and simultaneous look at basic engine performance plus mission range, fuel burn, acoustics and emissions for the CLEEN program (see Figure 28). The resulting cycle analysis (Figure 29) shows that the best

SFC and aircraft fuel burn do not necessarily occur at the same cycle conditions. Honeywell selected a balanced cycle that achieved excellent fuel burn reduction with minimal impact to emissions and noise.

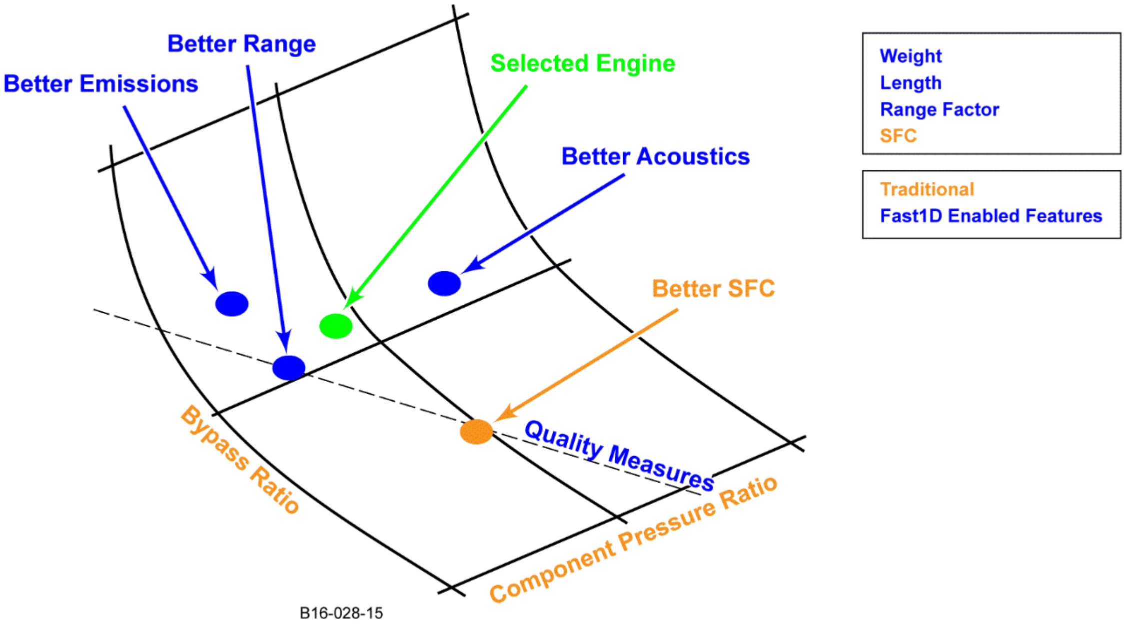


Figure 28. CLEEN Parametric Surface Plot.

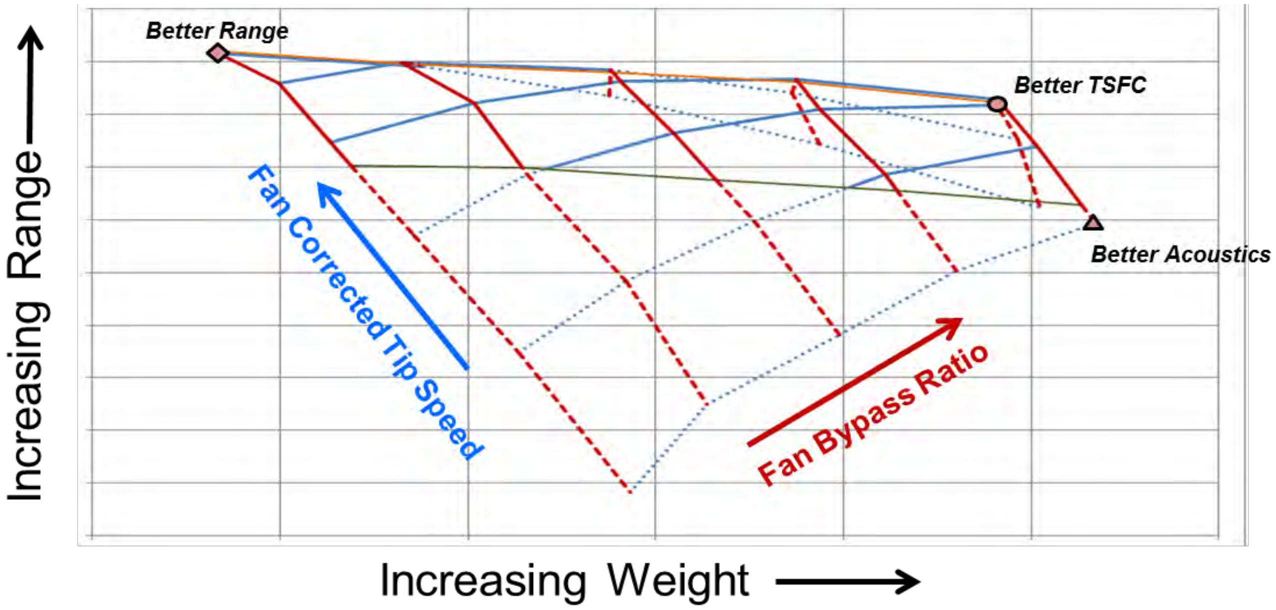


Figure 29. CLEEN Parametric Surface Plot.

2.3.2 Detail Design Review (DDR)

The Honeywell funded CLEEN effort focused on engine infused technologies centered on enabling higher T3 and T4 capabilities for reduce aircraft mission fuel burn. The core compressor increases T3 capability which enables higher cycle overall pressure ratio (OPR) leading to improved TSFC and thereby reduced aircraft mission fuel burn (Figure 30). The increase in turbine T4 is required to enable the HPT to drive the increased cycle pressure ratio. Increasing T4 also offers improved core power density, thereby reducing weight and enabling cycle efficiency to reduced aircraft mission fuel burn.

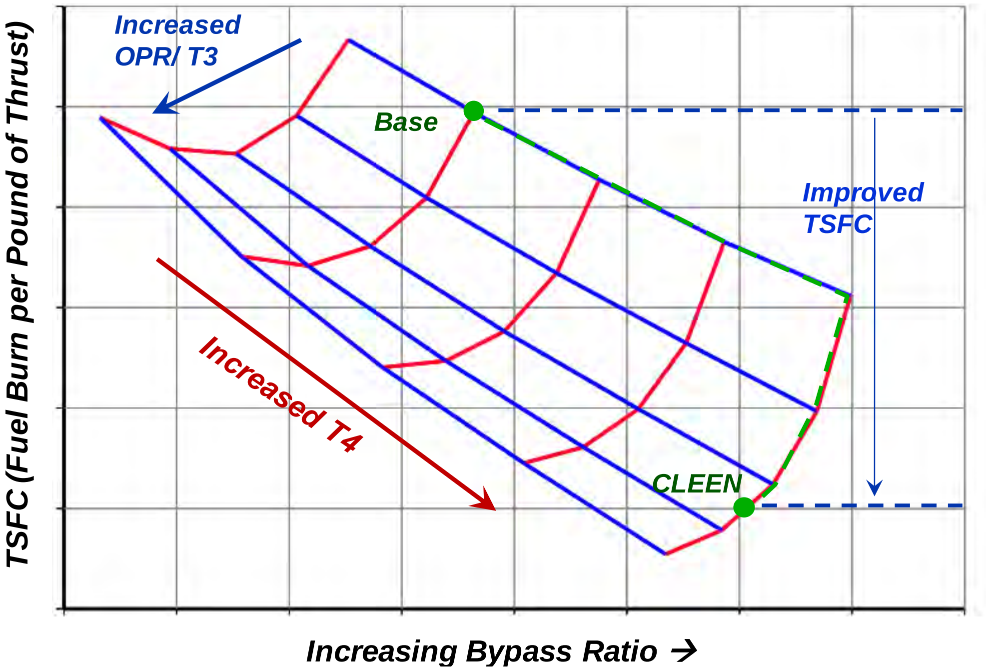


Figure 30. Fuel Burn Reduction Achieved Through Improved Cycle Capability.

Honeywell conducted a detail design of a gas turbine engine with the proposed technologies fully integrated (this work consisted of the conceptual engine envisioned to assess the benefits of technologies imbedded into the engine).

Honeywell assessed the gas turbine demonstrator core engine to identify hardware necessary for ground testing of the high T3 impeller. Associated core engine hardware necessary to conduct the ground testing was procured. Thermodynamic engine performance parameters were predicted for the core engine with the high T3 impeller.

Honeywell assessed the gas turbine demonstrator engine to identify hardware necessary for ground testing the technologies. Associated demonstrator engine hardware necessary to conduct the ground testing was procured. Thermodynamic engine performance parameters were predicted for the gas turbine demonstrator engine cycle with the imbedded technologies. A final design layout was created.

The CLEEN program was focused on aircraft fuel burn reduction. The baseline for this calculation was a Gulfstream aircraft and a Honeywell engine representing a 1996 year production technology level as proscribed in the CLEEN program. Honeywell partnered with Gulfstream to assess baseline and proposed engines for aircraft mission fuel burn.

The PDR effort resulted in 14.8 percent reduction in aircraft mission fuel burn with a further 0.9 percent improvement gain during the DDR effort.

Honeywell partnered with Gulfstream to define an optimal engine architecture and cycle for the aircraft mission fuel burn. Gulfstream assisted in quantifying aircraft system mission fuel burn reduction resulting from CLEEN and Honeywell infused technologies. Honeywell’s input to Gulfstream for aircraft mission analysis assessment consisted of: thrust and fuel flow data sets; integrated power plant system (IPPS) weight, and geometry to define nacelle wetted surface area. Honeywell and Gulfstream collaborated to develop a system level sensitivity or value equation for optimal TSFC, IPPS weight and mission fuel burn.

An engine architecture was selected that offered significant improvement in TSFC and fuel burn relative to the 1996 baseline (-10.7 percent). Technology infusion into this optimized engine architecture resulted in a further 5 percent fuel reduction. A total of 15.7 percent fuel burn reduction was realized under the CLEEN program (Figure 31).

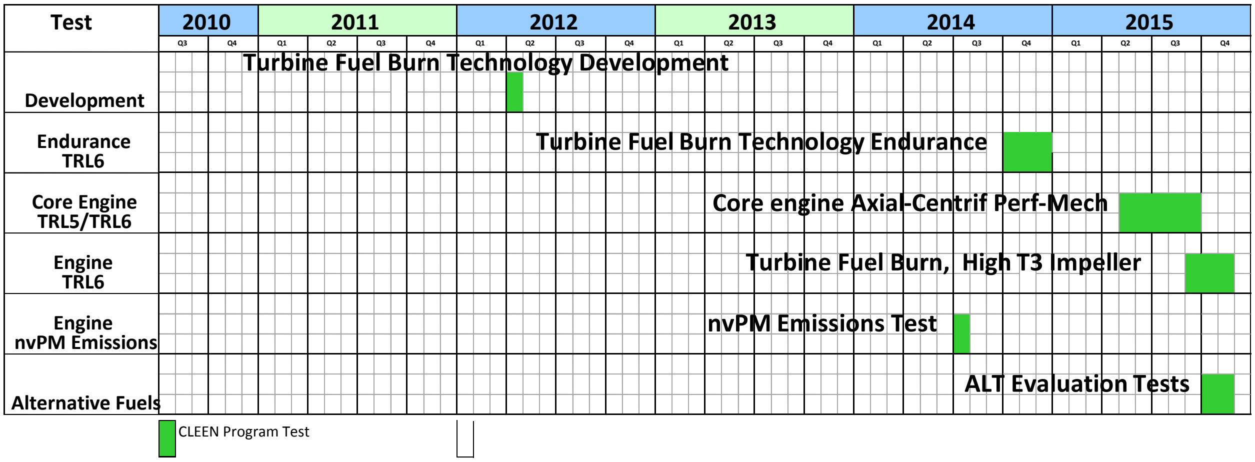


Figure 31. CLEEN Engine Fuel Burn Allocations.

2.4 Demonstration Tests

Honeywell conducted alternative fuels, non volatile particle emissions (nvPM) engine, core engine, development engine and endurance engine tests. These tests supported alternative fuels ASTM certification, nvPM emissions system validation and CLEEN Technology maturation to TRL 6.

2.4.1 TRL 5/TRL 6 Core Engine Test

The gas turbine core engine was used as a test vehicle for performance, mechanical and thermal testing of the high T3 impeller. Data from the core engine test supports both TRL 5 and TRL 6 maturation of the high T3 impeller. The core engine was assembled with a high T3 impeller and incorporated instrumentation specific for this test. During the test, the core engine completed testing with ambient air inlet as well as boosted conditioned inlet air to simulate operation with a fan spool. The core completed performance, mechanical and thermal testing to validate the high T3 impeller. No mechanical or aerodynamic deficiencies were found, and the high T3 impeller was cleared for engine testing.

2.4.2 TRL 6 Demonstrations

2.4.2.1 Development Engine Test

The Honeywell CLEEN program completed a development engine test in support of fuel burn technology maturation. This development engine test completed performance test and elevated turbine temperature endurance cycles.

An existing turbofan engine was used as the test vehicle. The turbofan engine was assembled with three CLEEN Technologies: Alloy10 discs, Gen II finger seals and TypeV HP turbine TBC shroud material. The engine incorporated instrumentation specific for this test.

During the test, the turbofan engine completed base-level engine performance before, after and periodically during the endurance cycles. The engine completed 526 starts, 286:42 operational hours and 500 endurance cycles. Test began April 3, 2012 and was completed May 8, 2012. Results of the test are discussed in the individual technology sections.

2.4.2.2 Endurance Engine Tests

Honeywell conducted two endurance turbofan engine tests with CLEEN Technologies. The endurance tests were designed as accelerated mission cyclic tests simulating in-service engine operational conditions for LCF and time duration at high power levels. Results of these tests provided data to mature technologies to TRL 6.

2.4.2.3 Endurance Engine Test (1)

The Honeywell CLEEN program completed the first of two endurance engine tests in support of turbine fuel burn technology maturation to TRL 6. This endurance engine test completed performance tests and endurance cycles.

An existing turbofan engine was used as the test vehicle. The turbofan engine was assembled with five CLEEN Technologies: Alloy10 discs, Gen II finger seals, advanced blade tip material, shaped film cooling holes and TypeV HP turbine tip shroud material. The engine also incorporated instrumentation specific for this test.

During the test, the engine completed base-level engine performance before, after and periodically during the endurance cycles. The engine completed 1039 starts, 408:12 operational hours and 1000 endurance cycles. Test began September 15, 2014 and was completed October 31, 2014. Results of the test are discussed in the individual technology sections.

Also included in this test was an nvPM test that was conducted as an added scope effort to support FAA effort to evaluate and develop a new particulate emission standard. Data from this test was provided under a separate cover.

2.4.2.4 Endurance Engine Test (2)

The Honeywell CLEEN program completed the second of two endurance engine tests in support of Compressor and Turbine fuel burn technology maturation to TRL 6. This endurance engine test completed performance tests and endurance cycles.

An existing turbofan engine was used as the test vehicle. The turbofan engine was assembled with five CLEEN Technologies: High T3 impeller, Alloy10 discs, Gen II finger seals, advanced blade tip material and TypeV HP turbine tip shroud material. The engine also incorporated instrumentation specific for this test.

During the test, the engine completed base-level engine performance before, after and periodically during the endurance cycles. The engine completed 833 starts, 299:04 operational hours and 800 endurance cycles. Test began September 11, 2015 and was completed November 6, 2015. Results of the test are discussed in the individual technology sections.

2.4.3 Alternate Fuel Demonstration

Honeywell conducted the combustor rig and auxiliary power unit (APU) tests listed below:

131-9 APU combustor rig test on two fuels (performance test only)

- -5 percent Diamond Green Diesel
- -5 percent F-76 Green Diesel

131-9 APU cold and altitude start tests on two fuels:

- -Virent 50 percent blend
- -3 percent Green Diesel blend (either Diamond or Navy F-76 Green Diesel)

Note: Honeywell used existing fuel supplies currently at Honeywell. No additional fuel was required beyond existing supplies

Alternative Fuels results provided in Appendix 2 and Appendix 3.

2.4.4 Technology Assessments

Honeywell quantified the benefits, relative to the CLEEN goals, of the demonstrated alternative fuel and fuel burn reduction technologies on fuel burn and NOx emissions. Honeywell quantified any effects of the technology on aircraft and/or engine performance. Gulfstream Aerospace corporation was subcontracted to support Honeywell with conducting aircraft level performance studies to evaluate the effects of CLEEN engine fuel burn reduction technologies.

Honeywell identified any issues that would prevent certification of the technology to existing noise, emissions, and airworthiness standards.

The following deliverables were prepared and delivered to Georgia Tech under this work element (ref section C.4.6 Deliverable Reports):

Data for Independent Government Assessment

Technology assessments provided in the PDR, DDR, periodic updates in the Monthly Progress Reports and the consortium meetings.

Appendix 1. Life Cycle Analysis (LCA) for Fully-Synthetic Jet Fuel Production Massachusetts Institute of Technology (MIT) Final Report for Phase I and Phase II (Honeywell Document 21-15318(02)

(72 pages)

Honeywell Aerospace
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Honeywell

CAGE 99193

LIFE CYCLE ANALYSIS (LCA) FOR FULLY-SYNTHETIC JET FUEL PRODUCTION

MASSACHUSETTS INSTITUTE OF TECHNOLOGY (MIT) FINAL REPORT FOR PHASE I AND PHASE II

PUBLIC RELEASE VERSION

Agreement No. DTFAWA-10-C-00040

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Approved By:
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CLEEN Technologies
Development Program

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Appendix 2. Aromatic Down-Selection Process (2 pages)

LIFE-CYCLE ANALYSIS FOR FULLY-SYNTHETIC JET FUEL PRODUCTION

1.0 INTRODUCTION

This document prepared by Honeywell Aerospace, Phoenix, Arizona for the Continuous Lower Energy Emissions and Noise (CLEEN) effort against contract DTFAWA-10-C-00040 includes the combined Phase I and Phase II results for the Massachusetts Institute of Technology (MIT) one hundred percent bio-based aromatic life cycle analysis (LCA).

2.0 BACKGROUND

As part of the CLEEN Phase I Alternative Fuels Green House Gas (GHG) LCA effort with MIT, a sustainability assessment was completed for 23 feedstocks options to be used in the production of HEFA-SPK jet fuels. A broad set of metrics were established to capture sustainability from environmental, economic and societal perspectives for both the HEFA-SPK and aromatic feedstocks. The goal of the down-selection process was to identify feedstock candidates with the greatest sustainability benefit and availability for near term fuel production. The process included the definition of metric threshold limits that removed feedstocks from the process if they included one of the following characteristics (shown in random order):

- Very low yield
- High land use change potential
- Competition with food
- Pathway ruled out by Environmental Protection Agency (EPA) for RFS2 eligibility
- Very low current production (indicates low level of ‘feedstock readiness’)
- Very high production cost
- Low level of data availability and information

Using the threshold limits (referenced above) and focusing on the HEFA-SPK component, the following options were identified as potential candidates:

- Rapeseed
- Canola
- Camelina
- Jatropha
- Castor oil plant

In Phase-I the CLEEN program down-selected Camelina for modeling based on the selection criteria and its ‘high’ potential to significantly reduce GHG emissions.

While current Camelina production is low, the amount of land used for growing camelina could be increased dramatically in the next few years. Data obtained through a research effort within

MIT's PARTNER program indicates that a very high fraction of cropland in the U.S. is generally suited for growing Camelina (160 million ha out of 165 million ha).

In a two-step down-selection process, while Camelina was chosen as one feasible feedstock for the hydro processed esters and fatty acids (HEFA) fuel component, sawmill residues were chosen as the feedstock for the aromatic kerosene fuel. This analysis was followed by a first order examination of the life-cycle GHG emissions of fully synthetic jet fuel (FSJF) obtained by blending 10 to 30 vol% pyrolysis-derived kerosene with Camelina-derived HEFA jet fuel.

The primary focus for Phase II of this study was to evaluate the variability of life-cycle GHG estimates for the FSJF by taking into account, inter alia, different co-product allocation rules and different sources for material inputs (e.g. hydrogen), and complement the GHG-centric sustainability assessment by an LCA of the water footprint of the FSJF.

The final MIT life-cycle analysis report for fully-synthetic jet fuel production, summarizing Phases I and II, is included in Appendix 1.

Appendix 2 contains information regarding the aromatic down-selection process.

Appendix 1. MIT Support for Honeywell CLEEN Technologies Development

Life Cycle Analysis for Fully-Synthetic Jet Fuel Production
(Final Report for Phase I and Phase II)

(63 pages)

Massachusetts Institute of Technology

MIT Support for Honeywell
Continuous Lower Energy, Emissions and Noise (CLEEN)
Technologies Development

Life Cycle Analysis for Fully-Synthetic Jet Fuel Production

(Final Report for Phase I and Phase II)

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Submitted on June 12, 2013
Submitted to Paul Yankowich at Honeywell

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Executive Summary

A life cycle assessment (LCA) has been carried out for fully-synthetic jet fuel (FSJF) obtained by blending 10-30 vol% pyrolysis-derived kerosene from sawmill or forest residues, or sugarcane bagasse into RFS2-compliant fuels of camelina- or tallow-derived HEFA (hydroprocessed esters and fatty acids) jet fuel. The calculations have been performed for the year 2017, primarily by relying on the GREET platform (GREET1_2011 and GREET1_2012 rev2) and complementing with SimaPro 7.3.3, where deemed instructive for additional detail or for comparison purposes.

In the analyses, two different production schemes have been considered for the HEFA fuels, one maximizing jet fuel production and the other maximizing distillate fuel production. The latter requires lower input requirements, and therefore, results in lower emissions. It can also be expected that this scheme would yield lower production costs. We, therefore, consider maximized distillate production as the optimal production scheme while treating maximized jet fuel production as the main focus of this report. In addition, for each of these production schemes, low, base and high emission cases have been defined based on different practices in the HEFA production chain. This corresponds to optimistic, nominal and pessimistic emission scenarios. The nominal scenario represents the “more likely” or “high probability” case; whereas the other two represent the “less likely” or “low probability” cases. For the pyrolysis-derived kerosene fuels, we define different emission scenarios (low, *mid*, high) based on the use of different feedstocks (sawmill residues, forest residues and sugarcane bagasse) and the resulting life cycle greenhouse gas (GHG) emissions.

The total GHG emissions from producing an FSJF based on the HEFA base emission scenarios and optimal HEFA production scheme have been found to vary between 25.6 and 36.8 gCO2e/MJ. This variation is due to the different blend ratios, and HEFA and pyrolysis kerosene feedstocks considered in this study. This “base range” corresponds to 57.9-70.7% GHG reductions compared to conventional jet fuel. When all the emission scenarios are considered along with different HEFA production schemes, the range becomes 21.8-47.8 gCO2e/MJ (i.e. 45.4-75.1% GHG reduction). Overall, we expect all the FSJFs considered in this study to qualify under the Renewable Fuels Standard (RFS2) since the base range satisfies the 50% GHG reduction criterion compared to a conventional jet fuel baseline. This reasoning, which depends on the base range, follows the EPA methodology. We also indicate that for the HEFA fuel we rely on non-confidential data sources, the use of which might result in higher GHG emissions.

Additionally, we acknowledge that improvements in the steps of the life cycle (e.g. lowered fertilizer use in cultivation steps) may further lower the GHG emissions presented in this report.

Additional studies carried out as part of this work include creation of a feedstock downselection matrix; sensitivity studies of emissions based on emission accounting methods, LCA tools and fluctuations in market prices; and analyses of different hydrogen production scenarios. Additional insight is provided on indirect emission benefits from crop residues, land use change and the final ruling of the Environmental Protection Agency (EPA) on camelina-derived HEFA fuels.

1. Introduction

Life cycle assessment (LCA) provides an analysis framework for estimating the greenhouse gas (GHG) emissions directly from a product, and from the material and energy flows, or services, through the supply chain. An LCA has been carried out for the production of a fully-synthetic jet fuel by blending a HEFA (hydroprocessed esters and fatty acids) jet fuel and a pyrolysis kerosene.

Conventional jet fuel is composed of both paraffinic (80%) and aromatic (20%) components.[15] HEFA jet fuel is a synthetic *paraffinic* kerosene (SPK), and blending of HEFA jet up to 50% with conventional jet fuel has been approved by ASTM. Aromatics, which are present in pyrolysis kerosene, help improve engine sealing. Hence, blending HEFA and pyrolysis fuels is a means to potentially use a 100% synthetic fuel in aircraft engines.

Two feedstocks have been analyzed for each of these synthetic fuels. The analysis presented in this report consisted of two phases over the course of two years. In Phase I, camelina was chosen as feedstock for HEFA jet fuel, and sawmill residues were chosen for pyrolysis kerosene. The life cycle GHG emissions for the two feedstock to fuel pathways were calculated. In Phase II, the life cycle GHG emissions of HEFA jet fuel derived from tallow and pyrolysis kerosene from sugarcane bagasse were calculated, and some of the analyses from Phase I have been updated. Methodology and results from both phases are presented in this report.

The well-to-wake analyses shown here include biomass growth (where applicable), recovery and transportation of the feedstocks and other material inputs, fuel production, transportation of the HEFA jet fuel and pyrolysis kerosene, blending, and finally combustion.

Plants sequester carbon from the atmosphere in the form of carbon dioxide (CO_2) during growth. Hence, biofuels produced from these biomass sources, such as the biomass-derived HEFA jet fuel and pyrolysis kerosene considered here, present an opportunity to balance the carbon emissions from biofuel combustion in aircraft. The CO_2 "biomass credit" is equal to the CO_2 combustion emissions, and any other biogenic CO_2 emissions during the production chain. However, the use of non-biomass resources during the production of biofuels, as well as other factors, such as land use change, mean that the *life cycle* GHG emissions from biofuels may even exceed those from conventional jet fuel. The life cycle GHG emissions in this report are reported in grams of CO_2 equivalent per megajoule of fuel (gCO2e/MJ).

This report used a life cycle GHG value of 87.5 gCO2e/MJ as a reference for conventional jet fuel.[1] This value, taken as the base case for conventional jet fuel, is an outcome of a top-down approach which utilizes the overall U.S. refining efficiency of 2005 while excluding any unconventional sources, such as Canadian oil sands. By employing a bottom-up approach that sums up all the energy requirements of individual refining processes based on the heaviness of crude oils and assumes the same average crude oil properties, the same study estimated a range to represent the carbon footprint of conventional jet fuel: 80.7-109.3 gCO2e/MJ. When we update the base case (i.e. 87.5 gCO2e/MJ) to include the unconventional sources based on the 2005 data, the carbon footprint increases to 87.9 gCO2e/MJ. Using 2012 refining data we yield a conventional jet carbon footprint of 87.3 gCO2e/MJ. If shale oil, the share of which is to increase in the U.S. refineries in the years to come, replaces light crude oil sources, then this base case carbon footprint is also likely to increase. It should be noted here that EPA's RFS2, which also derives conclusions regarding alternative jet fuels, does not provide a reference for conventional jet fuel but for conventional diesel (i.e. 91.9 gCO2e/MJ[21]).

The conversion of land for biofuel production may represent the largest potential source of emissions for biofuels. For example, if land use change emissions are avoided, a HEFA jet fuel from palm oil could have emissions of 30 gCO_2e/MJ (34% of conventional jet fuel). However, if the land used for palm cultivation had previously been a peatland rain forest, the life cycle GHG emissions could be 698

gCO_2e/MJ (800% of conventional jet fuel).[1] The feedstocks chosen for the HEFA and aromatic kerosene fuels in this analysis minimize impacts from land use change, as discussed in the respective sections.

This report has been further divided into three sections. Sections 2 and 3 summarize the details of the LCA carried out for camelina- and tallow-derived HEFA jet fuels, respectively, and the LCA for sawmill- and sugarcane bagasse-derived kerosene is discussed in Section 4. Section 5 gives the overall GHG emission values for different blending ratios based on different emission cases.

The report is supplemented by two brief annexes. Annex 1 explains the downselection process by which camelina was chosen as one feasible feedstock for HEFA jet fuel production in Phase I of the project. It also briefly discusses the properties of tallow as the HEFA feedstock chosen in Phase 2. Annex 2 provides a brief informational snapshot on the current level of uncertainty on indirect land use change emissions from renewable fuels.

2. Camelina-derived HEFA jet fuel

This section provides details about the analysis carried out for HEFA jet fuel from camelina. Section 2.1 presents the core LCA methodology and results. Section 2.2 demonstrates the sensitivity of results to emission accounting assumptions. In Section 2.3, the impact of different hydrogen sources on camelina HEFA life cycle GHG emissions are explored. During the course of this project different versions of the GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation) tool, one of the life cycle databases employed in this work, have been released. Section 2.4 compares two versions of GREET in terms of GHG emission results of the different hydrogen production scenarios that are investigated in Section 2.3. In Section 2.5, the potential life cycle GHG benefits of growing camelina in rotation with wheat, leading to reduced nutrient requirements, is investigated. Finally, Section 2.6 provides information about the final Environmental Protection Agency (EPA) ruling on the eligibility of camelina under the renewable fuels standard (RFS2), published in March 2013.

2.1. LCA for camelina-derived HEFA jet fuel

An LCA has been carried out for camelina-derived HEFA jet fuel, which includes the following process stages: 1) Recovery of feedstock from the field, 2) its transportation to an oil extraction facility, 3) oil extraction, 4) transportation of the extracted oil to a production facility, 5) its conversion into fuels through refining, 6) transportation and distribution of the fuel to the aircraft, and finally, 7) fuel combustion. The total GHG emissions associated with each of these stages have been calculated with the GREET1_2011 framework using cultivation input and processing data obtained from various references,[2-5] and from Honeywell-UOP. The simulations have been carried out for the year 2017.

The direct land use change due to camelina is considered to be negligible because camelina can be grown in rotation with wheat on land that would otherwise be fallow. This indicates that there will be no competition with other crops, and hence, no indirect land use change caused by camelina cultivation. The EPA estimates that there are 9 million acres available for growing camelina in rotation with wheat in the US, and that camelina grown outside of the US will also be produced on land that would otherwise be fallow.[5]

Table 1. Material and energy inputs that differ in the three emission cases studied (per kg seed).

	Units	Low	Base	High
Potassium chloride, as K_2O	kg	0.0033	0.0169	0.01
Thomas meal, as P_2O_5	kg	0.005	0.0253	0.015
Urea, as N	kg	0.0249	0.0169	0.037
Diesel, low-sulfur	Btu	320.4	1630.5	965.3
Hydrogen source		Catalytic reforming of petroleum-derived naphtha	Steam reforming of HEFA-derived naphtha and light ends	Natural gas steam reforming

In our analysis, we consider three emission cases (low, baseline and high) based on practical variations at the farming and fuel production stages. The key parameters used to create these emission cases include diesel fuel use and fertilizer application during farming, based on the work done by Shonnard et al.,[2] as well as different sources of hydrogen for the fuel production step. Table 1 lists the values employed in these emission cases. As indicated in Table 1, three sources of hydrogen have been considered in the analysis: a) Catalytic reforming of petroleum-derived naphtha, b) steam reforming of light ends and a portion of naphtha produced during the HEFA process along with HEFA jet fuel, c) natural gas steam reforming (also known as steam methane reforming, or SMR). A comparison of carbon intensities of producing hydrogen from these three alternative sources is available in Section 2.3. Other LCA inputs that are common for each case are given in Table 2.

Table 2. Material and energy inputs that are common for the three emission cases studied.

Processes	Inputs	Values	Units
Camelina Farming	Herbicide	0.0017	kg/kg seed
Camelina Oil Extraction	Natural gas	675	Btu/lb oil
	Electricity	46	
	Hexane	45	
Fuel Production	Natural gas[1]	7388	Btu/lb jet fuel
	Electricity	135	

[1] Includes natural gas required for hydrogen production.

Direct and indirect N_2O emissions from the nitrogen fertilizer and crop residues are based on the equations, data and assumptions presented by the EPA.[5] The amount of herbicide required for camelina cultivation is also obtained from this reference (see Table 2).

The amount of natural gas for steam production, electricity for oil extraction and refining, and hexane for oil extraction are based on Shonnard et al.[2] Mass and energy balances for fuel production from the oil are taken from Pearlson,[4] who analyzed the hydrotreatment process for two scenarios: maximum diesel fuel production and maximum jet fuel production. Input requirements and cost of maximizing distillate are lower than of maximizing jet fuel.[4] Hence, maximized distillate production is considered to be the optimal production scheme. Table 3 summarizes the assumptions for the maximum jet fuel production case. In Phase I, natural gas steam reforming was the only source of hydrogen, and a total amount of natural gas was considered in the analysis. This assumption did not take into account emissions from using part of this natural gas in an SMR unit for hydrogen production, but rather emissions from utilizing all of it in boilers. In Phase II the amount of hydrogen needed for the HEFA process is explicitly considered, and different sources of hydrogen are investigated. Only the Phase II results are reported here.

Table 3. HEFA processing assumptions from Pearlson[4] based on 100 lb of oil utilized. See text for details.

	Inputs			Outputs (lb)
	Phase I	Phase II		
Oil (lb)	100		Light ends	10.2
Hydrogen (lb)	-	4.0	Naphtha	7.0
Electricity (btu)	9400		Jet	49.4
Natural gas (lb)	15.9	4.9	Diesel	23.3

Table 4. Transportation assumptions.

	Mode	**Share[1]**	**Fuel Type**	**Mileage**
Seed Transportation	Truck	100%	Diesel	100
Oil Transportation	Rail	100%	Diesel	1243
	Truck	100%	Diesel	75
Jet Fuel Transportation	Truck	63%	Diesel	50
	Barge	8%	Residual oil	520
	Rail	29%	Diesel	800
Jet Fuel Distribution	Truck	100%	Diesel	30

[1] Weight-based share of a feedstock that relies on a certain transportation mode. The total can, therefore, exceed 100% as a certain amount of feedstock can be moved from location to location by different transportation modes until its final destination.

Table 4 presents the transportation-related assumptions used in the analysis in terms of transportation mode, share, fuel type and mileage. Camelina cultivation is assumed to take place in Montana. The camelina seeds are transported by truck from the fields to a processing facility 100 miles away in Culberston, Montana. The processed oil is transported by rail to Seattle, and by truck to a plant 75 miles away from the railway station for HEFA production. The railway freight is assumed to be 2 tonne-kilometers (tkm) per kg of seed.[2]

Table 5 summarizes the calculated life cycle GHG emissions in terms of gCO_2e/MJ for the three emission cases described above for camelina-derived HEFA jet fuel. The values in Table 5 are from a scenario that maximizes jet fuel production. Our analysis for the baseline emission case results in life cycle GHG emissions of 37.6 gCO_2e/MJ, which is 57.0% lower than conventional jet fuel.

The products of camelina are the oil and the meal, which is what is left behind after the oil has been extracted. Camelina meal is used as an animal feed, and is valued based on its protein content. Therefore, market based allocation is chosen to allocate emissions between camelina oil and meal. Results obtained from market-based allocation, however, fluctuate with changes in relative market prices. Therefore, we conducted a sensitivity analysis for changes in market prices, which is provided in Section 2.2.

The co-products of the HEFA process include diesel fuel, naphtha and light ends. The desired product, jet fuel, and all of the co-products are used for energy generation; for this reason the overall emissions have been allocated based on their energy contents. The allocation factors employed in this analysis are given in Table 6. Table 7 through Table 9 further break down the GHG emissions along with other emission types into various processes for the high, baseline and low emission cases, respectively.

Table 5. Summary of the GHG emissions and corresponding reductions from the reference case for the three emission cases studied.

	Low	**Base**	**High**
GHG emissions (gCO_2e/MJ)	30.3	37.6	48.8
Reduction from reference	65.4%	57.0%	44.2%

Note that EPA prefers system expansion method to account for emissions towards co-products except for when they generate RINs, in which case energy-based allocation is employed (see Section 2.6 for details). On the other hand, EU RED utilizes energy-based allocation; whereas the Roundtable on Sustainable Biomaterials (RSB) prefers market-based allocation to distribute emissions among products.

Table 6. Energy allocation factors applied in the analysis.

Main Product	Co-Products	Allocation Factor to Main Product
Camelina oil	Camelina meal	55.5%[1]
Jet fuel	Other fuels	55.1%[2]

[1] Market prices for soybean meal and oil are used as proxy. Based on Dec 2012 prices.[12]
[2] Based on GREET1_2011 default fuel prices.

Table 7. Life cycle GHG and other emissions by process stage based on the **high emission case** described in the text. Market-based and energy-based allocation has been applied at the oil extraction and HEFA fuel production steps, respectively. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	**1**											**2**	**3**
SCENARIO Camelina co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Camelina Farming - Diesel Production and Use**	**Camelina Farming - Nitrogen Fertilizer Production**	**Camelina Farming - Thomas Meal Production**	**Camelina Farming - Potassium Chloride Production**	**Camelina Farming - Direct NOx Emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from Nitrogen Fertilizer**	**Camelina Farming - Indirect N2O emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from crop residues**	**Camelina Farming - Indirect N2O Emissions from crop residues**	**Camelina Farming - Herbicide**	**Camelina Farming - Total**	**CO2 Credit from Camelina Growth**	**Camelina Seed Transportation**
Emissions (g/MJ)													
VOC	0.002	0.009	0.000	0.000						0.000	0.012		0.000
CO	0.008	0.009	0.001	0.000						0.001	0.018		0.000
NOx	0.017	0.005	0.003	0.001	0.021					0.002	0.049		0.001
PM10	0.002	0.001	0.001	0.000						0.001	0.005		0.000
PM2.5	0.001	0.001	0.001	0.000						0.000	0.003		0.000
SOx	0.001	0.003	0.039	0.000						0.002	0.045		0.000
CH4	0.005	0.032	0.002	0.001						0.004	0.043		0.002
N2O	0.000	0.002	0.000	0.000		0.024	0.008	0.012	0.003	0.000	0.049		0.000
CO2	3.731	3.822	0.582	0.254						1.415	9.803	-70.423	1.465
CO2 (w/ C in VOC & CO)	3.749	3.865	0.583	0.254	0.000	0.000	0.000	0.000	0.000	1.416	9.867	-70.423	1.467
GHGs (CO2e)	3.895	5.386	0.643	0.273	0.000	7.048	2.290	3.605	0.811	1.514	25.464	-70.423	1.527

	Fuel Production												
PROCESS NUMBERS →	**4**					**5**	**6**				**7**	**8**	
SCENARIO Camelina co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Camelina Oil Extraction - Natural Gas Production and Use**	**Camelina Oil Extraction - Electricity Generation and Use**	**Camelina Oil Extraction - Hexane Production and Use**	**Credit from Soy Meal Displacement**	**Camelina Oil Extraction - Total**	**Camelina Oil Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Hydrogen Production and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Combustion**	**Total**
Emissions (g/MJ)													
VOC	0.000	0.000	0.037	0.000	0.037	0.001	0.000	0.000	0.001	0.002	0.001		0.053
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.003	0.005	0.001		0.027
NOx	0.001	0.000	0.000	0.000	0.002	0.013	0.003	0.001	0.006	0.010	0.003		0.078
PM10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.000		0.010
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000		0.006
SOx	0.000	0.001	0.000	0.000	0.001	0.000	0.001	0.002	0.002	0.004	0.000		0.051
CH4	0.011	0.001	0.000	0.000	0.012	0.002	0.029	0.002	0.068	0.100	0.001		0.161
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.049
CO2	1.354	0.276	0.024	0.000	1.655	1.628	3.555	1.017	10.258	14.830	0.576	70.423	29.957
CO2 (w/ C in VOC & CO)	1.356	0.277	0.140	0.000	1.773	1.635	3.559	1.018	10.265	14.843	0.581	70.423	30.164
GHGs (CO2e)	1.644	0.295	0.145	0.000	2.083	1.703	4.316	1.084	11.983	17.382	0.604	70.423	48.765

Table 8. Life cycle GHG and other emissions by process stage based on the **baseline emission case** described in the text. Market-based and energy-based allocation has been applied at the oil extraction and HEFA fuel production steps, respectively. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	**1**											**2**	**3**
SCENARIO Camelina co-products: ***Market-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products and steam: ***Energy-based allocation***	**Camelina Farming - Diesel Production and Use**	**Camelina Farming - Nitrogen Fertilizer Production**	**Camelina Farming - Thomas Meal Production**	**Camelina Farming - Potassium Chloride Production**	**Camelina Farming - Direct NOx Emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from Nitrogen Fertilizer**	**Camelina Farming - Indirect N2O emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from crop residues**	**Camelina Farming - Indirect N2O Emissions from crop residues**	**Camelina Farming - Herbicide Production and Use**	**Camelina Farming - Total**	**CO2 Credit from Camelina Growth**	**Camelina Seed Transportation**
Emissions (g/MJ)													
VOC	0.004	0.005	0.000	0.000						0.000	0.010		0.000
CO	0.016	0.005	0.001	0.000						0.001	0.022		0.000
NOx	0.034	0.003	0.007	0.001	0.011					0.002	0.058		0.001
PM10	0.003	0.001	0.002	0.000						0.001	0.008		0.000
PM2.5	0.003	0.000	0.001	0.000						0.001	0.005		0.000
SOx	0.002	0.001	0.077	0.001						0.002	0.083		0.001
CH4	0.010	0.017	0.005	0.001						0.004	0.037		0.002
N2O	0.000	0.001	0.000	0.000		0.013	0.004	0.014	0.003	0.000	0.036		0.000
CO2	7.395	2.049	1.151	0.503						1.660	12.759	-70.423	1.720
CO2 (w/ C in VOC & CO)	7.433	2.072	1.154	0.504	0.000	0.000	0.000	0.000	0.000	1.662	12.824	-70.423	1.721
GHGs (CO2e)	7.721	2.887	1.273	0.541	0.000	3.778	1.228	4.231	0.952	1.776	24.387	-70.423	1.792

	Fuel Production												
PROCESS NUMBERS →	**4**					**5**	**6**				**7**	**8**	
SCENARIO Camelina co-products: ***Market-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products and steam: ***Energy-based allocation***	**Camelina Oil Extraction - Natural Gas Production and Use**	**Camelina Oil Extraction - Electricity Generation and Use**	**Camelina Oil Extraction - Hexane Production and Use**	**Credit from Soy Meal Displacement**	**Camelina Oil Extraction - Total**	**Camelina Oil Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Hydrogen Production and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Renewable Jet Fuel Combustion**	**Total**
Emissions (g/MJ)													
VOC	0.000	0.000	0.044	0.000	0.044	0.001	0.001	0.000	0.000	0.001	0.001		0.056
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.000	0.002	0.001		0.030
NOx	0.001	0.000	0.000	0.000	0.002	0.015	0.004	0.001	0.000	0.005	0.003		0.084
PM10	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.000	0.002	0.000		0.011
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000		0.007
SOx	0.000	0.001	0.000	0.000	0.001	0.000	0.001	0.002	0.000	0.003	0.000		0.088
CH4	0.013	0.001	0.000	0.000	0.014	0.003	0.035	0.003	0.000	0.038	0.001		0.095
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.036
CO2	1.589	0.324	0.029	0.000	1.943	1.910	4.173	1.202	0.000	5.374	0.576	70.423	24.282
CO2 (w/ C in VOC & CO)	1.591	0.325	0.164	0.000	2.080	1.918	4.177	1.202	0.000	5.380	0.581	70.423	24.504
GHGs (CO2e)	1.929	0.346	0.170	0.000	2.445	1.999	5.065	1.280	0.000	6.345	0.604	70.423	37.572

Table 9. Life cycle GHG and other emissions by process stage based on the **low emission case** described in the text. Market-based and energy-based allocation has been applied at the oil extraction and HEFA fuel production steps, respectively. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	1											2	3
SCENARIO Camelina co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Camelina Farming - Diesel Production and Use**	**Camelina Farming - Nitrogen Fertilizer Production**	**Camelina Farming - Thomas Meal Production**	**Camelina Farming - Potassium Chloride Production**	**Camelina Farming - Direct NOx Emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from Nitrogen Fertilizer**	**Camelina Farming - Indirect N2O emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from crop residues**	**Camelina Farming - Indirect N2O Emissions from crop residues**	**Camelina Farming - Herbicide**	**Camelina Farming - Total**	**CO2 Credit from Camelina Growth**	**Camelina Seed Transportation**
Emissions (g/MJ)													
VOC	0.001	0.006	0.000	0.000						0.000	0.007		0.000
CO	0.003	0.006	0.000	0.000						0.001	0.009		0.000
NOx	0.006	0.003	0.001	0.000	0.014					0.002	0.026		0.001
PM10	0.001	0.001	0.000	0.000						0.001	0.003		0.000
PM2.5	0.000	0.001	0.000	0.000						0.000	0.002		0.000
SOx	0.000	0.002	0.013	0.000						0.002	0.017		0.000
CH4	0.002	0.021	0.001	0.000						0.004	0.028		0.002
N2O	0.000	0.002	0.000	0.000		0.016	0.005	0.012	0.003	0.000	0.038		0.000
CO2	1.238	2.572	0.194	0.084						1.415	5.503	-70.423	1.465
CO2 (w/ C in VOC & CO)	1.245	2.601	0.194	0.084	0.000	0.000	0.000	0.000	0.000	1.416	5.540	-70.423	1.467
GHGs (CO2e)	1.293	3.624	0.214	0.090	0.000	4.743	1.541	3.605	0.811	1.514	17.435	-70.423	1.527

	Fuel Production												
PROCESS NUMBERS →	4					5	6				7	8	
SCENARIO Camelina co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Camelina Oil Extraction - Natural Gas Production and Use**	**Camelina Oil Extraction - Electricity Generation and Use**	**Camelina Oil Extraction - Hexane Production and Use**	**Credit from Soy Meal Displacement**	**Camelina Oil Extraction - Total**	**Camelina Oil Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Hydrogen Production and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Combustion**	**Total**
Emissions (g/MJ)													
VOC	0.000	0.000	0.037	0.000	0.037	0.001	0.000	0.000	0.003	0.003	0.001		0.050
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.001	0.003	0.001		0.017
NOx	0.001	0.000	0.000	0.000	0.002	0.013	0.003	0.001	0.004	0.008	0.003		0.053
PM10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002	0.000		0.006
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000		0.003
SOx	0.000	0.001	0.000	0.000	0.001	0.000	0.001	0.002	0.002	0.004	0.000		0.023
CH4	0.011	0.001	0.000	0.000	0.012	0.002	0.029	0.002	0.012	0.044	0.001		0.089
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.038
CO2	1.354	0.276	0.024	0.000	1.655	1.628	3.555	1.017	1.202	5.775	0.576	70.423	16.602
CO2 (w/ C in VOC & CO)	1.356	0.277	0.140	0.000	1.773	1.635	3.559	1.018	1.212	5.789	0.581	70.423	16.783
GHGs (CO2e)	1.644	0.295	0.145	0.000	2.083	1.703	4.316	1.084	1.521	6.920	0.604	70.423	30.274

2.2. Sensitivity analyses based on market prices and emission accounting methods

The analysis shown in Section 2.1 employs market-based allocation to account for emissions between camelina oil and meal. As previously indicated, camelina has no established market; for this reason, market prices for soybean oil and meal have been used as a proxy for camelina. In Phase I, default market prices from GREET1_2011 were chosen to calculate the relative allocation factors. The updated analysis presented in Section 2.1 makes use of relative prices from December 2012,[12] which is taken as the default allocation factor. Figure 1 demonstrates how the market-based allocation factor for soy oil is changing based on historical market prices of soy oil and soybean meal. Table 10 summarizes how the overall emissions change based on the allocation factors used. Based on this 5-year price data, the carbon footprint of producing camelina-derived HEFA jet fuel varies from 35.4 to 43.4 gCO2e/MJ.

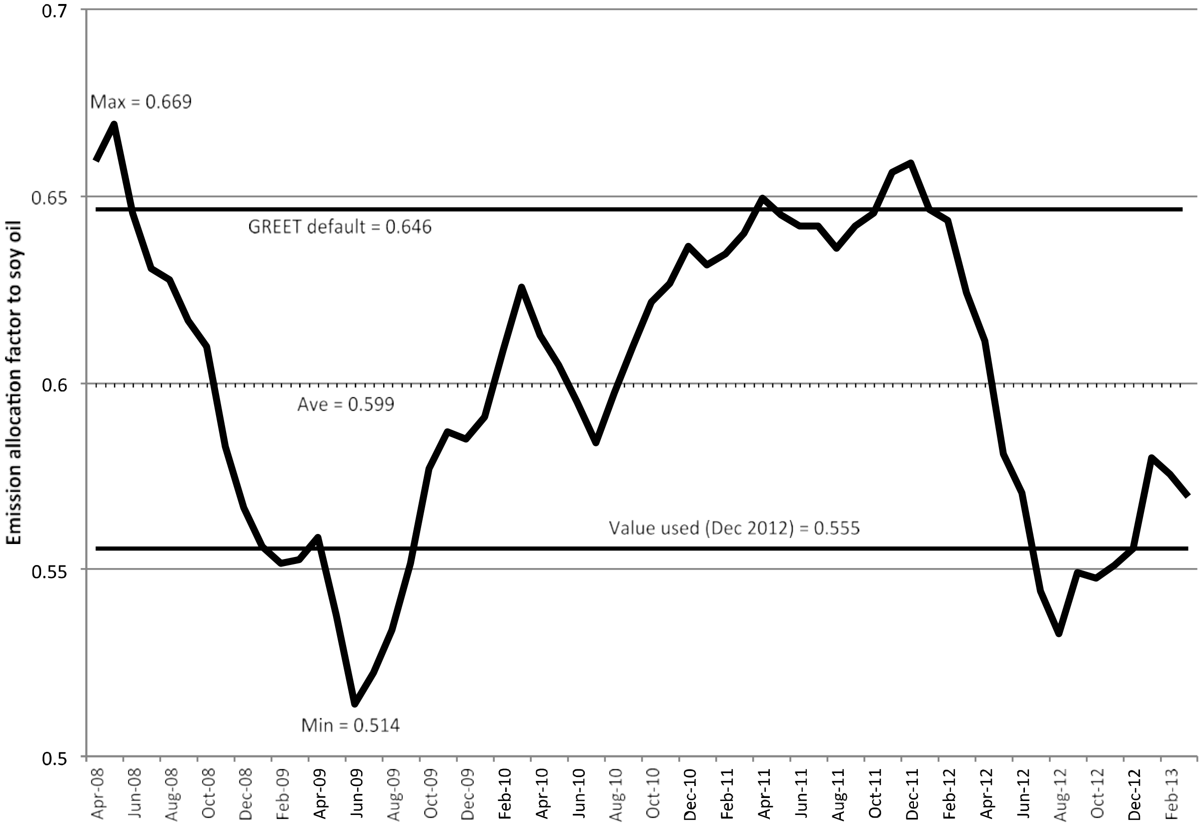


Figure 1. Change in market-based allocation factor for soy oil with fluctuation in the 5-year market prices[12] of soy oil and soybean meal. Lines – full line: factor used as default in analyses (Dec. 2012), dotted line: 5-year averaged allocation factor, dashed line: default GREET factor.

Table 10. Change in HEFA jet fuel GHG emissions based on market-based allocation factors outlined in Figure 1.

Factor	**GHG emissions (gCO2e/MJ)**
Max	43.4
GREET	42.2
Ave	39.8
Default	37.5
Min	35.4

Figure 2 through Figure 5 demonstrate the effects of different emissions accounting methods on the results of the baseline scenario for camelina-derived HEFA jet fuel, as outlined in Section 2.1. Each figure depicts a different method employed to account emissions among fuel co-products (i.e. downstream accounting). Each figure further compares different accounting methods applied for camelina oil and meal (i.e. upstream accounting) based on max distillate and max jet fuel production schemes. Table 11 and Table 12 summarize the allocation factors and displacement credits employed in these figures.

As previously reported,[1] when the desired product is not the main product, the displacement method should be avoided. As seen in Figure 2, when maximizing distillate production, the displacement credit is very high because the desired product, jet fuel, is not the main product, and conventional fuels have high carbon footprints, which are reflected as credits towards jet fuel. When upstream accounting methods are compared, it can be seen that displacing camelina meal with soy meal results in higher emissions than with the other methods. This is due to the fact that soy meal has a lower carbon footprint than camelina meal, which results in lower displacement credits towards the oil.

When the four figures are compared, the following trends can be deduced:

- GHG emissions after downstream accounting: Displacement < mass ≈ energy < market
- GHG emissions after upstream accounting: Mass < energy < market < displacement

When maximizing jet fuel production, minimum GHG emissions are calculated using mass-based allocation upstream, and the displacement method downstream (-35 $gCO2e/MJ_{jet}$). Maximum GHG emissions, on the other hand, are obtained using the displacement method upstream, and market-based allocation downstream (53 $gCO2e/MJ_{jet}$). Clearly, the choice of emission accounting method plays a very important role in the overall results.

Table 11. Allocation factors employed in Figure 2 through Figure 5, where applicable.

Allocation towards	Energy	Mass	Market
Camelina oil	44.5%	36.0%	64.7%
Jet (max distillate)	14.5%	14.5%	14.9%
Jet (max jet)	55.1%	54.9%	57.9%

Table 12. Displacement credits, in $gCO2e/MJ_{jet}$, employed towards jet fuel in Figure 2 through Figure 5, where applicable.

Production scheme	Upstream displacement credit				Downstream displacement credit
	Downstream emission accounting method				
	Displacement	Energy	Market	Mass	
Max jet	15.0	9.7	10.1	10.0	19.3
Max distillate	58.0	9.1	9.2	9.1	151.7

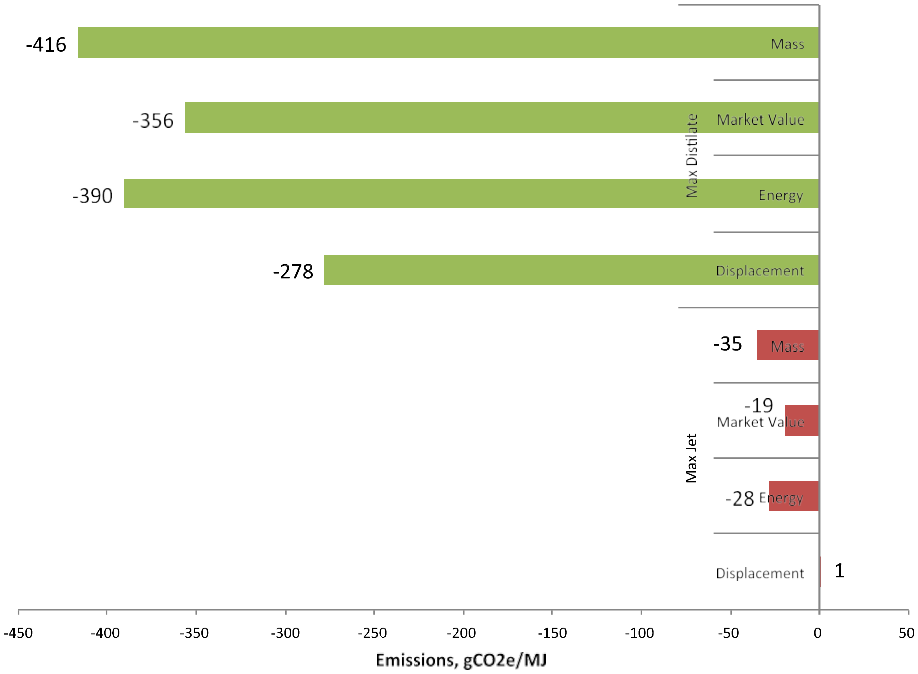


Figure 2. Effect of different methods to account for emissions between oil and meal. **Displacement method used for fuel co-products.**

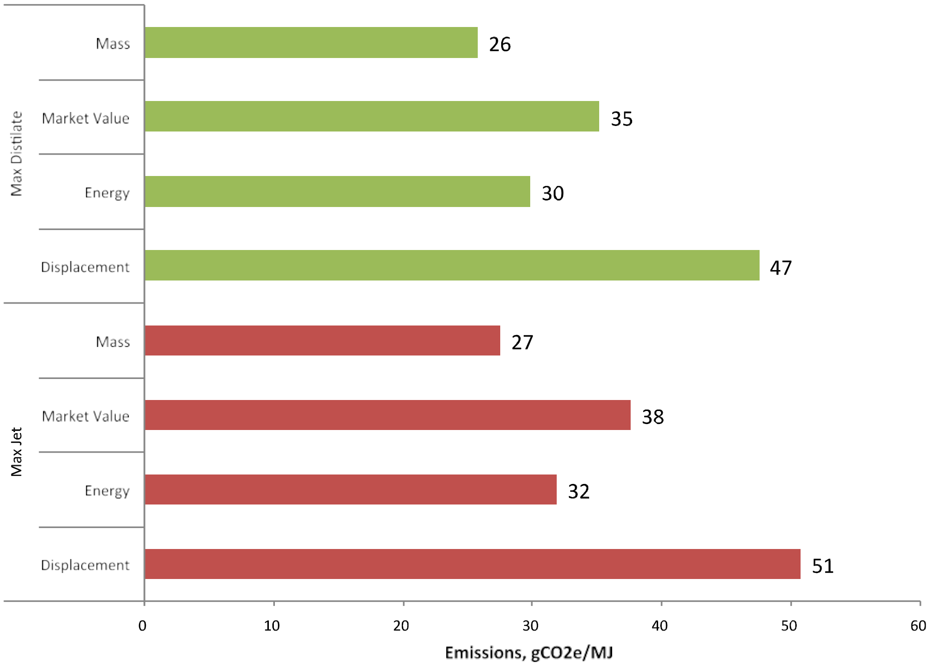


Figure 3. Effect of different methods to account for emissions between oil and meal. **Energy-based allocation used for fuel co-products.**

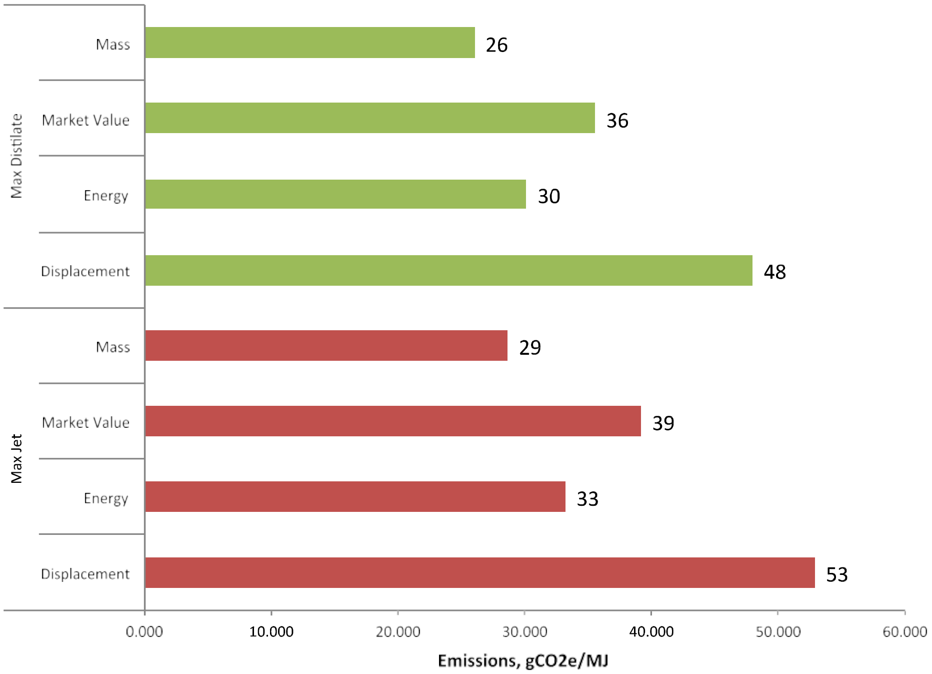


Figure 4. Effect of different methods to account for emissions between oil and meal. **Market-based allocation used for fuel co-products.**

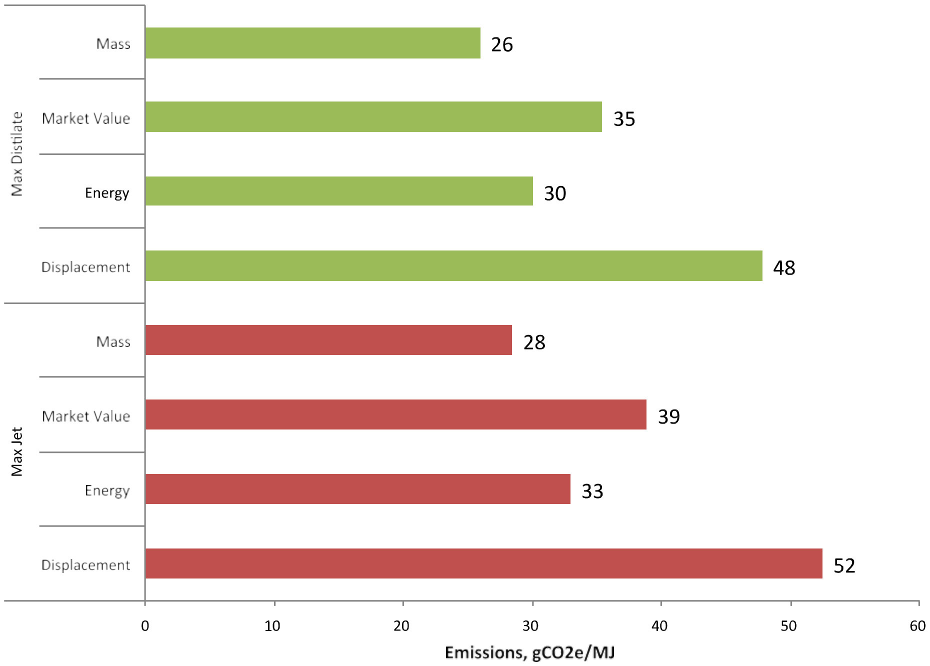


Figure 5. Effect of different methods to account for emissions between oil and meal. **Mass-based allocation used for fuel co-products.**

2.3. Comparison of different hydrogen production methods

As indicated in the previous sections, three different methods have been investigated for hydrogen production based on additional information provided by Honeywell-UOP:

- Scenario I: Natural gas steam reforming
- Scenario II: Catalytic reforming of petroleum-derived naphtha into gasoline
- Scenario III: Steam reforming of HEFA-derived naphtha and light ends

The analyses have been carried out using the GREET1_2011 platform. In order to observe the GHG impact of hydrogen production from these three sources, Scenarios I and II have initially been compared at the hydrogen production step, and then all the three scenarios have been modeled as part of the camelina-derived HEFA jet fuel analysis. Only Scenario I has been considered in the tallow-derived HEFA jet fuel analysis presented in Section 3.

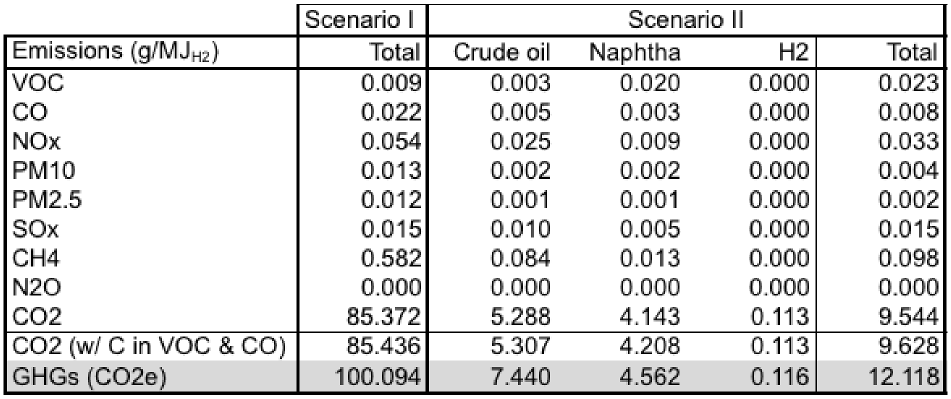
Scenario I is modeled based on default GREET1_2011 assumptions for natural gas steam reforming. Even though the providers of natural gas reforming technology have started offering carbon capture and sequestration (CCS) systems to help reduce the carbon footprint of hydrogen production, this has not been considered in this report. For Scenario II, additional information provided by Honeywell-UOP on the catalytic reformer has been considered in the analysis, along with the default petroleum-derived naphtha pathway available in GREET1_2011. Table 13 lists the assumptions employed for the catalytic reformer in Scenario II. Energy-based allocation has been used to account for emissions towards all the products of the catalytic reformer in this scenario. Table 14 presents the results of this analysis at the hydrogen production stage in terms of gCO2e/MJ$_{H2}$. Scenario II results have been broken out by process steps, which include crude oil extraction and transportation, naphtha production, and hydrogen production at the reformer. Note that GREET utilizes volume-based allocation to allocate emissions towards naphtha. As seen in Table 14, Scenario I results in a carbon footprint of 100.1 gCO2e/MJ$_{H2}$, which is an order of magnitude higher than Scenario II (12.1 gCO2e/MJ$_{H2}$). Scenario I's high GHG emissions are in accord with the literature data.[7]

Table 13. Material and energy inputs, and products of the catalytic reformer of Scenario II (UOP LLC Confidential). Also included in the table are other assumptions and the calculated allocation factor.

Feed		
Naphtha	Intentionally Omitted	lb
Utilities		
Electricity		kW
Fuel[1]		mmBTU
Products		
Hydrogen		lb
Fuel gas		
LPG		
Gasoline		
High-pressure steam[2]		
Allocation factor to hydrogen[3]		

Assumptions: [1]100% refinery fuel gas. [2]Saturated steam at 150 psig. [3]Energy-based.

Table 14. Comparison of the hydrogen production step for Scenarios I and II.



	Scenario I	Scenario II			
Emissions (g/MJ_{H2})	Total	Crude oil	Naphtha	H2	Total
VOC	0.009	0.003	0.020	0.000	0.023
CO	0.022	0.005	0.003	0.000	0.008
NOx	0.054	0.025	0.009	0.000	0.033
PM10	0.013	0.002	0.002	0.000	0.004
PM2.5	0.012	0.001	0.001	0.000	0.002
SOx	0.015	0.010	0.005	0.000	0.015
CH4	0.582	0.084	0.013	0.000	0.098
N2O	0.000	0.000	0.000	0.000	0.000
CO2	85.372	5.288	4.143	0.113	9.544
CO2 (w/ C in VOC & CO)	85.436	5.307	4.208	0.113	9.628
GHGs (CO2e)	100.094	7.440	4.562	0.116	12.118

Scenario III utilizes HEFA fuels to generate the hydrogen. Hence, this scenario has been used for the camelina-derived HEFA jet fuel analysis of Section 2. To allow for a comparison of all three scenarios, the remaining two scenarios have also been modeled using the same pathway. The underlying assumptions are chosen as the ones in the baseline emission case of Section 2 (note that Scenario III was considered as the hydrogen source in that analysis, see Table 1).

In all scenarios, emissions allocation is based on physical properties of the products by applying energy-based allocation both at the oil extraction step and the HEFA fuel production step to make the results time- and pathway-invariant. The allocation factor used at the oil extraction step for camelina oil is calculated as 44.5% for all scenarios. In both Scenarios I and II, the allocation factor at the HEFA production step towards jet fuel is calculated as 55.1% (same as in Section 2). A different allocation factor applies for Scenario III, as Scenario III utilizes its own fuels to generate the hydrogen it needs.

Further assumptions for Scenario III, in addition to the ones outlined for the baseline case in Section 2, include the following:

- All of the light ends are routed to hydrogen production.
- 83% of the naphtha is routed to hydrogen production, and the rest is included in the final product slate.
- Additional electricity required for the steam reforming: 0.006097 kWh/kg jet fuel.
- High-pressure steam at 600 psig (assumed to be saturated) co-produced during hydrogen production: 0.000831 tonne/kg jet fuel.

- Based on the final product slate, the energy-based allocation factor for jet fuel has been calculated as 64.7%.

Table 15 compares all three scenarios based on the baseline emissions case assumptions of the camelina-derived HEFA jet fuel pathway outlined in Section 2. The results indicate that Scenario I has the highest carbon footprint (39.5 gCO2e/MJ$_{jet}$), whereas Scenario II has the lowest (28.8 gCO2e/MJ$_{jet}$). Scenario III, on the other hand, results in GHG emissions of 31.9 gCO2e/MJ$_{jet}$. These results have been reflected to the definition of low, baseline and high emission cases described in Table 1. Detailed results are provided in Table 16 through Table 18.

Table 15. Comparison of Scenarios I, II and III based on camelina-derived HEFA jet fuel analysis.

Emissions (g/MJ$_{jet}$)	**Scenario I**	**Scenario II**	**Scenario III**
VOC	0.041	0.043	0.045
CO	0.031	0.029	0.025
NOx	0.085	0.083	0.072
PM10	0.011	0.010	0.009
PM2.5	0.007	0.006	0.006
SOx	0.064	0.064	0.071
CH4	0.144	0.085	0.084
N2O	0.025	0.025	0.029
CO2	28.379	19.176	21.000
CO2 (w/C in VOC & CO)	28.557	19.356	21.181
GHGs (CO2e)	**39.466**	**28.788**	**31.852**

Table 16. Life cycle GHG and other emissions by process stage based on the baseline emission case of Section 2 that utilizes **Scenario I** for hydrogen production. Co-products in the primary production pathway have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	1											2	3
SCENARIO Camelina co-products: ***Energy-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	Camelina Farming Diesel Production and Use	Camelina Farming Nitrogen Fertilizer Production	Camelina Farming Thomas Meal Production	Camelina Farming Potassium Chloride Production	Camelina Farming Direct NOx Emissions from Nitrogen Fertilizer	Camelina Farming Direct N2O Emissions from Nitrogen Fertilizer	Camelina Farming Indirect N2O emissions from Nitrogen Fertilizer	Camelina Farming Direct N2O Emissions from crop residues	Camelina Farming Indirect N2O Emissions from crop residues	Camelina Farming Herbicide Production and Use	Camelina Farming Total	CO2 Credit from Camelina Growth	Camelina Seed Transportation
Emissions (g/MJ)													
VOC	0.004	0.003	0.000	0.000						0.000	0.008		0.000
CO	0.017	0.003	0.001	0.000						0.000	0.022		0.000
NOx	0.034	0.002	0.005	0.001	0.008					0.002	0.051		0.001
PM10	0.003	0.001	0.002	0.000						0.001	0.006		0.000
PM2.5	0.003	0.000	0.001	0.000						0.000	0.005		0.000
SOx	0.001	0.001	0.052	0.001						0.002	0.057		0.000
CH4	0.007	0.012	0.003	0.001						0.003	0.026		0.002
N2O	0.000	0.001	0.000	0.000		0.009	0.003	0.010	0.002	0.000	0.024		0.000
CO2	5.010	1.404	0.795	0.351						1.145	8.705	-70.423	1.168
CO2 (w/ C in VOC & CO)	5.048	1.420	0.797	0.351	0.000	0.000	0.000	0.000	0.000	1.146	8.763	-70.423	1.169
GHGs (CO2e)	5.242	1.983	0.881	0.378	0.000	2.576	0.837	2.884	0.649	1.226	16.656	-70.423	1.217

	Fuel Production													
	4					5	6				7	8	
	Camelina Oil Extraction - Natural Gas Production and Use	Camelina Oil Extraction - Electricity Generation and Use	Camelina Oil Extraction - Hexane Production and Use	Credit from Soy Meal Displacement	Camelina Oil Extraction - Total	Camelina Oil Transportation	Jet Fuel Production - Natural Gas Production and Use	Jet Fuel Production - Electricity Generation and Use	Jet Fuel Production - Hydrogen Production and Use	Jet Fuel Production - Total	Renewable Jet Fuel Transportation and Distribution	Combustion	Total
VOC	0.000	0.000	0.030	0.000	0.030	0.001	0.000	0.000	0.001	0.002	0.001		0.041
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.003	0.005	0.001		0.031
NOx	0.001	0.000	0.000	0.000	0.001	0.016	0.004	0.001	0.007	0.011	0.004		0.085
PM10	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.002	0.003	0.000		0.011
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000		0.007
SOx	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.005	0.000		0.064
CH4	0.009	0.001	0.000	0.000	0.010	0.002	0.030	0.003	0.071	0.103	0.001		0.144
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.025
CO2	1.084	0.231	0.019	0.000	1.334	1.621	3.556	1.060	10.362	14.979	0.573	70.423	28.379
CO2 (w/ C in VOC & CO)	1.085	0.231	0.112	0.000	1.428	1.628	3.560	1.061	10.370	14.991	0.578	70.423	28.557
GHGs (CO2e)	1.321	0.246	0.115	0.000	1.682	1.696	4.332	1.132	12.149	17.613	0.602	70.423	39.466

Table 17. Life cycle GHG and other emissions by process stage based on the baseline emission case of Section 2 that utilizes **Scenario II** for hydrogen production. Co-products in the primary production pathway have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	1											2	3
SCENARIO Camelina co-products: ***Energy-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	Camelina Farming - Diesel Production and Use	Camelina Farming - Nitrogen Fertilizer Production	Camelina Farming - Thomas Meal Production	Camelina Farming - Potassium Chloride Production	Camelina Farming - Direct NOx Emissions from Nitrogen Fertilizer	Camelina Farming - Direct N2O Emissions from Nitrogen Fertilizer	Camelina Farming - Indirect N2O emissions from Nitrogen Fertilizer	Camelina Farming - Direct N2O Emissions from crop residues	Camelina Farming - Indirect N2O Emissions from crop residues	Camelina Farming - Herbicide Production and Use	Camelina Farming - Total	CO2 Credit from Camelina Growth	Camelina Seed Transportation
Emissions (g/MJ)													
VOC	0.004	0.003	0.000	0.000						0.000	0.008		0.000
CO	0.017	0.003	0.001	0.000						0.000	0.022		0.000
NOx	0.034	0.002	0.005	0.001	0.008					0.002	0.051		0.001
PM10	0.003	0.001	0.002	0.000						0.001	0.006		0.000
PM2.5	0.003	0.000	0.001	0.000						0.000	0.005		0.000
SOx	0.001	0.001	0.052	0.001						0.002	0.057		0.000
CH4	0.007	0.012	0.003	0.001						0.003	0.026		0.002
N2O	0.000	0.001	0.000	0.000		0.009	0.003	0.010	0.002	0.000	0.024		0.000
CO2	5.010	1.404	0.795	0.351						1.145	8.705	-70.423	1.168
CO2 (w/ C in VOC & CO)	5.048	1.420	0.797	0.351	0.000	0.000	0.000	0.000	0.000	1.146	8.763	-70.423	1.169
GHGs (CO2e)	5.242	1.983	0.881	0.378	0.000	2.576	0.837	2.884	0.649	1.226	16.656	-70.423	1.217

	Fuel Production												
	4					5	6				7	8	
	Camelina Oil Extraction - Natural Gas Production and Use	Camelina Oil Extraction - Electricity Generation and Use	Camelina Oil Extraction - Hexane Production and Use	Credit from Soy Meal Displacement	Camelina Oil Extraction - Total	Camelina Oil Transportation	Jet Fuel Production - Natural Gas Production and Use	Jet Fuel Production - Electricity Generation and Use	Jet Fuel Production - Hydrogen Production and Use	Jet Fuel Production - Total	Renewable Jet Fuel Transportation and Distribution	Combustion	Total
VOC	0.000	0.000	0.030	0.000	0.030	0.001	0.000	0.000	0.003	0.003	0.001		0.043
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.001	0.003	0.001		0.029
NOx	0.001	0.000	0.000	0.000	0.001	0.016	0.004	0.001	0.004	0.009	0.004		0.083
PM10	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.002	0.000		0.010
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000		0.006
SOx	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.005	0.000		0.064
CH4	0.009	0.001	0.000	0.000	0.010	0.002	0.030	0.003	0.012	0.045	0.001		0.085
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.025
CO2	1.084	0.231	0.019	0.000	1.334	1.621	3.556	1.060	1.158	5.775	0.573	70.423	19.176
CO2 (w/ C in VOC & CO)	1.085	0.231	0.112	0.000	1.428	1.628	3.560	1.061	1.169	5.790	0.578	70.423	19.356
GHGs (CO2e)	1.321	0.246	0.115	0.000	1.682	1.696	4.332	1.132	1.471	6.935	0.602	70.423	28.788

Table 18. Life cycle GHG and other emissions by process stage based on the baseline emission case of Section 2 that utilizes **Scenario III** for hydrogen production. Co-products in the primary production pathway have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.

	Feedstock Production												
PROCESS NUMBERS →	**1**											**2**	**3**
SCENARIO Camelina co-products: ***Energy-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products and steam: ***Energy-based allocation***	**Camelina Farming - Diesel Production and Use**	**Camelina Farming - Nitrogen Fertilizer Production**	**Camelina Farming - Thomas Meal Production**	**Camelina Farming - Potassium Chloride Production**	**Camelina Farming - Direct NOx Emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from Nitrogen Fertilizer**	**Camelina Farming - Indirect N2O emissions from Nitrogen Fertilizer**	**Camelina Farming - Direct N2O Emissions from crop residues**	**Camelina Farming - Indirect N2O Emissions from crop residues**	**Camelina Farming - Herbicide Production and**	**Camelina Farming - Total**	**CO2 Credit from Camelina Growth**	**Camelina Seed Transportation**
Emissions (g/MJ)													
VOC	0.003	0.004	0.000	0.000						0.000	0.008		0.000
CO	0.013	0.004	0.001	0.000						0.001	0.018		0.000
NOx	0.027	0.002	0.005	0.001	0.009					0.002	0.046		0.001
PM10	0.002	0.001	0.002	0.000						0.001	0.006		0.000
PM2.5	0.002	0.000	0.001	0.000						0.000	0.004		0.000
SOx	0.001	0.001	0.061	0.001						0.002	0.066		0.000
CH4	0.008	0.014	0.004	0.001						0.003	0.030		0.002
N2O	0.000	0.001	0.000	0.000		0.010	0.003	0.011	0.003	0.000	0.029		0.000
CO2	5.917	1.639	0.921	0.403						1.329	10.209	-70.423	1.376
CO2 (w/ C in VOC & CO)	5.947	1.658	0.924	0.403	0.000	0.000	0.000	0.000	0.000	1.330	10.261	-70.423	1.377
GHGs (CO2e)	6.178	2.310	1.019	0.433	0.000	3.023	0.982	3.385	0.762	1.421	19.513	-70.423	1.434

	Fuel Production												
	4					**5**	**6**				**7**	**9**	
	Camelina Oil Extraction - Natural Gas Production and Use	**Camelina Oil Extraction - Electricity Generation and Use**	**Camelina Oil Extraction - Hexane Production and Use**	**Credit from Soy Meal Displacement**	**Camelina Oil Extraction - Total**	**Camelina Oil Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Hydrogen Production and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Renewable Jet Fuel Combustion**	**Total**
Emissions (g/MJ)													
VOC	0.000	0.000	0.035	0.000	0.035	0.001	0.001	0.000	0.000	0.001	0.001		0.045
CO	0.001	0.000	0.000	0.000	0.001	0.003	0.002	0.000	0.000	0.002	0.001		0.025
NOx	0.001	0.000	0.000	0.000	0.001	0.015	0.004	0.001	0.000	0.005	0.003		0.072
PM10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.002	0.000		0.009
PM2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000		0.006
SOx	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.002	0.000	0.003	0.000		0.071
CH4	0.011	0.001	0.000	0.000	0.011	0.003	0.035	0.003	0.000	0.038	0.001		0.084
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.029
CO2	1.272	0.260	0.023	0.000	1.554	1.910	4.173	1.202	0.000	5.374	0.576	70.423	21.000
CO2 (w/ C in VOC & CO)	1.273	0.260	0.132	0.000	1.665	1.918	4.177	1.202	0.000	5.380	0.581	70.423	21.181
GHGs (CO2e)	1.544	0.277	0.136	0.000	1.956	1.999	5.065	1.280	0.000	6.345	0.604	70.423	31.852

2.4. Comparison of different GREET versions

The primary LCA modeling tool in Phase I was GREET1_2011. In Phase II, some of the analyses have been carried out and/or updated using the newest version of GREET, GREET1_2012 rev.2. In this section, these two GREET platforms have been compared in terms of two of the hydrogen production scenarios of Section 2.3. The results are shown in Table 19. As seen from this table, the newer GREET version results in a decrease of about 2% in carbon footprint when both hydrogen production scenarios are compared. This difference is not significant.

Table 19. Comparison of GREET1_2011 and GREET1_2012 rev.2 based on hydrogen production scenarios I and II of Section 2.3. Emissions are reported in terms of g/MJ_{H2}.

	GREET 2011					GREET 2012 rev 2				
	Scenario I	Scenario II				Scenario I	Scenario II			
Emissions (g/MJ_{H2})	Total	Crude oil	Naphtha	H2	Total	Total	Crude oil	Naphtha	H2	Total
VOC	0.009	0.003	0.020	0.000	0.023	0.009	0.003	0.001	0.000	0.004
CO	0.022	0.005	0.003	0.000	0.008	0.022	0.005	0.002	0.000	0.007
NOx	0.054	0.025	0.009	0.000	0.033	0.050	0.024	0.004	0.000	0.028
PM10	0.013	0.002	0.002	0.000	0.004	0.013	0.002	0.001	0.000	0.004
PM2.5	0.012	0.001	0.001	0.000	0.002	0.012	0.002	0.001	0.000	0.002
SOx	0.015	0.010	0.005	0.000	0.015	0.015	0.010	0.003	0.000	0.014
CH4	0.582	0.084	0.013	0.000	0.098	0.546	0.095	0.012	0.000	0.108
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	85.372	5.288	4.143	0.113	9.544	84.452	5.490	3.539	0.107	9.137
CO2 (w/ C in VOC & CO)	85.436	5.307	4.208	0.113	9.628	84.515	5.509	3.545	0.107	9.162
GHGs (CO2e)	100.094	7.440	4.562	0.116	12.118	98.260	7.918	3.861	0.110	11.889

2.5. Indirect reduction in nutrients to be applied after camelina harvest

As previously mentioned, camelina can be grown in rotation with wheat. In this study, potential carbon credits due to any indirect reduction in nutrients to be applied to soil after camelina has been harvested have been quantified as part of the camelina-to-HEFA jet fuel pathway analysis. Additional nutrients are released to the soil as a result of the decomposition of camelina residues. This could lower the nutrient requirements for the following crops to be cultivated in rotation with camelina, such as wheat.

This analysis is based on a study by Nikolova et al.[13], who quantified the amount of nitrogen (N), phosphorus (P) and potassium (K) removed along with harvested camelina seeds, oil, and fiber. The harvested portion of camelina is primarily the seeds which contain the oil. Fiber is what is left behind. Nikolova et al. carried out camelina cultivation at two locations with different soil and climate conditions: Location (a) – medium to high soil nutrient content, annual precipitation of 606 mm; location

(b) – low soil nutrient content, annual precipitation of 825 mm. Table 20 summarizes their findings. Even though the values in this table are for nutrients removed from the field with the harvested biomass, they can also be interpreted as the amount of nutrients supplied to the soil with biomass left on the field.

An average harvest index of 0.211 has been reported in the literature for camelina, over three years following winter wheat in rotation near Lingle, WY.[9] Therefore, assuming that the harvested biomass is only composed of seeds, for every gram of seed harvested there is 3.7 g of residue left on the field. Using the average nutrient values reported in Table 20 for fiber, this translates into 0.24 g N, 0.37 g P and 0.01 g K nutrients left on the field for every gram of camelina seed harvested.

Table 20. Nutrients supplied to the soil with biomass left on the field, or removed from the soil with harvested biomass.[13]

Biomass	**Location**	**Nutrient supplied/removed (g/100 g biomass)**		
		N	**P**	**K**
Seed	a	5.0	0.9	1.9
	b	5.9	0.8	2.7
Oil	a	24.1	4.4	9.4
	b	24.0	3.2	10.5
Fiber	a	5.3	1.4	1.9
	b	7.7	0.6	3.5
	Average	*6.5*	*1.0*	*2.7*

GREET assumes a mixture of ammonia (14%), urea (49%) and ammonium nitrate (37%) in nitrogen fertilizer applications. These nitrogen fertilizers have nitrogen contents of 82.4%, 46.7% and 35.0%, respectively. The GHG emissions from producing this mixture are equal to 3.6 gCO2e/g N in mixture. Phosphorus fertilizer (P2O5) has a carbon footprint of 2.4 gCO2e/g P in fertilizer in GREET, and potassium fertilizer has 0.80 gCO2e/g K in fertilizer. Therefore, for every gram of camelina seed harvested, emissions of 1.8 gCO2e are saved by using less fertilizer in the next wheat cultivation.

The nutrients in the fibers that are left on the field are essentially co-products of camelina cultivation, which displace conventional fertilizers. Therefore, any GHG benefit from using less fertilizers in the next cultivation could be credited towards camelina-derived jet fuel. 1.8 gCO2e/seed of above discussion corresponds to a credit of 85.9 gCO2e/MJ. This value is presented here for informational purposes only, and not included in the analyses previously presented, as true benefit could only be evaluated with a complete evaluation of wheat cultivation with and without camelina rotation (i.e. change in fertilizer use, yield, oil content, diesel use, etc.), which is not currently possible due to lack of data.

2.6. Summary of EPA's final ruling on camelina

Camelina-derived diesel, jet fuel and naphtha are RFS2 compliant biofuels. This section summarizes the camelina-related information and analysis presented in EPA's final ruling published on March 5, 2013,[8] and is included here for the completeness of the study.

Based on the survey by the EPA, camelina is being cultivated on trial plots in 12 states across the U.S. and primarily in Montana, eastern Washington and the Dakotas on a total of approximately 50,000 acres. Only 5% of the current U.S. production is used as dietary supplement and in the cosmetics industry, and the rest is for testing for biofuels production, especially to be used in aviation. The quantity of camelina produced will be tracked by the EPA by monitoring the number of RINs generated for camelina-derived biofuel. According to the EPA, its production is not likely to increase in the near future.

The EPA suggests that camelina cultivation in the U.S. will not induce any land use changes. First of all, since there is no established, commercially traded market for camelina, farmers are not likely to devote any land for its cultivation and will continue to grow commercial crops. Even though expected returns on camelina are currently uncertain, it can be grown on soils with low moisture and nutrient content as a rotation crop. Hence, it is more likely that camelina will be cultivated on fallow land without inducing any *direct* land use changes. Additionally, as mentioned above, the non-biofuel use of camelina is limited, which will decrease the possibilities for any *indirect* land use changes.

Due to limited productivity, the expectation that it will be grown on fallow land with no LUC, and because of the fact that it has no known invasive properties reported in the U.S., the EPA suggests that the initial production of camelina will have the lowest opportunity cost.

According to the EPA, current farming practice in the semi-arid regions of the Northern Great Plains involves rotation of winter and spring wheat with fallow months once every three to four years. Short-term trials have indicated that there is a positive benefit of including camelina into this rotation scheme by preventing soil erosion, increasing soil organic matter and disrupting pest cycles. However, long-term effects are still unclear. In case significant negative impacts of growing camelina in rotation arises in the future, EPA will re-consider its final ruling.

It has been estimated by the EPA that there is a total of 22 million acres in the U.S. where wheat/fallow rotation is practiced, out of which 9 million acres have suitable climate, soil profile and market access for camelina cultivation. In a three-year rotation scheme, this would correspond to 3 million acres every year, which would not impact the food supply. Additionally, there are trials where camelina is grown in rotation with kanaf, peanuts, cotton and corn, such as in Florida where wheat is not cultivated. In their analysis, EPA considers rotation of camelina only with wheat; however, as stated by the EPA, the final ruling is also applicable to situations where camelina is grown elsewhere, including outside the U.S.

EPA reports the current average yield of camelina to be on the order of 800 lb/ac. Yields as high as 1650 lb/ac have been achieved on trial plots, and future projections estimate 3000 lb/ac. EPA assumes 1650 lb/ac in their analysis.

EPA utilizes a complex LCA approach, which includes use of not only the LCA tool GREET but also partial equilibrium economic models like FASOM and FAPRI, to estimate GHG emissions for the only oily crop-derived biofuel that they fully analyzed, i.e. soybean-derived biodiesel.[20] This approach is therefore analogous to employing system expansion, also known as displacement, to account for emissions towards co-products, and is very hard to implement without the right tools. Table 21 presents the results of EPA's analysis for soybean-derived biodiesel and compares it with the conventional diesel, which is taken as the reference case. Emissions, reported in kgCO2e/mmBtu, are given as a range of 14-76 kgCO2e/mmBtu based on variability and uncertainty involved, which has a mean value of 42 kgCO2e/mmBtu. Comparison of this mean value with the conventional diesel (97 kgCO2e/mmBtu) shows a 57% reduction in GHG emissions, which makes soybean-derived biodiesel qualify under RFS2 as an advanced biofuel. Later analyses by the EPA certify biofuel pathways not based on utilization of a similar complex LCA but solely based on comparison of certain steps in the life cycles with those of soybean-derived biodiesel's. Table 22 and Table 23 present such a comparison for camelina-derived biofuels. Because of similarity with the soybean-derived biodiesel; camelina-derived biodiesel, diesel, jet, naphtha and LPG also qualify under RFS2.[5] Note that the values shown in Table 22 are from an analysis which does not employ any emissions accounting for the co-products. On the other hand, analyses, the results of which are presented in Table 23, utilize displacement method for the biodiesel pathways (glycerin displaces residual oil) and energy-based allocation for the HEFA pathways (RIN-generating biofuels displace their counterparts).

Table 21. Life cycle GHG emissions for biodiesel as calculated by EPA for the year 2022.[21] Values are reported in kgCO2e/mmBtu (1 kg/mmBtu = 0.95 g/MJ).

Fuel type	**Soy-based biodiesel**	**2005 Diesel baseline**
Net domestic agriculture (w/o LUC)	-10	
Net international agriculture (w/o LUC)	1	
Domestic LUC	-9	
International LUC, mean (low/high)*	43 (15/76)	
Fuel production	13	18
Fuel and feedstock transport	3	
Tailpipe emissions	1	79
Total emissions, mean (low/high)	*42 (14/76)*	*97*

*Includes uncertainty and variability ranges in the analysis.

Table 22. Comparison of camelina- and soybean-derived biodiesels based on inputs at cultivation steps.[5] Values are reported in kgCO2e/mmBtu (1 kg/mmBtu = 0.95 g/MJ).

	Camelina-based biodiesel	Soy-based biodiesel
N2O	22	9-12
Nitrogen fertilizer	7	1-3
Phosphorous fertilizer	1	0-2
Potassium fertilizer	0	0-2
Herbicide	3	0-2
Pesticide	0	0-2
Diesel	5	7-20
Gasoline	0	3-5
Total	*39*	*21-47*

Table 23. Comparison of fuel production life cycle GHG emissions.[5] Note that system expansion is used for biodiesel and energy-based allocation for the others to account for emissions. Values are reported in kgCO2e/mmBtu (1 kg/mmBtu = 0.95 g/MJ).

Feedstock	Production process	RIN-generating products	Other co-products	Oil extraction	Processing	Total
Soybean oil	Trans-esterification	Biodiesel	Glycerin	14	(1)	13
Camelina oil				4	(1)	3
	HEFA (max distillate)	Diesel Jet fuel Naphtha LPG	Propane	4	8	12
	HEFA (max jet)			4	11	14

3. Tallow-derived HEFA jet fuel

Tallow is a potential alternative feedstock for HEFA fuels. Similar to camelina, tallow-derived diesel, jet fuel and naphtha are also RFS2 compliant biofuels. Tallow, which can be differentiated into edible and inedible tallow, is derived from rendering edible or inedible portions of beef carcasses. While edible tallow is mainly used as shortening for baked goods, inedible tallow is used in animal feeds, soap production and lubricants.[10] In order to melt the animal fat and extract it from the surrounding nonfat tissues containing proteins and water, a technology known as “rendering” is used. The rendering process is the heat-treatment of animal by-products (bones, offal, fats, etc.) from carcasses of livestock and used cooking oil, in either the presence (wet rendering) or the absence (dry rendering) of water/steam.[11]

In Section 3.1 we present the methodology and assumptions for the LCA of tallow-derived HEFA jet fuel. In Section 3.2 we discuss the sensitivity of our results to co-product allocation assumptions, market prices and the use of different life cycle emissions tools.

3.1. LCA for tallow-derived HEFA jet fuel

An LCA has been carried out for tallow derived HEFA jet fuel. Two different system boundaries are considered. The first system treats tallow as a waste product of the meat production industry and includes the following process stages: 1) transportation of tallow from the rendering plant to a fuel production facility, 2) conversion of tallow into fuels through refining, 3) transportation and distribution of the fuel to the aircraft, and 4) fuel combustion. The second system considers tallow as a by-product of the rendering industry and includes the following stages: 1) rendering of animal by-products, 2) transportation of tallow from rendering plant to a fuel production facility, 3) conversion of tallow into fuels through refining, 4) transportation and distribution of the fuel to the aircraft, and 5) fuel combustion. Cattle is not raised to produce tallow. Therefore biofuel production from tallow will not lead to additional cattle being raised, and consequently tallow HEFA will not induce any direct land use change. The total GHG emissions associated with each of these stages have been calculated with the GREET1_2011 framework and SimaPro using rendering input and processing data obtained from various references.[16-19]

For System 1, the fuel production step is the main contributor to overall emissions. Two different emissions cases were considered for the fuel production process. While one of these cases maximizes the jet fuel production (max jet), the other maximizes the diesel production (max distillate). The difference in the use of natural gas during the hydrotreatment process for fuel production is the main reason for this variability. The mass and energy balances for fuel production from the oil are taken from Pearlson,[4] who analyzed the hydrotreatment process for these two scenarios (maximum diesel fuel production, and maximum jet fuel production). Table 24 lists the material and energy inputs for the fuel production step for System 1.

Table 24. Material and energy inputs for fuel production step for max jet and max distillate scenarios for System 1 and System 2.

Processes	*Inputs*	*Values (Btu/lb of tallow)*
Fuel Production (max jet)	Natural gas[1] Electricity	Intentionally Omitted
Fuel Production (max distillate)	Natural gas[1] Electricity	

[1] Includes natural gas required for hydrogen production.

Table 25 presents the transportation-related assumptions used in the analysis in terms of transportation mode, share, fuel type and mileage. These assumptions are taken from GREET1_2011.

Table 25. Transportation assumptions for System 1.

Processes	*Mode*	*Share*	*Fuel Type*	*Mileage*
Jet Fuel Transportation	Truck	63 %	Diesel	50
	Barge	8 %	Residual oil	520
	Rail	29 %	Diesel	800
Jet Fuel Distribution	Truck	100 %	Diesel	30

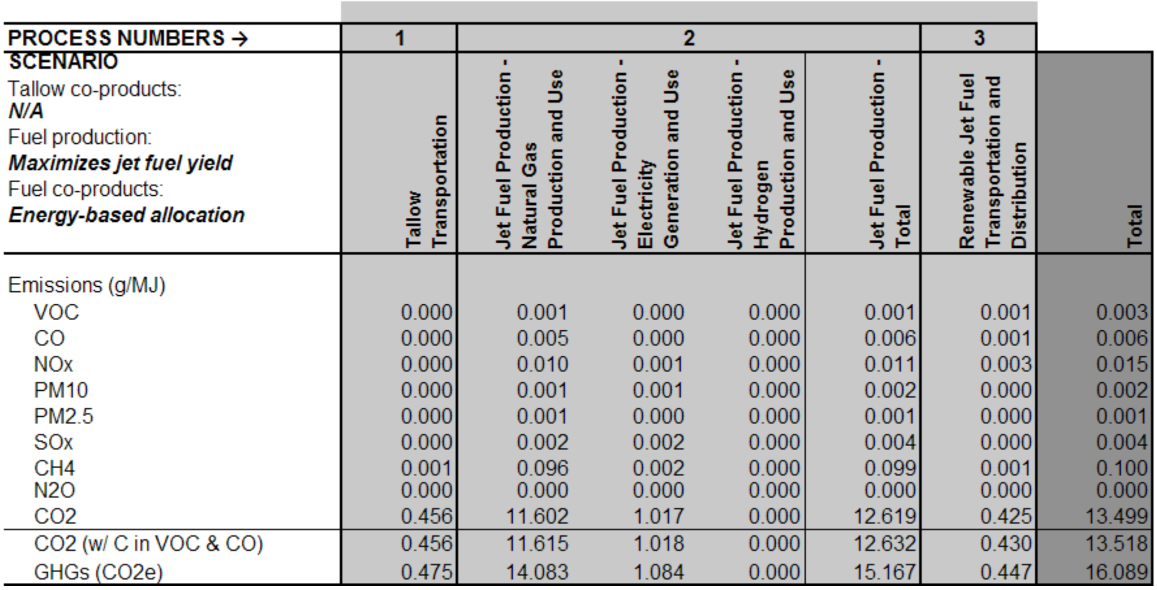
Table 26 summarizes the calculated life cycle GHG emissions in terms of gCO_2e/MJ for System 1 for tallow-derived HEFA jet fuel production. The values in Table 26 are from a scenario of maximized jet fuel production. Our analysis for the baseline emission case results in life cycle GHG emissions of 16.1

gCO_2e/MJ, which is 81.6% lower than our baseline for conventional jet fuel (87.5 gCO_2e/MJ[1]). In this process, all the petroleum co-products, as well as the desired product, jet fuel, are used eventually for energy generation; and for this reason, the overall emissions have been allocated based on their energy contents. The allocation factor employed is given in Table 26. Table 27 gives a further break down of the GHG emissions along with other emission types into various processes.

Table 26. Allocation factor applied for System 1.

Main Product	***Co-Products***	***Allocation Factor to Main Product***
Jet fuel	Other fuels	55.1%

Table 27. Life cycle GHG and other emissions for System 1. All fuel co-products have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.



PROCESS NUMBERS →	**1**	**2**				**3**	
SCENARIO Tallow co-products: ***N/A*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Tallow Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Hydrogen Production and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Total**
Emissions (g/MJ)							
VOC	0.000	0.001	0.000	0.000	0.001	0.001	0.003
CO	0.000	0.005	0.000	0.000	0.006	0.001	0.006
NOx	0.000	0.010	0.001	0.000	0.011	0.003	0.015
PM10	0.000	0.001	0.001	0.000	0.002	0.000	0.002
PM2.5	0.000	0.001	0.000	0.000	0.001	0.000	0.001
SOx	0.000	0.002	0.002	0.000	0.004	0.000	0.004
CH4	0.001	0.096	0.002	0.000	0.099	0.001	0.100
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	0.456	11.602	1.017	0.000	12.619	0.425	13.499
CO2 (w/ C in VOC & CO)	0.456	11.615	1.018	0.000	12.632	0.430	13.518
GHGs (CO2e)	0.475	14.083	1.084	0.000	15.167	0.447	16.089

In our analysis of System 2, we consider three emission cases (low, baseline and high) based on variations at the rendering stage. The key parameters used to create these emission cases are natural gas and electricity use during the rendering process. The difference stems from the different rendering practices executed at each facility (e.g. dry vs. wet rendering). Table 28 lists the values employed in these emission cases.

Table 28. Material and energy inputs that differ in the three emission cases studied.

	Units	*Low*	*Base*	*High*
Natural gas	Btu/lb of tallow	2360	3606	4956
Electricity		245	271	671

The amounts of natural gas required for steam production and electricity for oil rendering are taken from SimaPro, EcoInvent database for the baseline case.[19] For the low case, data is adapted from a survey on the energy use of US rendering facilities performed by Lopez.[16] For the high case, survey data from CA GREET is used.[18] Material and energy inputs for the fuel production step and the transportation assumptions are the same as in System 1.

Table 29. Summary of the GHG emissions and corresponding baseline reductions for the three emission cases studied for System 2.

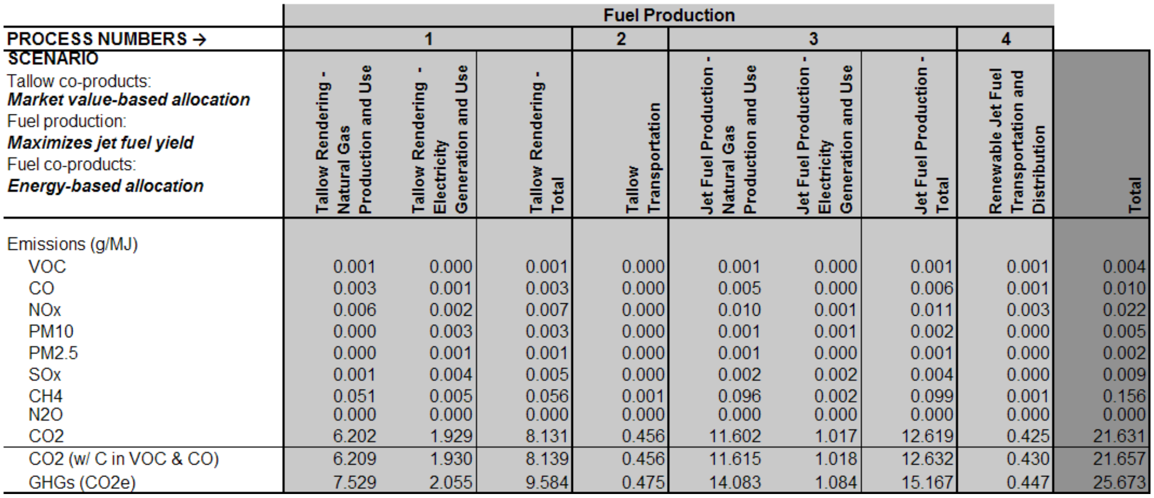
	Low	*Base*	*High*
GHG emissions (gCO_2e/MJ)	25.7	29.9	37.5
Baseline reduction	70.6 %	65.8 %	57.1 %

Table 29 summarizes the calculated life cycle GHG emissions in terms of gCO_2e/MJ for the three emission cases described above for tallow-derived HEFA jet fuel production. The values in Table 29 are from a scenario of maximized jet fuel production. Our analysis for the baseline emission case results in life cycle GHG emissions of 29.9 gCO_2e/MJ, which is 65.8 % lower than our baseline for conventional jet fuel (87.5 gCO_2e/MJ). In this process, meat and bone meal is the co-product of the rendering process, and the fuel co-products include diesel fuel, naphtha and propane gas mix. Both meat and bone meal and tallow are economically valuable products, and market allocation is used for the allocation of the emissions from the rendering process. All the petroleum co-products, as well as the desired product, jet fuel, are used eventually for energy generation; for this reason the overall emissions have been allocated based on their energy contents. The allocation factors employed in this analysis are given in Table 30. Table 31 through Table 33 further break down the GHG emissions along with other emission types into various processes for the low, baseline and high emission cases, respectively.

Table 30. Allocation factors applied in the analysis for System 2.

	Allocation Factor (%)	*Allocation Type*
Rendering process		Market
Tallow Meat	72.8	
and bone meal	27.2	
Fuel production process	**Jet**	Energy
Jet fuel	55.1	
Diesel	25.9	
Naphtha	7.9	
Propane	11.1	

Table 31. Life cycle GHG and other emissions by process stage based on the **low emission case** described in the text. Rendering co-products have been allocated based on their market prices, fuel co-products have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.



	Fuel Production								
PROCESS NUMBERS →	1			2	3			4	
SCENARIO Tallow co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Tallow Rendering - Natural Gas Production and Use**	**Tallow Rendering - Electricity Generation and Use**	**Tallow Rendering - Total**	**Tallow Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Total**
Emissions (g/MJ)									
VOC	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.004
CO	0.003	0.001	0.003	0.000	0.005	0.000	0.006	0.001	0.010
NOx	0.006	0.002	0.007	0.000	0.010	0.001	0.011	0.003	0.022
PM10	0.000	0.003	0.003	0.000	0.001	0.001	0.002	0.000	0.005
PM2.5	0.000	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.002
SOx	0.001	0.004	0.005	0.000	0.002	0.002	0.004	0.000	0.009
CH4	0.051	0.005	0.056	0.001	0.096	0.002	0.099	0.001	0.156
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	6.202	1.929	8.131	0.456	11.602	1.017	12.619	0.425	21.631
CO2 (w/ C in VOC & CO)	6.209	1.930	8.139	0.456	11.615	1.018	12.632	0.430	21.657
GHGs (CO2e)	7.529	2.055	9.584	0.475	14.083	1.084	15.167	0.447	25.673

Table 32. Life cycle GHG and other emissions by process stage based on the **baseline emission case** described in the text. Rendering co-products have been allocated based on their market prices, fuel co-products have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.

	Fuel Production								
PROCESS NUMBERS →	**1**			**2**	**3**			**4**	
SCENARIO Tallow co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Tallow Rendering - Natural Gas Production and Use**	**Tallow Rendering - Electricity Generation and Use**	**Tallow Rendering - Total**	**Tallow Transportation**	**Jet Fuel Production - Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Total**
Emissions (g/MJ)									
VOC	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.004
CO	0.004	0.001	0.005	0.000	0.005	0.000	0.006	0.001	0.011
NOx	0.008	0.002	0.010	0.000	0.010	0.001	0.011	0.003	0.025
PM10	0.001	0.003	0.003	0.000	0.001	0.001	0.002	0.000	0.006
PM2.5	0.001	0.001	0.001	0.000	0.001	0.000	0.001	0.000	0.002
SOx	0.002	0.004	0.006	0.000	0.002	0.002	0.004	0.000	0.010
CH4	0.079	0.005	0.084	0.001	0.096	0.002	0.099	0.001	0.184
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO2	9.475	2.138	11.613	0.456	11.602	1.017	12.619	0.425	25.112
CO2 (w/ C in VOC & CO)	9.486	2.139	11.625	0.456	11.615	1.018	12.632	0.430	25.143
GHGs (CO2e)	11.502	2.278	13.780	0.475	14.083	1.084	15.167	0.447	29.869

Table 33. Life cycle GHG and other emissions by process stage based on the **high emission case** described in the text. Rendering co-products have been allocated based on their market prices, fuel co-products have been allocated based on their energy contents. The hydrotreatment process is assumed to maximize jet fuel production.

	Fuel Production								
PROCESS NUMBERS →	**1**			**2**	**3**			**4**	
SCENARIO Tallow co-products: ***Market value-based allocation*** Fuel production: ***Maximizes jet fuel yield*** Fuel co-products: ***Energy-based allocation***	**Tallow Rendering - Natural Gas Production and Use**	**Tallow Rendering - Electricity Generation and Use**	**Tallow Rendering - Total**	**Tallow Transportation**	**Jet Fuel Production- Natural Gas Production and Use**	**Jet Fuel Production - Electricity Generation and Use**	**Jet Fuel Production - Total**	**Renewable Jet Fuel Transportation and Distribution**	**Total**
Emissions (g/MJ)									
VOC	0.002	0.000	0.002	0.000	0.001	0.000	0.001	0.001	0.005
CO	0.006	0.001	0.008	0.000	0.005	0.000	0.006	0.001	0.014
NOx	0.012	0.005	0.016	0.000	0.010	0.001	0.011	0.003	0.031
PM10	0.001	0.007	0.008	0.000	0.001	0.001	0.002	0.000	0.010
PM2.5	0.001	0.002	0.003	0.000	0.001	0.000	0.001	0.000	0.004
SOx	0.002	0.010	0.012	0.000	0.002	0.002	0.004	0.000	0.016
CH4	0.108	0.013	0.121	0.001	0.096	0.002	0.099	0.001	0.221
N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
CO2	13.023	5.288	18.312	0.456	11.602	1.017	12.619	0.425	31.811
CO2 (w/ C in VOC & CO)	13.038	5.292	18.330	0.456	11.615	1.018	12.632	0.430	31.848
GHGs (CO2e)	15.809	5.635	21.444	0.475	14.083	1.084	15.167	0.447	37.533

3.2. Sensitivity analyses based on market prices, emission accounting methods and LCA tools

Fluctuation in the market prices of tallow and MBM changes the allocation factors for the LCA, and therefore affects the overall emissions results. To evaluate the impact of the market prices of tallow, and meat and bone meal on LCA results, a sensitivity analysis has been performed (see Table 34). Using historic market prices from years 2003-2012 for tallow, and meat and bone meal, the lowest and highest relative prices (i.e. allocation factors) were calculated. These allocation factors were then used for the calculation of emissions from jet fuel. The analysis for jet fuel indicates that historical fluctuations in the market prices can result in an 11% decrease or a 4% increase compared to the GHG emissions based on current prices.

Table 34. Sensitivity to market prices for System 2.

	Low	*High*	*Now*
Tallow prices (¢/lb)	17.0	62.0	42
MBM prices (¢/lb)	15.4	18.4	17.9
Allocation factors (%)	55.8	79.4	72.8
CO_2 emissions (gCO_2e/MJ)	26.6	31.1	29.9

The effects of other emissions accounting methods on overall GHG emissions have also been investigated. Figure 6 through Figure 9 demonstrate the effects of using different accounting methods on the overall life cycle results in a similar manner followed in Section 2.2. Note that these figures not only compare different emission accounting methods, but also different LCA tools. In addition to the primary tool used in all the studies presented in this report (i.e. GREET), the analyses have also been carried out in SimaPro 7.3.3. The only difference in the analyses carried out using these two LCA tools is that when displacement method is used to account for emissions between the meal and the oil, camelina meal displaces soybean meal in the SimaPro analysis, whereas GREET assumes displacement of soybean (not soybean meal) by default.

As seen in Figure 6 through Figure 8, the use of GREET tends to result in higher GHG emissions compared to SimaPro. This is due to higher carbon footprints for natural gas, electricity and diesel fuel, when emissions are *allocated* among fuel co-products. In these figures the gap between the two LCA tools is the largest when the displacement method is used, due to higher carbon footprint of soybean meal in SimaPro which is credited towards jet fuel. As seen in Figure 9, when the displacement method is used among fuel co-products the GREET results are lower than the SimaPro results because of higher carbon footprints of conventional fuels in GREET, which are credited towards HEFA jet fuel. Again, we note that using the displacement method yields distorted results if the product under investigation is not the main product, as is the case here.

Since the allocation factors for mass (54.9%-jet) and energy (55.1%-jet) allocation are very similar to each other for jet fuel production, the change in allocation method for fuel co-products does not have a significant influence on the overall GHG emission results. Price-based allocation yields slightly higher emission results since the allocation factor (57.9%-jet) is higher than it is for energy and mass allocation. The allocation factors employed in this study are summarized in Table 35.

Table 35. Allocation factors employed in Figure 6 through Figure 9, where applicable.

Allocation towards	***Energy***	***Mass***	***Market***
Tallow	72.3%	53.3%	72.8%
Jet (max distillate)	14.5%	14.5%	14.9%
Jet (max jet)	55.1%	54.9%	57.9%

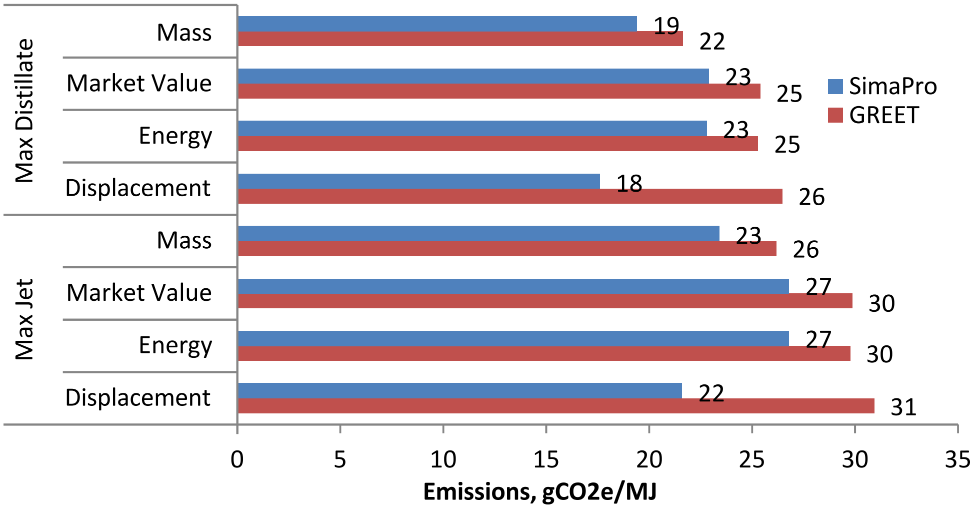


Figure 6. Effect of different methods to account for emissions between oil and meal. **Energy-based allocation used for fuel co-products.**

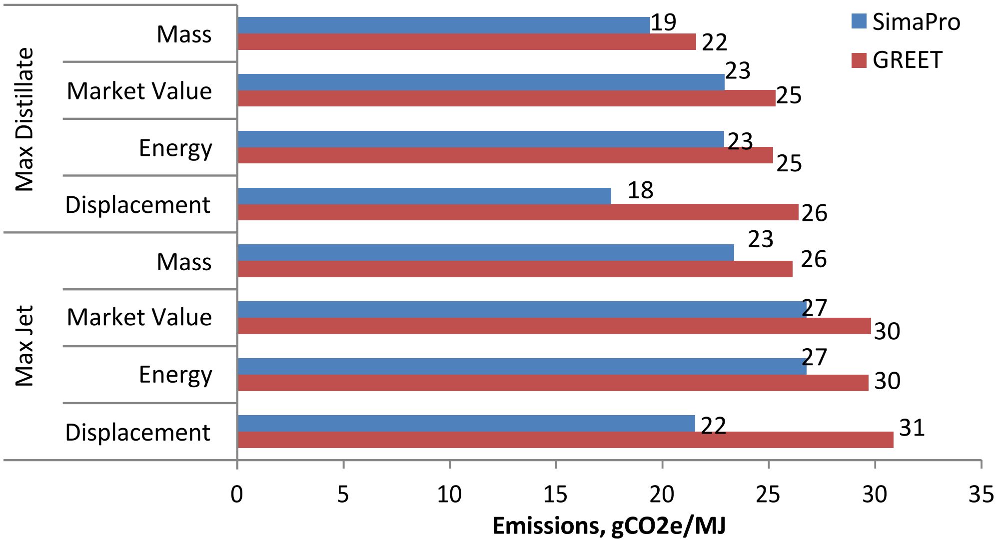


Figure 7. Effect of different methods to account for emissions between oil and meal. **Mass-based allocation used for fuel co-products.**

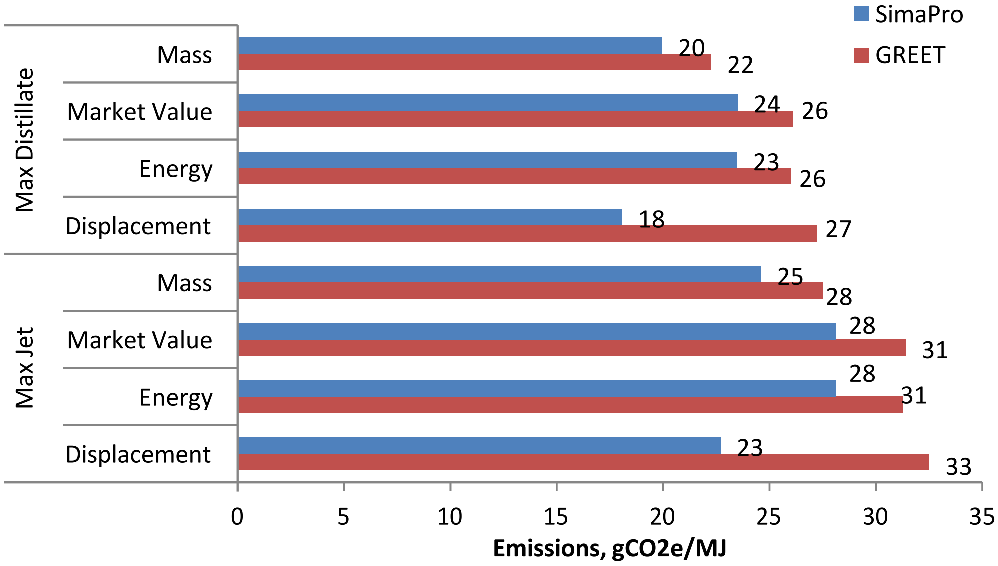


Figure 8. Effect of different methods to account for emissions between oil and meal. **Market-based allocation used for fuel co-products.**

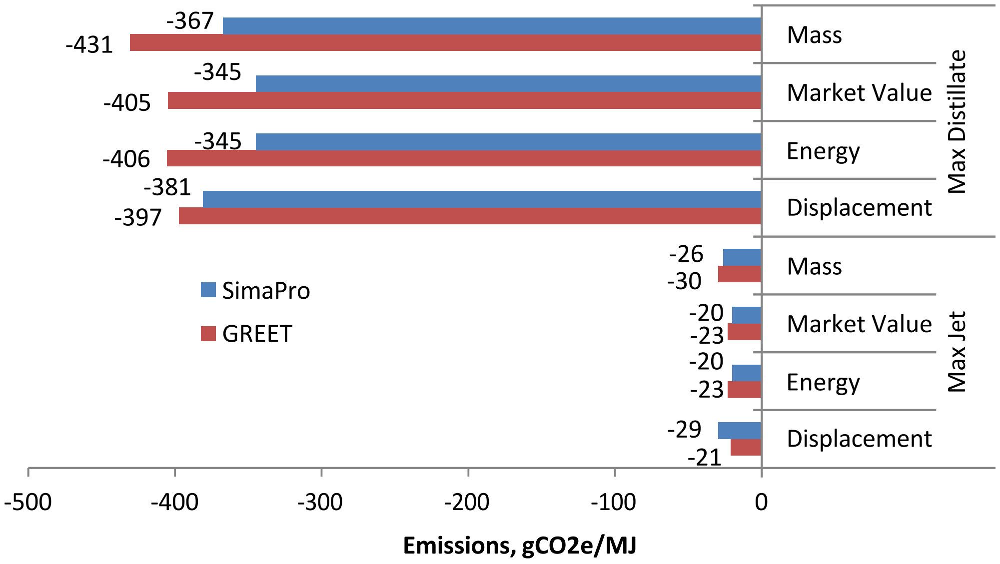


Figure 9. Effect of different methods to account for emissions between oil and meal. **Displacement method used for fuel co-products.**

4. LCA for pyrolysis kerosene production

LCA for the pyrolysis kerosene production includes biomass cultivation, feedstock transportation, feedstock-to-pyrolysis oil conversion, pyrolysis oil transportation, pyrolysis oil-to-kerosene conversion and finally kerosene transportation. Unlike the analyses previously presented, the LCA here also involves wastewater treatment, landfill emissions and carbon sequestration in landfills based on the information provided by Honeywell-UOP. It is generally agreed that the use of residues such as sawmill residues and bagasse as a feedstock for renewable fuels does not lead to significant changes in land use.[6] As a consequence, no land use change scenarios were investigated within the analysis.

Section 4.1 outlines the approach followed in the kerosene production LCA, and presents energy and material inputs for the systems considered, as well as the product slate from the conversion process. Sections 4.2 and 4.3 further detail the analyses based on the type of the feedstocks considered; i.e. residues and sugarcane bagasse, respectively.

4.1. Approach, energy and material inputs and product slate

An LCA for kerosene production from sawmill residues, and sugarcane bagasse via pyrolysis has been carried out by modifying and using the GREET1_2012 rev.2 framework as the primary tool. Other tools used in this study are indicated in the text. The GREET database does not include sawmill residues. For this reason, forest residues have also been modeled in GREET, which are used as a proxy for sawmill residues. The simulation has been performed for the year 2017.

Table 36 and Table 37 show the overall material and energy inputs necessary to produce kerosene from the residues and sugarcane bagasse, respectively, which is based on UOP's Rapid Thermal Processing Technology. This technology includes biomass pretreatment, fast pyrolysis, pyrolysis oil stabilization, hydrogen production, pyrolysis oil conversion to hydrocarbon fuels and hydrocarbon product recovery.

Table 36. LCA inputs per kg of residue kerosene produced.

Material and Energy Inputs	Values	Units
Residues (with 6% moisture content)	Intentionally Omitted	kg
Ethanol		
Sulfuric acid		
Sodium hydroxide		
Sodium chloride		
Natural gas		Btu
Electricity		

Table 37. LCA inputs per kg of sugarcane bagasse kerosene produced.

Material and Energy Inputs	Values	Units
Bagasse (with 6% moisture content)	Intentionally Omitted	kg
Ethanol		
Sulfuric acid		
Sodium hydroxide		
Sodium chloride		
Natural gas		Btu
Electricity		

Table 38. Production outputs (per kg of residue kerosene), product energy densities and energy-based allocation factor to residue kerosene (i.e. the main product).

Products	Amount (kg)	Energy Density (MJ/kg)
Residue kerosene	Intentionally Omitted	
Renewable LPG		
Renewable gasoline		
Renewable diesel		
Renewable solid fuel		
Steam		
Allocation factor		

Table 39. Production outputs (per kg of sugarcane bagasse kerosene), product energy densities and energy-based allocation factor to sugarcane bagasse kerosene (i.e. the main product).

Products	Amount (kg)	Energy Density (MJ/kg)
Bagasse kerosene	Intentionally Omitted	
Renewable LPG		
Renewable gasoline		
Renewable diesel		
Renewable solid fuel		
Steam		
Allocation factor		

The product slate from the pyrolysis process involves four co-products: renewable LPG, gasoline, diesel and solid fuel. The process also generates steam to be exported, which is also considered a co-product. Table 38 and Table 39 summarize the production volumes along with the product energy densities for residue and bagasse kerosene, respectively. Both the production volumes and the energy densities are used to calculate the energy-based allocation factors for kerosene, which is also indicated in the tables.

Table 40 presents the transportation-related assumptions used in the analysis in terms of transportation mode, share, fuel type and mileage. We considered the mileage information that was provided by UOP for residues and bagasse, pyrolysis oil (assumed to be stabilized), and kerosene. For these three, we have assumed that transportation is by diesel-powered truck. For the transportation of the other material inputs, we relied on the default GREET values. Please note that transportation from the bulk center to the plant has been considered only for ethanol, and that no transportation emissions have been accounted for sodium hydroxide. In the analysis, it has been assumed that the other material inputs, water and sand, are readily available at the plant. The transportation of these materials to the plant and that of the waste solids to landfills have not been taken into account.

Table 40. Transportation assumptions.

	Mode	Share[1]	Fuel Type	Mileage
Residues/bagasse				
To pyrolysis plant	Truck	100%	Diesel	31.1/6.2
Ethanol				
To bulk center	Barge	40%	Residual oil	520
	Rail	40%	Diesel	800
	Truck	20%	Diesel	80
To plant	Truck	100%	Diesel	30
Sulfuric acid				
To bulk center	Ocean tanker	60%	Residual oil	1500
	Barge	50%	Residual oil	400
	Rail	50%	Diesel	750
Sodium chloride				
To bulk center	Ocean tanker	60%	Residual oil	5200
	Barge	50%	Residual oil	400
	Rail	50%	Diesel	750
Stabilized pyrolysis oil				
To conversion plant	Truck	100%	Diesel	62.1
Kerosene				
To jet fuel terminal	Truck	100%	Diesel	62.1

[1] Weight-based share of a feedstock that relies on a certain transportation mode. The total can, therefore, exceed 100% as a certain amount of feedstock can be moved from location to location by different transportation modes until its final destination.

4.2. Details and results of analysis for pyrolysis kerosene from sawmill residues

All the life cycle steps in the analysis have been modeled and analyzed in Phase II using GREET1_2012 rev.2 except for sawmill residues production and wastewater treatment. SimaPro 7.3.3 has been used with the TRACI 2 v.4.00 GHG impact assessment method to analyze the latter two processes.

The sawmill residues-to-kerosene pathway has been modeled based on sawmill plant data obtained from the SimaPro database for Southeast United States. The primary product from sawmill is rough green lumber, while the by-products include the sawmill residues composed of sawdust, pulp chips and bark. Emissions have been allocated towards sawmill residues on a mass basis (allocation factor: 50.4%). Energy-based allocation is not used because the main product, lumber, is not used for energy generation. Market-based allocation, on the other hand, is not preferred either due to the fact that there is no market for the residues that are to be converted to kerosene.

A wastewater treatment facility, class 2 has been chosen in SimaPro 7.3.3 to analyze the contribution from this life cycle step. This is the preferred process for wastewater treatment in the available fuel-producing pathways in SimaPro 7.3.3.

Even though related information was available from the UOP, in Phase I LCA of producing kerosene from residues was carried out without considering landfill emissions, carbon sequestration and emissions from wastewater treatment. This analysis has been updated in Phase II to include these steps. Additionally, the previous analysis assumed harvested moisture content of 11.6% for the residues, whereas here it is taken as 50% for forest residues and 55% for sawmill residues. Moreover, the natural gas requirement as shown in Table 36 was assumed to be for boiler use in Phase I; whereas in the updated analysis in Phase II, it is assumed that only 5% of this natural gas requirement is to be used in boilers, and the rest is for hydrogen production in an SMR. The platform used to analyze these pathways in Phases I and II also differed. In Phase I, GREET1_2011 was chosen as the primary LCA tool; whereas in Phase II, it was GREET1_2012 rev.2. A comparison of the effects of using different platforms on the overall results is available in Section 2.4. An example of the factors contributing to different overall results with different platforms is the default platform assumptions regarding ethanol. Note that ethanol is required in the conversion process (see Table 36), and corn ethanol is considered in this analysis.

Landfill emissions from the waste solids have been accounted for based on guidelines by NCASI.[14] Information obtained from UOP assumes that 10% of these wastes is carbon, which is further considered to be organic carbon in this analysis. Following the NCASI guidelines, 50% of this carbon is assumed to be released as gas from the landfills; and 50% of the carbon in gas phase is assumed to be methane, while the rest is released as carbon dioxide. Carbon that is not lost to gas is assumed to be sequestered. Any carbon dioxide released during this process will be offset in the life cycle, as it will be taken up from the atmosphere by the biomass during its growth. Even though the carbon in methane is also from biogenic sources, methane has a higher global warming potential (GWP) than carbon dioxide, which needs to be considered here. First, the amount of methane released from the landfills is calculated in terms of carbon dioxide-equivalent (CO2e) using relative GWPs. Carbon in methane is then traced back to the photosynthesis stage, and the amount of photosynthesized carbon dioxide having the same carbon content is calculated, which is reflected as a biomass credit. The difference between the former and the latter, therefore, is the overall effect of the methane release in the LCA.

Table 41 presents the calculated life cycle GHG emissions in terms of gCO_2e/MJ, along with other types of emissions, broken down by process. The values shown in Table 41 are after the emissions have been allocated among the co-products based on their energy contents. In (a), where the forest residues have been used as a proxy for the sawmill residues, the resulting overall GHG emissions assigned to sawmill kerosene comes out to be 37.7 gCO_2e/MJ. This is 56.9% lower than our baseline for conventional jet fuel (87.5 gCO_2e/MJ, [1]). On the other hand, (b), which couples results from two LCA tools, results in a 53.9% reduction from the conventional baseline with an overall GHG emission value of 40.3 gCO_2e/MJ.

4.3. Details and results of analysis for pyrolysis kerosene from sugarcane bagasse

Sugarcane bagasse used to be a mere waste product of the sugar plant. When this is the case, no emissions from the previous life cycle processes until its generation are accounted towards it in an LCA. Today, however, bagasse is generally being used along with the straw for steam and electricity generation in sugar and ethanol plants. In this study, we investigate the use of the bagasse for kerosene production. Now that bagasse is no longer a waste product, and instead may be used in other ways, it should bear some of the burden from its production steps. Since there is still no established market for bagasse, market-based allocation is not used in this analysis. In a sugar plant, bagasse is produced along with the main product, sugar. Sugar is not valued based on its energy production; hence, allocating emissions between sugar and bagasse based on their relative energy contents would not be logical. Other emission accounting methods include mass-based allocation and system expansion, which is also called displacement. As outlined in Section 2.6, EPA prefers system expansion to deal with co-products which do not generate any RINs. Hence, the displacement method is used in this analysis.

Two different system boundaries (System I and System II) have been investigated in terms of suitability for this analysis:

- Figure 10 depicts System I, which includes bagasse production at a sugar plant and kerosene production at a pyrolysis plant in one system. In such a system, sucrose becomes the co-product of the sugar plant, which is to displace a similar product in the market. Sucrose is known as table sugar, which can also be produced from sugar beets. Hence, cane sucrose could potentially displace beet sucrose. Sugarcane and sugar beets are cultivated at different climates. Sugarcane is produced in tropical and subtropical regions; whereas sugar beets are cultivated at temperate climate. Since such a displacement would not be appropriate, System I has not been considered for the LCA.
- Figure 11 depicts System II, which expands the previous system to include a total of three systems: Kerosene from bagasse (System 1), ethanol from sugarcane (System 2) and conventional natural gas production (System 3). In this scenario, natural gas from System 3 displaces the bagasse for steam and electricity generation in System 2, and bagasse is converted into kerosene in System 1. Additional emissions from displacing bagasse by natural gas are reflected towards kerosene as a discredit. The LCA study presented here is based on System II.

The analysis has been carried out using GREET1_2012 rev.2 except for the wastewater treatment step. The analysis also considers emissions from waste products sent to landfills and carbon sequestered with the wastes. The details regarding the wastewater treatment step and the landfills are given in Section 4.2.

Harvested moisture content affects the emissions from transporting bagasse to the pyrolysis plant. The moisture content considered in this analysis is 25%.

As shown in Table 37 ethanol is used in the conversion process. Since sugarcane bagasse is considered as the feedstock in this analysis, ethanol is also assumed to be derived from sugarcane.

The life cycle results for sugarcane bagasse kerosene, broken down by process step, are given in Table 42. The overall result for jet fuel production from this LCA is 27.1 gCO2e/MJ, which is 69.0% lower than its conventional counterpart.

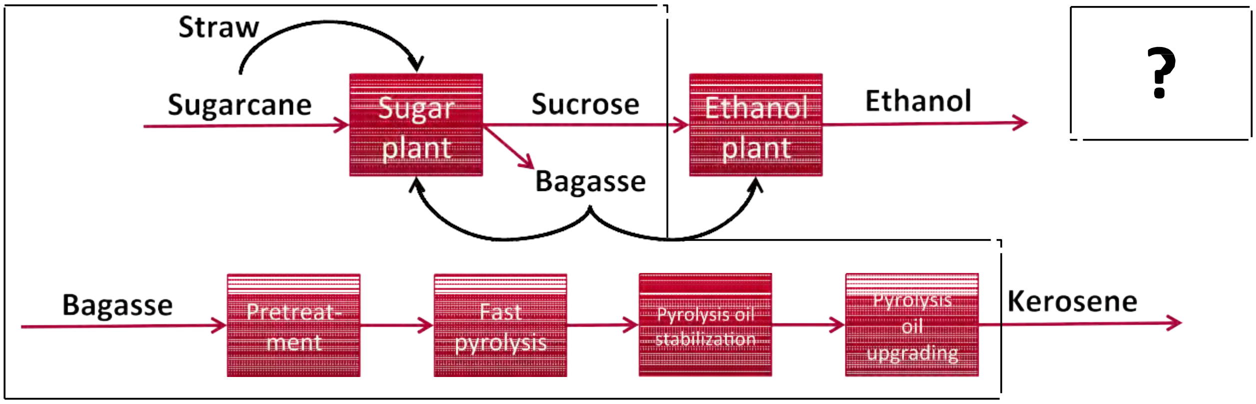


Figure 10. System I: Sugarcane-to-kerosene system considering sucrose as a co-product.

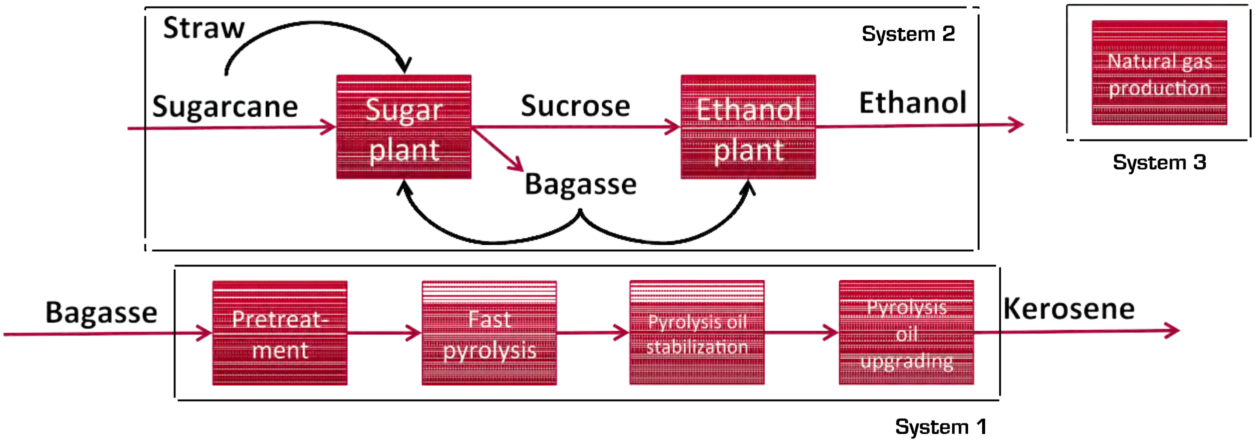


Figure 11. System II: System expansion involving bagasse-to-kerosene, sugarcane-to-ethanol and conventional natural gas production systems.

Table 41. Process-stage life cycle GHG emissions and other emissions having health impacts calculated for kerosene production from (a) forest residues and (b) sawmill residues. Emissions among the product slate have been allocated based on their energy contents (except for the sawmill lumber and residues considered under (b) for which mass allocation is applied). Also note that ethanol values are based on default GREET assumptions (e.g. corn is used as feedstock, and co-products displace corn feed, urea and soy meal/oil).

(a)

	Raw Material Production and Transportation							Fuel Production and Transportation								
Energy-based allocation among co-products (renewable LPG, renewable gasoline, renewable diesel, renewable solid fuel, steam)	**CO2 Credit from Biomass Growth**	**Forest Residue Collection**	**Residue Transportation to Pyrolysis Plant**	**Corn Ethanol Production and Transportation**	**Sulfuric Acid Production and Transportation**	**Sodium Hydroxide Production**	**Sodium Chloride Production and**	**Stabilized Pyrolysis Oil Transportation to Conversion Plant**	**Overall Process - Conversion of Residues to Kerosene**	**Landfill emissions**	**Landfill sequestration**	**Wastewater treatment**	**Kerosene Transportation to**	**Combustion**	**Total**
Emissions (g/MJ)															
VOC		0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.003				0.001		0.007
CO		0.003	0.000	0.001	0.000	0.000	0.000	0.000	0.008				0.002		0.014
NOx		0.007	0.001	0.003	0.000	0.000	0.000	0.001	0.024				0.004		0.040
PM10		0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.022				0.001		0.025
PM2.5		0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.009				0.001		0.011
SOx		0.000	0.000	0.002	0.004	0.001	0.000	0.000	0.033				0.002		0.043
CH4		0.002	0.002	0.008	0.000	0.000	0.000	0.001	0.146	0.044			0.001		0.206
N2O		0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000				0.000		0.002
CO2	-73.748	1.563	1.206	1.671	0.009	0.262	0.124	0.747	26.198	0.122	-0.245		0.471	73.504	31.884
CO2 (w/ C in VOC & CO)	-73.748	1.571	1.207	1.679	0.009	0.263	0.124	0.747	26.219	0.122	-0.245		0.477	73.504	31.928
GHGs (CO2e)	-73.748	1.635	1.260	2.352	0.010	0.275	0.134	0.780	29.943	1.234	-0.245	0.008	0.528	73.504	37.670

(b)

	Raw Material Production and Transportation							Fuel Production and Transportation							
Energy-based allocation among co-products (renewable LPG, renewable gasoline, renewable diesel, renewable solid fuel, steam)	**CO2 Credit from Biomass Growth**	**Sawmill Residues Analyzed with SimaPro**	**Residue Transportation to Pyrolysis Plant**	**Corn Ethanol Production and Transportation**	**Sulfuric Acid Production and Transportation**	**Sodium Hydroxide Production**	**Sodium Chloride Production and**	**Stabilized Pyrolysis Oil Transportation to Conversion Plant**	**Overall Process - Conversion of Residues to Kerosene**	**Landfill emissions**	**Landfill sequestration**	**Wastewater treatment**	**Kerosene Transportation to**	**Combustion**	**Total**
Emissions (g/MJ)															
GHGs (CO2e)	-73.748	4.125	1.400	2.352	0.010	0.275	0.134	0.780	29.943	1.234	-0.245	0.008	0.528	73.504	40.300

Table 42. Process-stage life cycle GHG emissions and other emissions having health impacts calculated for kerosene production from sugarcane bagasse. Emissions among the product slate have been allocated based on their energy contents, and conventional natural gas is assumed to displace bagasse at the sugar and ethanol plants. Also note that ethanol values are based on default GREET assumptions for sugarcane ethanol.

	Raw Material Production and Transportation							Fuel Production and Transportation							
Energy-based allocation among co-products (renewable LPG, renewable gasoline, renewable diesel, renewable solid fuel, steam). ***Energy-based displacement*** between bagasse and natural gas.	CO2 Credit from Biomass Growth	Discredit from Displacing Bagasse with Natural Gas in Ethanol Production	Bagasse Transportation to Pyrolysis Plant	Sugarcane Ethanol Production and Transportation	Sulfuric Acid Production and Transportation	Sodium Hydroxide Production	Sodium Chloride Production and	Stabilized Pyrolysis Oil Transportation to Conversion Plant	Overall Process - Conversion of Bagasse to Kerosene	Landfill emissions	Landfill sequestration	Wastewater treatment	Kerosene Transportation to	Combustion	Total
Emissions (g/MJ)															
VOC		-0.001	0.000	0.004	0.000	0.000	0.000	0.000	0.002				0.001		0.007
CO		0.057	0.000	0.031	0.000	0.000	0.000	0.000	0.006				0.002		0.096
NOx		0.000	0.000	0.012	0.000	0.001	0.000	0.001	0.018				0.004		0.036
PM10		0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.016				0.001		0.025
PM2.5		0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.007				0.001		0.012
SOx		0.000	0.000	0.004	0.004	0.001	0.000	0.000	0.024				0.002		0.035
CH4		0.000	0.000	0.004	0.000	0.001	0.000	0.001	0.116	0.046			0.001		0.170
N2O		0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000				0.000		0.001
CO2	-73.755	0.000	0.128	0.710	0.010	0.292	0.137	0.829	20.084	0.126	-0.251		0.471	73.504	22.285
CO2 (w/ C in VOC & CO)	-73.755	0.085	0.129	0.772	0.010	0.292	0.137	0.830	20.101	0.126	-0.251		0.477	73.504	22.457
GHGs (CO2e)	-73.755	0.085	0.134	1.233	0.011	0.306	0.148	0.867	23.052	1.267	-0.251	0.008	0.528	73.504	27.136

5. LCA for fully-synthetic jet fuel

Fully-synthetic jet fuel (FSJF) is obtained by blending pyrolysis-derived kerosene into a HEFA jet fuel. To meet the current minimum required volumetric density, the FSJF will require at least 10 vol% pyrolysis-derived kerosene. To meet maximum aromatics specifications (60% of the pyrolysis-derived kerosene is composed of aromatics) and minimum smoke point, the blended ratio of sawmill kerosene should not exceed 30 vol%. Hence, three volumetric pyrolysis-derived kerosene blend ratios of 10%, 20% and 30% have been considered in this section.

Table 43. Life cycle GHG emissions (gCO_2e/MJ) associated with fully-synthetic jet fuel production from **camelina-derived maximized-jet** HEFA jet fuel and pyrolysis-derived kerosene based on % blended volume of pyrolysis-derived kerosene and the emission cases described in the text. Minimum and maximum values are underlined. Values that don't qualify under RFS2 are highlighted.

		% Blended Volume	Camelina-Derived HEFA Jet Fuel (max jet)		
			Low	**Base**	**High**
Pyrolysis-derived Kerosene	**Low (Bagasse)**	10	29.9	36.4	46.4
		20	29.6	35.3	44.1
		30	**29.3**	34.2	41.8
	Mid (Forest res.)	10	31.1	37.6	47.5
		20	31.9	37.6	46.3
		30	32.7	37.6	45.2
	High (sawmill res.)	10	31.4	37.9	**47.8**
		20	32.5	38.2	46.9
		30	33.5	38.5	46.0

Table 44. Life cycle GHG emissions (gCO_2e/MJ) associated with fully-synthetic jet fuel production from **camelina-derived maximized-distillate** HEFA jet fuel and pyrolysis-derived kerosene based on % blended volume of pyrolysis-derived kerosene and the emission cases described in the text. Minimum and maximum values are underlined. Values that don't qualify under RFS2 are highlighted.

		% Blended Volume	**Camelina-Derived HEFA Jet Fuel (max distillate)**		
			Low	**Base**	**High**
Pyrolysis-derived Kerosene	**Low (Bagasse)**	10	29.9	34.3	43.6
		20	29.6	33.4	41.6
		30	**29.3**	32.6	39.6
	Mid (Forest res.)	10	31.1	35.5	44.7
		20	31.9	35.7	43.9
		30	32.7	36.0	43.0
	High (sawmill res.)	10	31.4	35.7	**45.0**
		20	32.5	36.3	44.4
		30	33.5	36.8	43.9

Table 43 and Table 45 tabulate the overall GHG emissions from producing an FSJF by blending pyrolysis-derived kerosene into camelina- and tallow-derived HEFA jet fuel, respectively, for the production of a maximized HEFA jet fuel product slate and for different emission cases. The results based on producing a maximized HEFA distillate fuel product slate are given in Table 44 and Table 46 for blended camelina- and tallow-derived HEFA jet fuels, respectively. The low, base and high cases which are referred to in the tables for both camelina- and tallow-derived HEFA jet fuels are described in Sections 2.1 and 3.1, respectively. Due to their relative carbon footprints, kerosene derived from sugarcane bagasse, forest residues and sawmill residues (see Section 4) is assumed to represent low, mid and high cases for the pyrolysis-derived kerosene shown in these tables. The highest and lowest values in all the tables have been underlined. Accordingly, emissions from an FSJF fuel made with camelina-derived maximized-jet

HEFA fuel vary between 29.3 and 47.8 gCO2e/MJ, which corresponds to GHG savings of 45.3-66.5% compared to conventional jet fuel. An FSJF with tallow-derived maximized-jet HEFA fuel, on the other hand, results in 25.9-38.4 gCO2e/MJ corresponding to 56.1-70.4% GHG savings. Additionally, FSJF made with HEFA fuels from a maximized *distillate* fuel production provides up to 8% emissions reduction compared to maximized jet fuel production.

Table 45. Life cycle GHG emissions (gCO$_2$e/MJ) associated with fully-synthetic jet fuel production from **tallow-derived maximized-jet** HEFA jet fuel and pyrolysis-derived kerosene based on % blended volume of pyrolysis-derived kerosene and the emission cases described in the text. Minimum and maximum values are underlined. All values qualify under RFS2.

		% Blended Volume	**Tallow-Derived HEFA Jet Fuel (max jet)**		
			Low	**Base**	**High**
Pyrolysis-derived Kerosene	**Low (Bagasse)**	10	**25.9**	29.6	36.4
		20	26.0	29.3	35.2
		30	26.2	29.0	34.2
	Mid (Forest res.)	10	27.0	30.8	37.5
		20	28.3	31.6	37.5
		30	29.6	32.4	37.6
	High (sawmill res.)	10	27.3	31.0	37.8
		20	28.9	32.2	38.1
		30	30.4	33.3	**38.4**

Table 46. Life cycle GHG emissions (gCO_2e/MJ) associated with fully-synthetic jet fuel production from **tallow-derived maximized-distillate** HEFA jet fuel and pyrolysis-derived kerosene based on % blended volume of pyrolysis-derived kerosene and the emission cases described in the text. Minimum and maximum values are underlined. All values qualify under RFS2.

		% Blended Volume	**Tallow-Derived HEFA Jet Fuel (max distillate)**		
			Low	**Base**	**High**
Pyrolysis-derived Kerosene	**Low** (Bagasse)	10	**21.8**	25.6	32.5
		20	22.4	25.8	31.9
		30	23.1	26.0	31.2
	Mid (Forest res.)	10	22.9	26.7	33.7
		20	24.7	28.1	34.2
		30	26.5	29.4	34.6
	High (sawmill res.)	10	23.2	27.0	34.0
		20	25.3	28.6	34.7
		30	27.3	30.2	**35.5**

As shown in Table 43, only one case out of nine cases for the high emission scenario of camelina-derived HEFA jet fuel results in blending carbon footprints that is lower than the threshold defined for RFS2's advanced biofuel category assuming the conventional jet fuel reference to be 87.5 gCO_2e/MJ. The underlying camelina-derived fuel LCA of Table 43 is carried out using an upstream market-based allocation based on Dec. 2012 soybean oil and meal prices, as outlined in Section 2.1. Table 47 shows how the blending carbon footprints change when different upstream allocation methods are employed for the high emission scenario of camelina-derived maximized-jet HEFA jet fuel. These allocation methods include mass- and energy-based, both of which result in lower emissions than the default market-based (as shown in Section 2.2). Application of these allocation methods results in blending emissions that meet the relevant RFS2 threshold. Even when an extreme value for market-based allocation is used among oil and meal that results in the lowest allocation factor for oil based on the last

5-year price data (see Figure 1 and Table 10 for the definition of Market (MIN) in Table 47), three out of nine cases meet the RFS2 threshold.

Table 47. Life cycle GHG emissions (gCO_2e/MJ) from **high emission scenario** of **camelina-derived maximized-jet** HEFA jet fuel with different upstream allocation methods (see Figure 1 and Table 10 for the definition of Market (MIN)). Values that are <50% GHG emissions reduction compared to the conventional jet fuel baseline are highlighted in grey.

		% Blended Volume	Camelina-Derived HEFA Jet Fuel – HIGH CASE		
			Upstream Allocation		
			Mass	Energy	Market (MIN)
Pyrolysis-derived Kerosene	Low (Bagasse)	10	37.3	41.2	44.4
		20	36.0	39.5	42.3
		30	34.8	37.8	40.3
	Mid (Forest res.)	10	38.4	42.4	45.6
		20	38.3	41.8	44.6
		30	38.2	41.2	43.7
	High (sawmill res.)	10	38.7	42.7	45.9
		20	38.9	42.4	45.2
		30	39.1	42.1	44.5

Even though we have investigated how the variability in the HEFA jet fuel production affects the overall emissions from an FSJF, all the scenarios that are deemed realistic and highly likely here result in emissions that qualify under RFS2. We note that EPA in its rulemaking also takes into account variability and uncertainty and reports emission results as a range, and that not all values that fall in the EPA range necessarily provide GHG benefits that meet or exceed the threshold. EPA determines RFS2 qualification based on the mean values of their analyses, which is analogous to our base/optimal cases.

REFERENCES

1. Stratton, RW et al. *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels*, Partnership for Air Transportation Noise and Emissions Reduction Project 28 (2010).
2. Shonnard, DR et al., Camelina-derived jet fuel and diesel: Sustainable advanced biofuels, *Environmental Progress & Sustainable Energy*, 29(3), 382 (2010).
3. Shonnard, DR and Koers K, *Life Cycle Assessment of Camelina-Derived Transportation Fuels: Comparion of Biodiesel, Green Diesel and Green Jet*, Sustainable Technologies Laboratory, Michigan Technology University (2009).
4. Pearlson, MN, *A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels*, Massachusetts Institute of Technology (2011).
5. Environmental Protection Agency, *Regulation of Fuels and Fuel Additives: Identification of Additional Qualifying Renewable Fuel Pathways Under the Renewable Fuel Standard Program*, EPA-HQ-OAR-2011-0542, (2012), and supplemental Microsoft Excel files: https://federalregister.gov/a/2011-31580.
6. US Department of Energy, U.S. Billion Ton- Update, Biomass Supply for a Bioenergy and Bioproducts Industry (2011).
7. Spath, PL and Mann, MK, *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming*, NREL/TP-570-27637 (2001).
8. Environmental Protection Agency, *Regulation of Fuels and Fuel Additives: Identification of Additional Qualifying Renewable Fuel Pathways Under the Renewable Fuel Standard Program*, EPA-HQ-OAR-2011-0542, (2013), http://www.gpo.gov/fdsys/pkg/FR-2013-03-05/pdf/2013-04929.pdf.
9. Hess, B, et al., *Evaluation of Camelina Sativa as an Alternative Seed Crop and Feedstock for Biofuel and Developing Replacement Heifers*, SARE Report No. SW07-049 (2011).
10. Haas, MJ, *Animal Fats, In: Shahidi, F. (editor), Bailey's Industrial Oil and Fat Products*, John Wiley & Sons, Inc. (2005).
11. Meeker, DL, *Essential Rendering, All About the Animal By-Products Industry*, National Renderers' Association, Alexandria, Virginia (2006).
12. Index Mundi, *Historical Commodity Prices*, http://www.indexmundi.com (last accessed May 2013).
13. Nikolova, M, et al., *Nutrient Consumption of Some Non-traditional Energy Crops*, http://www.ipipotash.org/udocs/Nutrient_consumption_of_some_non-traditional_energy_crops_paper.pdf
14. National Council for Air and Stream Improvement, Inc. (NCASI), *Calculation Tools for Estimating Greenhouse Gas Emissions from Wood Product Facilities* (2005).
15. Shafer, LM, et al., *Chemical Class Composition of Commercial Jet Fuels and Other Specialty Kerosene Fuels*, 14th AIAA/AHI Space Planes and Hypersonic Systems and Technologies Conference, AIAA Paper Number 2006-7972 (2006).
16. Lopez, DE, et al.. "Energy Life Cycle Assessment for the Production of Biodiesel from Rendered Lipids in the United States," *Ind. Eng. Chem. Res.* 49, 2419-2432 (2010).
17. Niederl, A and Narodoslawsky, M, *Ecological Evaluation of Processes Based on By-Products or Waste from Agriculture: Life Cycle Assessment of Biodiesel from Tallow and Used Vegetable Oil. In: Bozell J, editor. Feedstocks for the Future*, American Chemical Society, Washington DC, 239-252 (2006).
18. California Environmental Protection Agency Air Resources Board, *Detailed California- Modified GREET Pathway for Renewable Diesel Produced in California from Tallow (U.S. Sourced), Version 1.0* (2009).

19. PRé consultants, *SimaPro 7.3.3 LCA Software* (2013): http://www.pre-sustainability.com/simapro-lca-software.
20. Environmental Protection Agency, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, EPA-HQ-OAR-2009-0491-4406 (February 2010).
21. Environmental Protection Agency, *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program*, EPA–HQ–OAR–2005–0161 (March 2010).

Annex 1: Additional Information on feedstock downselection process for the HEFA component of the fully synthetic jet fuel investigated in this study

We carried out a sustainability assessment for 23 feedstocks that are technically feasible for HEFA jet fuel production. We used a broad set of metrics to capture sustainability from environmental, economic and societal perspectives. We grouped the feedstocks into categories for each metric. Our downselection process is driven by the aim of selecting one sample feedstock that has overall beneficial properties in terms of sustainability, and at the same time, is well researched as a feedstock for fuel production and is readily available today, or in the very near future.

The fully-synthetic jet fuel to be analyzed in the overall project with regard to its life cycle GHG emissions was agreed to be derived from one feedstock from the HEFA side and one feedstock from the aromatics side (which was predetermined in the SOW as sawmill residues). Therefore, we had to downselect the HEFA feedstocks to just one remaining choice. The choice we made in agreement with the sponsor does not represent the "best" choice and does not imply that other choices would be worse: The choice represents one sample feedstock which has beneficial properties as defined above, but other feedstocks could be feasible solutions, as well.

In order to help with the downselection process, we defined threshold values that would lead to a feedstock being eliminated in case it did not meet the threshold criterion. Each feedstock was eliminated if it had at least one of the following characteristics (characteristics shown in random order):

- very low yield
- high land use change potential
- competition with food
- pathway ruled out by EPA for RFS2 eligibility
- very low current production (indicates low level of 'feedstock readiness')
- very high production cost
- low level of data availability and information

Again, it should be noted that the feedstocks that were eliminated in the downselection of phase I process might still be feasible for jet fuel production. Moreover, our assessment was based on a short-run perspective, and some of the obstacles for using a certain feedstock for HEFA fuel production can, potentially, be overcome over time (e.g. very low production volume, very high production costs).

Using these threshold values we obtained the following shortlist:

- Rapeseed
- Canola
- Camelina
- Jatropha
- Castor Oil plant

All of these feedstocks would be well suited to be used as the HEFA feedstock within our study. In agreement with the sponsor, we chose camelina as our sample feedstock. Camelina has shown a high potential to significantly reduce GHG emissions in comparison to conventional jet fuel. While current camelina production is low, the amount of land used for growing camelina could be increased dramatically in the next years. Data obtained through a research effort within MIT's PARTNER program shows that virtually all cropland in the US is generally suited for growing camelina (160 million ha out of 165 million ha) and the same applies to Europe.

In Phase 2 of the project we chose tallow as a feedstock for HEFA fuel production. Tallow is a particular interesting feedstock because it does not induce adverse changes in land-use. This is because cattle is raised for meat production purposes and not for producing tallow. Tallow did not make the shortlist in Phase 1 because it is limited in availability by the number of cattle being raised. This reduces its suitability for large-scale biofuel production. However, a survey by the U.S. Census Bureau shows that the total production of tallow in the United States in 2010 reached around 2.3 billion kilograms [A12]. This could yield up to 1.5 billion liters of HEFA jet fuel, 0.7 billion liters of HEFA diesel and 0.2 billion liters of naphtha per year if the product slate is optimized for maximum jet fuel production. This would account for approx. 40% of the FAA goal of using 3.9 billion liters (1 billion gallons) of alternative jet fuel annually by 2018 in the US.

Annex 2: Uncertainty related to impact on indirect land use change on life cycle greenhouse gas emissions of the most common biofuels

Note: *This annex is a brief informational snapshot on the current knowledge and uncertainty on indirect land use change issues for the most common biofuels, as agreed in the Statement of Work for Phase I of the project. For a detailed discussion of the issues involved and in- depth overview on the available literature, we refer to the references.*

Numerous studies have shown that potential reductions in GHG emissions from substituting fossil fuels with fuels from renewable sources are highly dependent on the resulting changes in emissions from land use (see below). There are two types of land use changes [A1;A2]: Direct land use change occurs when biomass is grown with the purpose of being converted into fuel on land that was formerly used for other purposes. Indirect land use change (ILUC) occurs when this displacement induces changes in market prices (from one crop to another, one region to another, one land value to another), which leads to land not directly used for biofuels to be used differently than before. For example, if US farmers are starting to grow corn for corn ethanol instead of growing soy, this would constitute a direct land use change. As soy production in the US decreases, soy prices increase and this might induce foreign farmers (e.g. in Brazil) to increase acreage and soy production by expanding into pastures. As a consequence, cattle ranchers are displaced and might move to the Amazon, clearing forests in order to create pasture land. This would release CO_2 sequestered in the biomass into the atmosphere and would be regarded as to be indirectly caused by increased corn to ethanol production in the US.

Whereas changes in emissions due to direct land use changes are well understood and an academic consensus has been reached on the fundamentals of measurement, the level of uncertainty with indirect effects is still very high. The uncertainty stems from the fact that different models used for calculating the emissions demonstrate highly different results and that the ranges derived with a consistent methodology within these studies are extraordinarily wide (see studies discussed below). As indicated above, ILUC is brought about by market forces, which, in turn, are a consequence of complex human responses that are difficult to measure and predict. As a consequence, virtually all life cycle studies on renewable fuels take into account emissions from direct land use change, whereas indirect emissions are often omitted.

Ethanol and fatty acid methyl ester (FAME or biodiesel) currently dominate worldwide renewable fuel production.[A11] Ethanol from primarily corn, and to smaller extent, sugarcane is the main renewable fuel in the US. In Europe, biodiesel from rapeseed oil and, to some extent, from soybean oil dominates the market in Europe, although ethanol use in the EU has also increased substantially in the last couple of years. In consequence, studies on land use change generally focus on the biomass feedstocks producing these first generation renewable fuels.

For the US, most research on the importance of indirect land use changes as a result of biomass cultivation has, so far, focused on corn ethanol [A2-A8]. Recent studies by Wang et al.[A2] and Plevin et al.[A3] compare the results on the magnitude of emissions due to indirect land use change and find that 1) there is strong evidence that emissions from indirect land use change due to corn cultivation increase life-cycle GHG emissions for corn ethanol; and 2) that the level of uncertainty of the magnitude of emissions is extremely high. For example, Schlesinger et al.[A4] estimate an ILUC emission factor of 104 gCO_2e/MJ for corn ethanol, which would more than offset the carbon credit of the fuel due to the CO_2 uptake during corn growth. Contrary to this, Wang et al.[A2] argue that even when taking into account indirect land use change emissions, corn ethanol produced in the US would still reduce GHG life-cycle emissions by more than 20% compared to conventional jet fuel from crude. Table A1 shows reported ILUC emission factors from various studies.

Table A1. Point and range estimates of GHG impact of indirect land use change induced by corn ethanol production

Study	Target year	ILUC factor (gCO_2e/MJ)	Impact range (gCO_2e/MJ)
Searchinger et al. 2008	2016	104	20-200
Dumortier et al. 2009	2018/2019	n/a	21-118
Hertel et al. 2010	2001	27	15-90
US EPA 2010	2022	34	25-45
Al Riffai et al. 2010	2020	36	36-53
Plevin et al. 2010	n/a	n/a	21-142
Laborde 2011	2020	10	6-13

Note: Wang et al. report LUC on an aggregated basis, no separate ILUC emissions factor is presented. Hence, this study is not present in this table.

The same conclusions can be drawn from studies dealing with indirect land use changes due to biodiesel production in Europe. For example, a recent report by Laborde[A10] estimates an emission factor from land use change (direct and indirect) of 54 gCO_2e/MJ for biodiesel for the year 2020, leading to slightly higher total lifecycle GHG emissions of biodiesel compared to conventional diesel. However, the level of uncertainty is, again, very high as the 95% confidence interval ranges from 29 to 81 gCO_2e/MJ. Other studies have come to similar conclusions.[A9]

Non-first-generation biofuels have received much less scholarly attention, so far. However, studies which deal with fuel from biomass that does not compete with food or feed perform better than first generation fuels in terms of ILUC emissions.[A2,A11] The main reason for the lower ILUC impact is that a lower level of competition with existing agricultural markets reduces changes in market prices, and therefore, induces smaller changes in supply and demand of existing markets. Wang et al.[A2] find that cellulosic ethanol, for example, from corn stover, forest residues and switchgrass bears the potential to reduce GHG emissions by more than 70% compared to conventional crude even when ILUC changes are taken account for. These results are supported by Havlik et al.[A11] for a second generation biofuel from woody biomass.

ANNEX REFERENCES

A1. Gawel, E.; Ludwig, G.; The iLUC dilemma: How to deal with indirect land use changes when governing energy crops? Land Use Policy, 28 (2008).

A2. Wang,M.; Han, J.; Haq, Z.; Tyner, W.; Wu, M.;Elgowainy, A., Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes, *Biomass and Bioenergy*, 2001, 35 (2011).

A3. Plevin, R.; O'Hare, M; Jones, A.; Torn, M.; Gibbs, H. Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated; Environmental Science & Technology, 44(21) (2010).

A4. Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H., Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. *Science*, 319(5867) (2010).

A5. Dumortier, J.; Hayes, D. J.; Carriquiry, M.; Dong, F.; Du, X.; Elobeid, A.; Fabiosa, J. F.; Tokgoz, S., Sensitivity of Carbon Emission Estimates from Indirect Land-Use Change. In Center for Agricultural and Rural Development, Iowa State University: Ames, Iowa (2009).

A6. Hertel, T. W.; Golub, A.; Jones, A. D.; O'Hare, M.; Plevin, R. J.; Kammen, D. M., Global Land Use and Greenhouse Gas Emissions Impacts of U.S. Maize Ethanol: Estimating Market-Mediated Responses. *BioScience,* 60 (3) (2010).

A7. USEPA *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*; US Environmental Protection Agency: Washington, DC, Feb 3, 2010.

A8. Harris, N.; Grimland, S.; Brown, S. *GHG Emission Factors for Different Land-Use Transitions in Selected Countries of the World. Report submitted to US EPA*; Winrock International: Oct (2008).

A9. Al-Riffai, P.; Dimaranan, B.; Laborde, D. *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*; IFPRI (2010).

A10. Laporde, D. Assessing the Land Use Change Consequences of European Biofuel Policies, Final report of the ATLASS consortium for the European Commission, October (2011).

A11. Havlik, P.; Schneider, U.; Schmid, E. ;Böttcher, H. Fritz, S.; Skalsky, R.; Aoki, K.; DeCara, S.; Kindermann, G.; Kraxner, F; Leduc, S.; McCallum, I., Mosnier, A.; Sauer, T.; Obersteiner. M, Global land-use implications of first and second generation biofuel targets, *Energy Policy*, 39 (2011).

A12. U.S. Census Bureau. Current Industrial Report (CIR) M311K; June 2011.

Appendix 2. Aromatic Down-Selection Process

(2 pages)

	HEFA	REASON FOR ELIMINATION	CURRENT LAND DEVOTED TO BIOMASS[1]	BIOMASS YIELD[2]	5 YEAR AVERAGE ($/METRIC TONNE)[3]	2 YEAR AVERAGE ($/METRIC TONNE)[3]	PRICE FLUCTUATION	FARMING INTENSITY[4]	LUC POTENTIAL[5]	LIFECYCLE/ ROTATION	EXTRACTED HYDROCARBON DISTRIBUTION				ASH CONTENT	NITROGEN CONTENT	ENERGY/DENSITY (Btu/lb)	RISK POTENTIAL[8]	CURRENT REGULATORY STATUS[9]	COMPETITION WITH FOOD[10]	DATA AVAILABILITY AND QUALITY[11]
Oil-extracted biomass				*Oil/Hydrocarbon*	*oils*	*oils*						C8-	C8-C16	C16+							
1	~~Soybean~~	yield/food competition	highest	Very low	1,044	1,148	med	High	Moderate	A		0	11	89				Low	EPA/FB	Yes	High
2	~~Corn~~	yield/food competition	highest	Very low	1,077	1,184	high	High	Moderate	A		0	11	89				Low	EPA/FB	Yes	High
3	Rapeseed (Not Canola)	(LC GHG emissions)	very high	Low	1,084	1,276	med	High	Moderate	A		0	3	97				Medium	EPA/FB	No	High
4	Canola	(LC GHG emissions)	high	Low	992	1,005	med	High	Moderate	A		0	4	96				Medium	EPA/FB	No	High
5	~~Palm~~	luc/regulation	very high	High	870	1,000	high	High	High	P	Palm oil	0	46	54				High	~~EPA~~	No	High
											Palm kernel oil	0	79	20							
6	~~Algae~~	costs	very low	Very high	estimation 5,000	estimation 5,000	N/A	Moderate	Low	<A								Depends	EPA/~~BCAP~~	No	Moderate
											Bacillariophyta	0	74-79	21-26							
											Eustigmatophyta	0	54	46							
											Chlorophyta	0	10-72	28-90							
											Haptophyta	0	42	58							
											Pinguiophyceae	0	28	72							
											Cyanophyta	0	52-93	7-48							
											Cryptophyta	0	31-42	58-69							
											Dinophyta	0	14-34	66-86							
7	~~Coconut~~	luc/food competition	very high	Moderate	1,100	1,340	med	High	High	P		1	87	11				Low	N/M	Yes	High
8	Sunflower	fod competition	very high	Low	1,050	1,125	high	High	Moderate	A		0	7	93				High	FB	Yes	High
9	Camelina		low	Low	N/A	N/A	N/A	Moderate	Low	R		0	6	90				High	EPA/BCAP	No	High
10	~~Pennycress~~	current production	very low	Low	N/A	N/A	N/A	Moderate	Moderate	R		0	3	95				High	N/M	No	Medium
11	Jatropha	(production potential US/toxicity)	moderate	Low	static indian market 140*	static indian market 140*	N/A	Moderate	Moderate	P		0	13	87				High	N/M	No	High
12	~~Salicornia~~	current production	very low	Low	N/A	N/A	N/A	Moderate	Low	A		0	8	91				Medium	N/M	No	High
13	Castor oil plant	(production potential/toxicity)	high	Moderate	1,412	1,819	med	Moderate	Moderate	P		0	2	98				High	N/M	No	Medium
14	~~Ethiophian mustard (Brassica Carinata)~~	current production/data	very low	Moderate	N/A	N/A	N/A	Moderate	Moderate	A		0	5	95				Low	N/M	No	Low
15	~~Cuphea~~	yield/current production	very low	Very low	N/A	N/A	N/A	Moderate	Moderate	P/A		1	93	6				Medium	N/M	No	Medium
16	~~Copaiba~~	yield/current production	very low	Very low	N/A	N/A	N/A	Moderate	High	P		0	13	87				Medium	N/M	No	Medium
17	~~Pongamia pinnata (Milletia pinnata)~~	current production	very low	Moderate	static indian market 80*	static indian market 80*	N/A	Moderate	Moderate	P		0	11	81				High	N/M	No	Medium
18	~~Jojoba~~	costs	low	Moderate	static indian market 2500*	static indian market 2,500*	N/A	Moderate	Low	P		0	4	97				Low	N/M	No	Medium
19	~~Petroleum Nut (Pittosporum resiniferum)~~	current prodcution/data	very low	Low	N/A	N/A	N/A	Moderate	High	P		90	13	0				Medium	N/M	No	Low
20	~~Paradise Tree (Simarouba glauca)~~	current production/data	very low	Low	static indian market 400*	static indian market 400*	N/A	Moderate	Moderate	P		0	12	88				Low	N/M	No	Low
21	~~Nahor (Mesua ferrea)~~	yield/current prodcution/data	very low	Very low	N/A	N/A	N/A	Moderate	High	P		0	17	83				Low	N/M	No	Low
22	~~Lesquerella (Lesquerella fendleri)~~	yield/current production/data	very low	Very low	N/A	N/A	N/A	Moderate	Low	P/A		0	2	98				Low	N/M	No	Low
23	~~Indian Mustard (Brassica juncea)~~	yield/costs	low	Very low	static indian market 2690*	static indian market 2,690*	N/A	Moderate	Moderate	P/A		0	6	94				Medium	N/M	No	Medium
Other:	*Fats/Waste Oils*																				
24	Edible tallow			High								0	33	67					Low	Yes	Low
25	Inedible tallow			High								0	29	71					N/M	No	Low
26	Used cooking oil			Low								0	14.5	85.5					N/M	No	Low
27	Tall oil			N/A								0	5.4	94.6					~~BCAP~~	No	Medium
AROMATICS (PYROLYSIS)				*Lignocellulosic*																	
Agricultural residues																					
1	*Sugarcane*							High	Moderate	A								Medium	EPA		
2	Sugarcane bagasse			Moderate											5%	0.16%	8211		EPA	No	High
3	*Corn*							High	Moderate	A								Low	FB		
4	Corn stover			Low											11.63%	0.67%	7867		EPA/BCAP	No	High
5	*Wheat*							High	Moderate	A								Low	FB		
6	Straw			Low											10.22%	0.63%	7481		BCAP	No	High
7	*Palm*			High				High	High	P								High	~~BCAP~~		
8	Empty fruit bunches (EFB)			Low											3.10%	0.35%			BCAP	No	Low
9	Kernels			Low															BCAP	No	Low
10	Shells			Low											4.44%	0.41%	8770		BCAP	No	Low
11	Fronds			High											4.15%	0.7	6702		BCAP	No	Low
12	Switchgrass			Moderate				Moderate	Low	P					5.49%	0.77%	8040	High	EPA/BCAP	No	High
13	Guinea Grass			High				Moderate	High						12.50%	1.50%		High	N/M	No	Low
14	Miscanthus			High				Moderate	Low	P					4%	0.2-0.67%	7863	Low	EPA/BCAP	No	High
15	Sorghum			Low				Moderate	Moderate	A					4.85%		7298	Medium	FB	Yes	High
Aquatic biomass																					
16	Algae			High				Moderate	Low	<A					2-26%	3-9%	6460	Depends	~~BCAP~~	No	Medium
Forestry-related																					
17	Sawmill residues			Low											1%		8500		~~BCAP~~	No	Low
18	Forest slash			Low												0.50%			EPA/BCAP	No	Low
19	Pulp & paper plant residues			N/A															~~BCAP~~	No	Low
20	Short rotation forestry (Poplar, willow, albizia, eucalyptus)																		BCAP		
	Poplar			Moderate				Moderate	Low	P					1.12%	0.26%	8429	Low		No	High
	Eucalyptus			Moderate				Moderate	Moderate	P					0.88%	0.20%	8415	High		No	High
21	Collected cardboard/paper			High													mixed paper 6477		~~BCAP~~	No	
Wastes																					
22	Collected yard wastes			Moderate											8%		3000-4500		EPA/~~BCAP~~	No	Low
23	Poultry litter			Moderate											16%	5%	4600		~~BCAP~~	No	Medium
24	Concentrated animal feeding operation (CAFO) wastes			Moderate											3-10%	0.4-0.65%	7500-8300		EPA/~~BCAP~~	No	Low

HEFA	REASON FOR ELIMINATION	CURRENT LAND DEVOTED TO BIOMASS[1]	BIOMASS YIELD[2]	5 YEAR AVERAGE ($/METRIC TONNE)[3]	2 YEAR AVERAGE ($/METRIC TONNE)[3]	PRICE FLUCTUATION	FARMING INTENSITY[4]	LUC POTENTIAL[5]	LIFECYCLE/ ROTATION	EXTRACTED HYDROCARBON DISTRIBUTION	ASH CONTENT	NITROGEN CONTENT	ENERGY/DENSITY (Btu/lb)	RISK POTENTIAL[8]	CURRENT REGULATORY STATUS[9]	COMPETITION WITH FOOD[10]	DATA AVAILABILITY AND QUALITY[11]
Oil-extracted biomass			*Oil/Hydrocarbon*	*oils*	*oils*					C8- C8-C16 C16+							
		1	2	3			4	5	6	7				8	9	10	11
		highest 100,000,000+ Very high 10,000,000-100,000,000 High 1,000,000-10,000,000 Moderate 50,000-1,000,000 Low 500 - 50,000 Very low 0 - 500	Very high 20,000+ High 3,000 - 20,000 Moderate 1,500 - 3,000 Low 500 - 1,500 Very low 0 - 500 kg/ha-yr High 1b+ Moderate 0.1b - 1b Low 0 - 0.1b kg/yr High 20,000+ Moderate 5,000 - 20,000 Low 0 - 5,000 kg/ha-yr High 1.5b+ Moderate 1.5b - 15b Low 0 - 1.5b kg/yr N/A 0	* N/A	price for seeeds price data not available		Based on irrigation and fertilizer use	Based on potential to grow on different types of land (positive) or being constrained to tropical areas	A Annual <A Less than a year P Perennial R Rotational For HEFA: Perennial is advantageous because the plant, once mature, will keep providing hydrocarbons or oil containing seeds/grains/ fruits. This will minimize the amount of resources that need to go into growing the biomass. Rotation is also advantageous for the refreshment of the soil. The crops that are rotated can cycle nutrient in the soil. For pyrolysis: If the crop is to be harvested completely (e.g. sugarcane, corn or wheat), it is advantageous if it is an annual crop. The quicker it grows, the more lignocellulosic feedstock it can provide. This also applies to algae. However, if the crop is to be cut and let to re-grow (e.g. grasses), then perennials should be preferred. This also applies to palm since in this study we are not considering utilizing the whole palm tree.	The hydrocarbon and fatty acid content of the feedstocks have been grouped into 3 categories based on their chain lengths: "C8-", "C8-C16" and "C16+" indicate gasoline, jet fuel and diesel fuel ranges, respectively. (Diesel fuel range can be extended into jet fuel range.) Our primary purpose is to produce jet fuel. Hence, feedstocks with higher share in the jet fuel range could be ideal for such production. When there were large variations in the compositions due to different varieties of species, US-native varieties were reported. When there are different compositions reported in the literature a certain species, the ones with the highest C8-C16 composition were provided. Algae represents a very large group of species that can vary dramatically in oil composition. To reflect this, various algal groups have been indicated.				Most of the comparison under this metric was based on Australian Weed Risk Assessment studies. When such a study is not available, reasoning is done taking into account whether a species is considered to be invasive and/or toxic.	EPA RFS2 FB Farm Bill BCAP Biomass Crop Assistance Program eligible ~~BCAP~~ ~~EPA~~ ruled to be non EPA conform N/M Not mentioned under EPA, FB or BCAP “EPA” signifies that the feedstock has a US-EPA approved biofuel pathway. After evaluation, the feedstock has been deemed to meet the reduction thresholds as stated in RFS2. RIN generation can also occur from using this feedstock to produce biofuel. Biomass Crop Assistance Program supports the establishment and production of eligible crops for conversion to bioenergy and assists producers with the collection, harvest, storage, and transportation of biomass. BCAP eligible materials are indicated by “BCAP” and have been deemed to be feedstock that are (1) byproducts of preventive treatments, (2) would not otherwise be used for higher value products; and (3) are harvested in accordance with applicable law and land management plans. Harvested grains, fiber, or other commodities eligible to receive payments under Title I of the 2008 Farm Bill are excluded from BCAP Title 1 offers payments per bushel produced to farmers. The phrase “FB” signifies any crop that receives such payments. Other materials ruled to be ineligible are signified by “BCAP”, and include animal waste and animal waste-byproducts, food waste and yard waste, and algae. In addition, some materials violate condition (1), (2) or (3) and receive the ineligible “BCAP” valuation as a result. Sawmill residue, which can serve a higher value market, is an example of this.	This metric considers whether a seed/grain/fruit is used as food, not the oil extracted.	The comparison is done based on the experience during literature search and the number of hits obtained from databases.

Appendix 2. Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development Program Test Report to Determine the Effects of Alternative Fuel Blends on 131-9 APU Combustion System Performance and Emissions Public Version (Honeywell Document 21-15836-1)

(46 pages)

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Honeywell

CAGE 99193

CONTINUOUS LOWER ENERGY, EMISSIONS AND NOISE (CLEEN) TECHNOLOGIES DEVELOPMENT PROGRAM

TEST REPORT TO DETERMINE THE EFFECTS OF ALTERNATIVE FUEL BLENDS ON 131-9 APU COMBUSTION SYSTEM PERFORMANCE AND EMISSIONS

PUBLIC VERSION

CONTRACT FA8650-09-D-2925-0007

21-15836-1
March 23, 2016

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REFERENCES

21-15370	Test Instructions: 131-9 Combustor Rig Test With Emerging Alternative Fuels, Honeywell Document
ASTM D1655	Standard Specification for Aviation Turbine Fuels
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

ACRONYM LIST

CO	Carbon Monoxide
DET	Deteriorated (simulated APU health)
DP/P	Combustor Pressure Drop
ECS	Environmental Control System (APU operating mode)
FAA	Federal Aviation Administration
ft	foot
GD	Green Diesel
Hz	Hertz
kg	Kilogram
L	Liter
LHV	Lower Heating Value
MES	Main Engine Start (APU operating mode)
Min	Minimum
MJ	Mega Joules
mm	millimeter
Mn	Mach Number (simulated aircraft condition)
NOx	Oxides of Nitrogen
P/N	Part Number
SAE	Society of Automotive Engineers
TC	Thermocouple
UHC	Unburned Hydrocarbons

1.0 INTRODUCTION AND TEST SUMMARY

This report, prepared by Honeywell Aerospace, Phoenix, Arizona (AZ), hereinafter referred to as Honeywell, contains the test report for a combustor rig test evaluating alternative fuels. This combustor rig test is part of the Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development Program, Federal Aviation Administration (FAA) Agreement No. DTFAWA-10-C-00040. This test report will be submitted to the FAA for review in accordance with contract data requirements.

This report documents the test results from full annular combustor rig testing with a 131-9[B] Auxiliary Power Unit (APU) combustion system. The 131-9 APU combustor is a reverse-flow combustor design with effusion cooled liner walls and dual-orifice fuel atomizers. The purpose of this combustor rig test was to evaluate the impact of low blend ratios of biologically derived Green Diesel (GD) fuels on combustion system performance characteristics.

The testing summarized in this document took place in the combustion test cell C-100 at the Honeywell facility in Phoenix AZ. Testing was conducted on full scale hardware at actual APU operating conditions. The test report describes the test setup and the test procedures that were utilized to ensure a safe and successful test, and results of the testing.

1.1 General Information

Figure 1 shows a photograph of the combustor rig installed in the C-100 test cell. The rig is operated at full-scale 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.

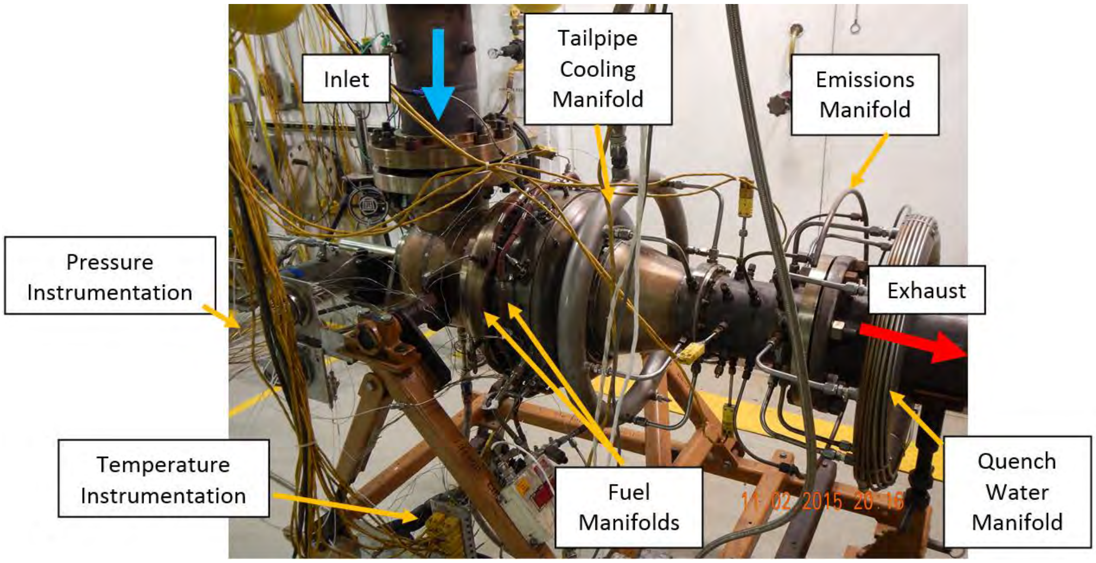


Figure 1. Combustor Rig Installed on Cold/Vacuum Line in C-100 Test Cell.

1.2 Combustion System Hardware

The 131-9 combustor rig was used for combustion system performance tests since it provides the most severe conditions for ignition and lean stability testing. The 131-9[B] rig operates up to 41,000 feet altitude, which provides a “worst case” for both lean stability (lean blowout) tests and cold and altitude ignition tests due to the low combustor airflows and pressures. The 131-9 combustion system is representative of all Honeywell APU combustion systems due to the common combustion system design (reverse-flow annular), similar primary zone stoichiometry, and similar fuel injection systems (radially installed pressure-type fuel atomizers that spray tangentially). The 131-9[B] APU is used in the Boeing 737-600/700/800/900 commercial aircraft, and the C-40A and P-8A military transport aircraft.

The aero hardware that was utilized for this testing included the deswirl, combustor, containment ring, and the combustor case.

1.3 Fuel System

The 131-9[B] production fuel system, which consists of the fuel flow-divider and ten dual-orifice fuel atomizers, was used for this rig test. Fuel atomizers were flow tested prior to rig testing and after the test was completed.

1.4 Test Objectives

The overall goal of this combustor rig test was to evaluate the combustion system performance, specifically pattern factor and radial profile, when using 5 percent Green Diesel fuel blended with Jet A. During a previous alternative fuel effort, instrumentation sealant blocked air flow pathways and resulted in an excessive pattern factor when using GD blends. Two GD fuels supplied from different manufacturers were blended with Jet A for this evaluation; Diamond GD produced by Valero and Navy F-76 GD produced by Solazyme. The GD fuels were blended with petroleum-derived Jet A fuel to produce a 5 percent Diamond GD blend and a 5 percent F-76 GD blend. The two 5 percent GD blends were expected to perform similarly to a Jet A baseline. The combustion system performance and emissions results were expected to fall within typical experimental variation and were not expected to be statistically significant.

2.0 TEST PROCEDURE

Details of the combustor rig hardware, instrumentation, data acquisition, test conditions and test procedures are provided in the rig test plan. Performance and exhaust emission tests were completed per the test plan.

3.0 HARDWARE AND RIG INSPECTIONS

3.1 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.

3.2 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.

3.3 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.

3.4 Data Acquisition

Digital data acquisition recorded all measured parameters. Temperature and pressure traverses of the combustor exit gaspath were performed with a rotating drum consisting of a pressure rake and a temperature rake to cover the entire exit annulus. The “fast scan” method was employed for all cases using a forward traverse, with a traverse rate of one degree per second, recording at a frequency of 2 Hz.

3.5 Test Fuels

The test fuels consisted of the following:

- ASTM D1655 Jet A (baseline)
- Blend of 5 percent Diamond Green Diesel and 95 percent Jet A
- Blend of 5 percent Navy F-76 Green Diesel and 95 percent Jet A

The neat Diamond GD fuel was provided by the Boeing Company while the neat Navy F-76 GD fuel was provided by the U.S. Navy. Both neat GD fuels were delivered in 55-gallon drums. The neat GD fuels were blended with Jet A to create a blend of 5 percent Diamond GD and 95 percent Jet A, and a blend of 5 percent F-76 GD and 95 percent Jet A. Honeywell Jet A from Fuel Farm 2 Tank 207 was used as the baseline fuel for comparison to the GD blend results.

Each fuel, the Jet A baseline and the two 5 percent GD blends, was analyzed before and after each test for lower heating value (LHV), specific gravity, and viscosity to ensure the fuel properties were consistent throughout the test and that the fuel system was thoroughly flushed prior to test initiation with the subsequent fuel; those results can be found in Appendix 1.

3.6 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 1 lists various pre-performance test properties of the two test fuels, and Table 2 lists post-performance test properties. Complete fuel analysis results are shown in Appendix 1. Freeze point of the GD blends was just above the specification minimum (-40°C).

Table 1. Pre-Performance Test Fuel Analysis.

Property	Unit	ASTM D1655 Requirements	Jet A Baseline	5% Diamond GD	5% F-76 GD
			CMR 769802	CMR 769926	CMR 769966
Density	kg/L	0.775-0.840	0.808	0.807	0.806
LHV	MJ/kg	42.8 minimum	43.2	43.2	43.1
Viscosity at 25°C	mm^2/s		1.67	1.71	1.71
Viscosity at 40°C	mm^2/s		1.33	1.36	1.36
Viscosity at -20°C	mm^2/s	8.0 maximum	4.49(1)	4.63(1)	4.63(1)
Aromatics	% vol	8.0 – 25.0	16.5	16.5	15.5
Water Content	ppmw		33	54	44
(1) calculated					

Table 2. Post-Performance Test Fuel Analysis.

Property	Unit	ASTM D1655 Requirements	Jet A Baseline	5% Diamond GD	5% F-76 GD
			CMR 769816	CMR 769947	CMR 770079
Density	kg/L	0.775-0.840	0.810	0.806	0.806
LHV	MJ/kg	42.8 minimum	43.1	43.2	43.1
Viscosity at 25°C	mm^2/s		1.68	1.70	1.71
Viscosity at 40°C	mm^2/s		1.34	1.35	1.36
Viscosity at -20°C	mm^2/s	8.0 maximum	4.48(1)	4.64(1)	4.63(1)
Aromatics	% vol	8.0 – 25.0	17.0	16.0	16.5
Freeze Point	°C	-40 maximum	-46	-39	-38
Flash Point	°C	38 minimum	43.3	42.8	43.3
Smoke Point	mm	18 minimum	23.7	24.7	24.7
Water Content	ppmw		53	45	32
(1) calculated					

4.0 TEST RESULTS

4.1 Combustor Pressure Drop (Isotherm)

Combustor Pressure Drop (DP/P) was measured to ensure that the test rig and combustion system were functioning correctly. These measurements were completed with no fuel flow, only air flowing through the combustor. Unusually high or low pressure drops would be evidence of significant aerodynamic blockages or leaks within the combustion system. The rig was subjected to a range of corrected air flow values and the resulting pressure drop from inlet plenum to the combustor exit was recorded.

Pressure drop results are plotted below in Figure 2. The pressure drop is plotted against the square of corrected airflow $[(W\sqrt{\theta})/\delta]^2$ to give a straight line through the origin.

The slopes of the trend lines are related to the through-flow area ("air effective area") of the combustor. For the current test series, the combustion system was analyzed for the combustor pressure drop before each fuel was tested in order to ensure the combustion system was performing equally prior to each test. Little difference exists between the two measurements and is well within the bounds of variation experienced in historical 131-9[B] combustor rig tests.

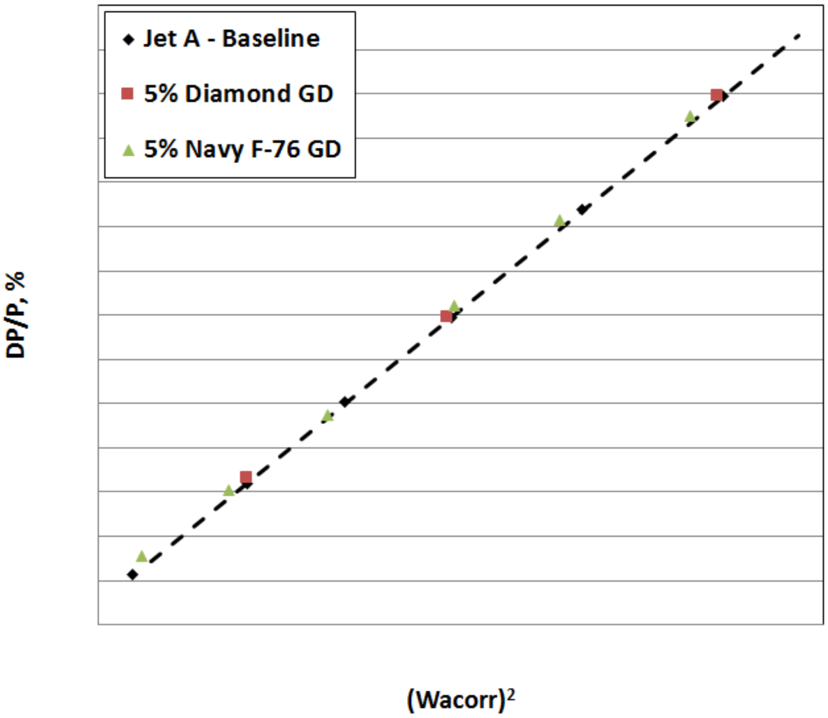


Figure 2. Isothermal Combustor Pressure Drop.

4.2 Combustor Exit Temperature Pattern Tests

The impact of the two GD fuel blends on combustor performance was evaluated at several different engine operating conditions. During these tests, the rotating instrumentation rake was rotated 360 degrees over the course of several minutes. During each scan, test technicians maintain the values of all the inlet parameters so as to keep constant test conditions throughout the scan.

Test condition set points were identical between the baseline Jet A and the two GD blend tests, with the exception of the fuel flow. Due to the higher LHV of the neat GD, the fuel flow for the 5 percent GD blends were set to a slightly lower value to maintain a constant heat input (MJ/hr) to the rig, though the differences in the set points were minimal since the LHVs of the fuels were so similar. The fuel flows were calculated based on the LHV measurements from the pretest fuel sample analyses.

Normalized pattern factor (PF) results are displayed in Figure 3 as a bar chart showing the normalized pattern factor results of the two GD blends, relative to the PF of the Jet A baseline. Pattern factor is calculated using the measured combustor inlet and exit temperatures shown in Equation 1, and is a measure of the gas temperature distribution at the turbine inlet plane.

$$PF = \frac{T_{3.9}^{\max} - T_{3.9}^{avg}}{T_{3.9}^{avg} - T_{3.0}^{avg}} \qquad [1]$$

Where:

PF = pattern factor

$T_{3.9}^{\max}$ = maximum temperature at turbine inlet plane (combustor exit)

$T_{3.9}^{avg}$ = average gas temperature at turbine inlet plane

$T_{3.0}^{avg}$ = average gas temperature at combustor inlet

The goal is to have low PFs which represent uniform combustor exit temperatures. Pattern factor is related to APU durability with higher PFs decreasing turbine nozzle life. For all conditions, the two GD blends have similar results to the baseline Jet and are within a reasonable test-to-test variation. Also, all results had PFs well below the design limit. These results indicate no adverse effect of the GD blends on turbine stator durability.

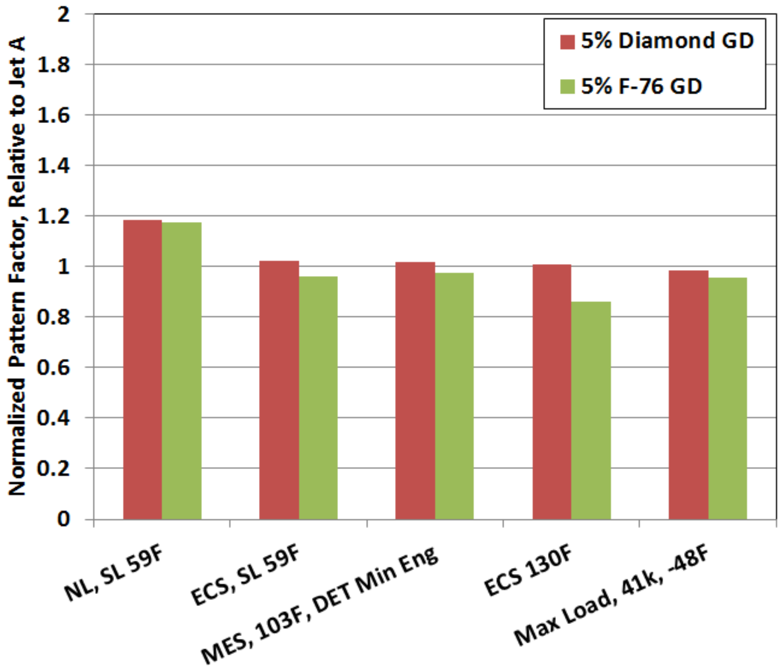
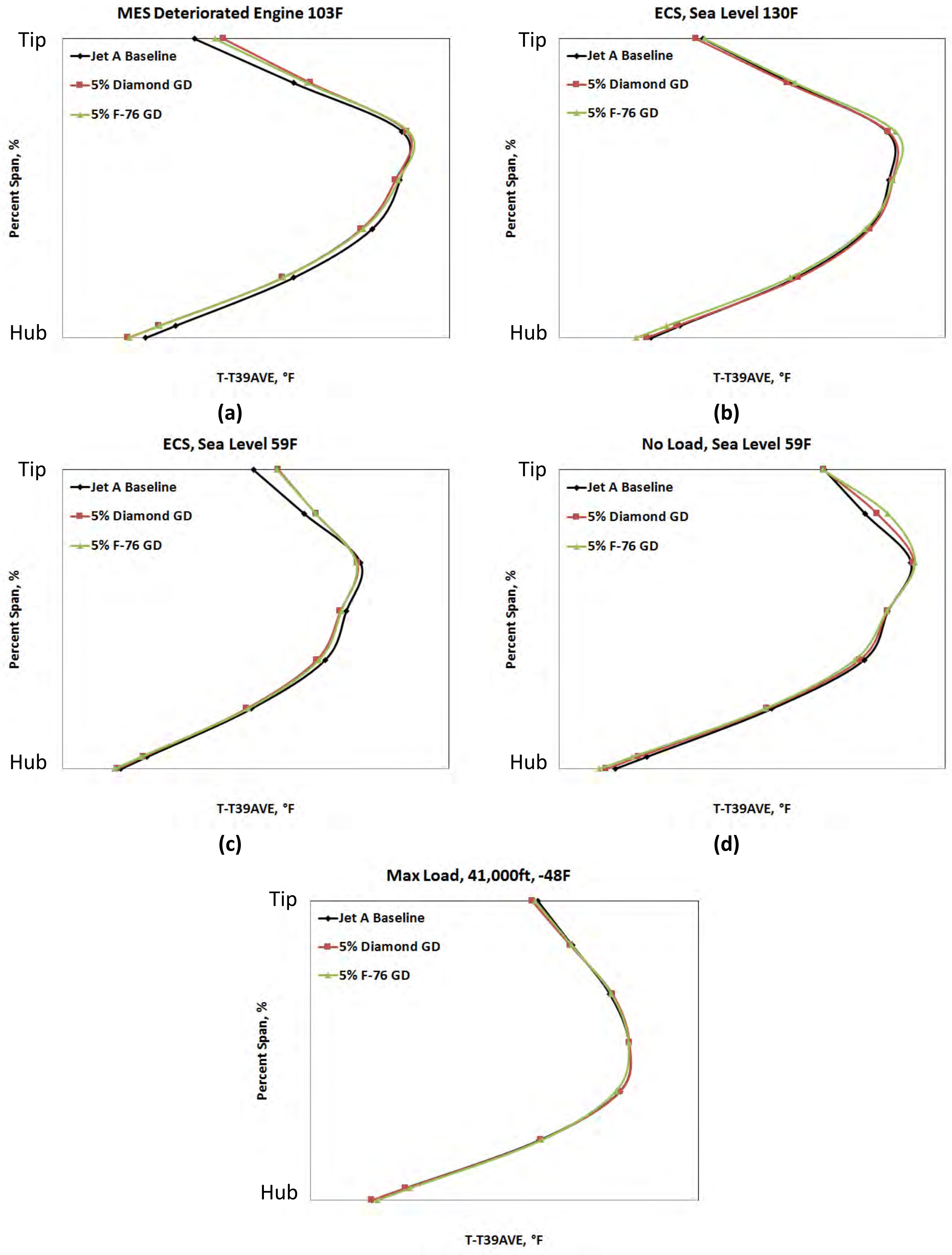


Figure 3. Thermodynamic Pattern Factor at All Test Conditions.

4.2.1 Temperature Pattern Tests – Radial Profile

Combustor exit temperature radial profile results are shown in Figure 4. Radial profile is associated with turbine blade durability. There is little difference in temperature profiles (circumferentially averaged temperature minus overall average temperature) between the three fuels. Peak profile temperatures were located at 69 percent of the duct height for all the peak profile temperatures for all three fuels, with the typical exception of the 41,000 ft high-altitude condition, which peaks at 50 percent span for all fuels. From these radial temperature profile results, it is concluded that the GD blends have no negative impact on the turbine entry temperature profile for the 131-9[B] combustion system.



MES Deteriorated Engine 103F

(a)

ECS, Sea Level 130F

(b)

ECS, Sea Level 59F

(c)

No Load, Sea Level 59F

(d)

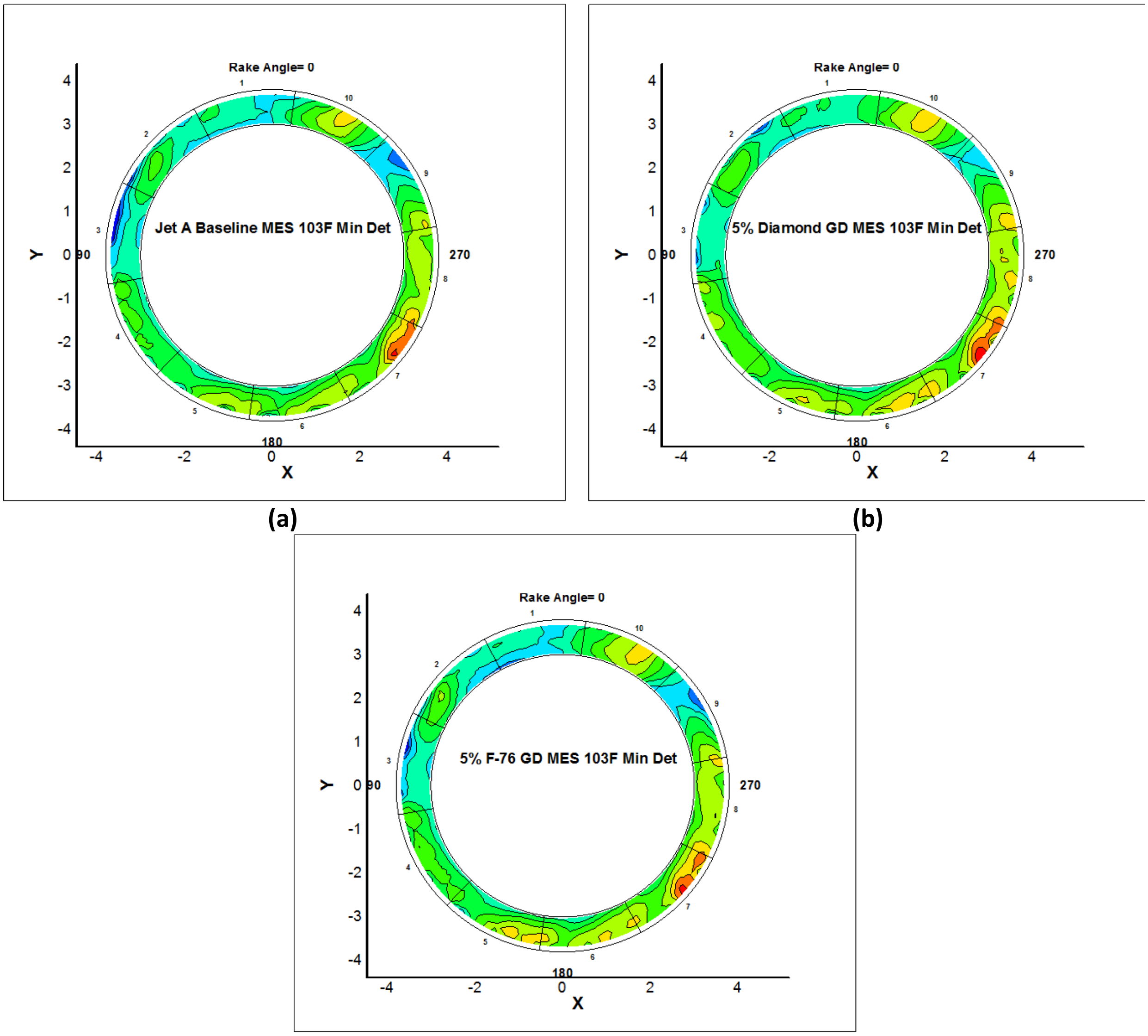
Max Load, 41,000ft, -48F

(e)

Figure 4. Best Estimate Radial Profile for a) MES 103°F Minimum Deteriorated Engine, b) ECS 130°F, c) ECS 59°F, d) No-Load 59°F, and e) 41k Maximum Load.

4.2.2 Temperature Pattern Tests – Temperature Contour

In addition to the radial profile and pattern factor, the circumferential exit temperature variation is also examined. Figure 5 displays the temperature contour plots from the MES 103°F minimum deteriorated condition and shows slight differences between the three test fuels.



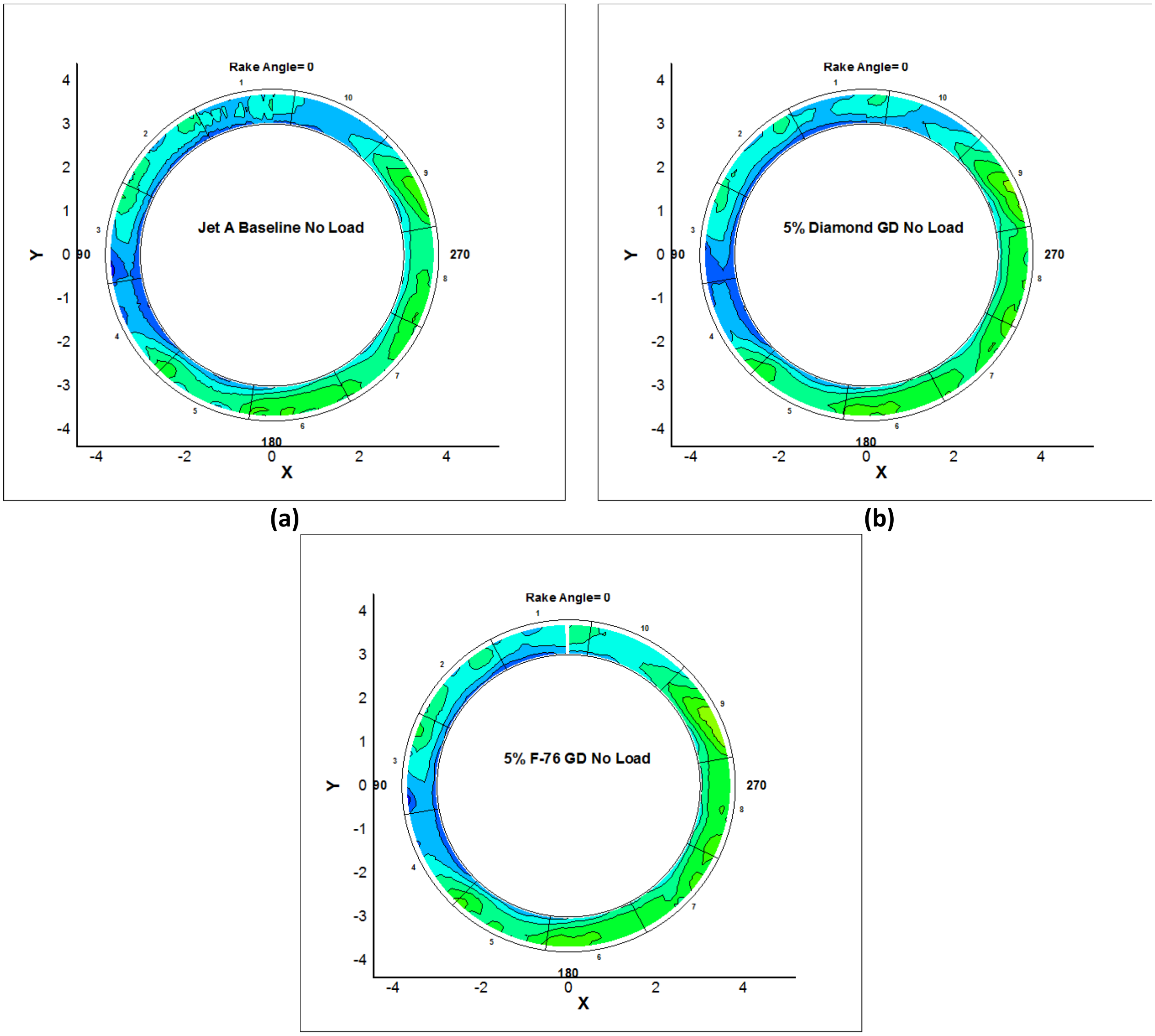
(a)

(b)

(c)

Figure 5. Contour Plots at MES 103°F Minimum Deteriorated a) Jet A Baseline, b) 5% Diamond GD, and c) 5% F-76 GD.

Figure 6 shows the contour plots from the No-Load 59°F condition. The three No-Load contour plots are nearly identical. Similar results were obtained at the other test conditions, as shown in Appendix 2.



(a)

(b)

(c)

Figure 6. Contour Plots at No-Load 59°F for a) Jet A Baseline, b) 5% Diamond GD, and c) 5% F-76 GD.

4.3 Smoke and Gaseous Emissions

4.3.1 Results

Figure 7 through Figure 9 show the normalized results of the smoke and gaseous emissions measurements taken during the performance conditions with both GD blends, relative to the Jet A baseline results. Figure 7 shows that the relative smoke numbers measured with the GD blends are slightly lower than with the Jet A baseline at three of the five conditions. Smoke emissions typically correlate with fuel aromatic content, but in this case the Jet A and GD blends all had similar aromatic contents. Smoke emissions with all three fuels were well below the exhaust visibility limit of 50 for small engines. Smoke emissions for this test were measured with an optical smoke analyzer that correlates well with the Society of Automotive Engineers (SAE) smoke method (ARP1179), with readings converted to equivalent SAE smoke number. The low smoke emissions with all fuels were near the limit of the instrument's detection range.

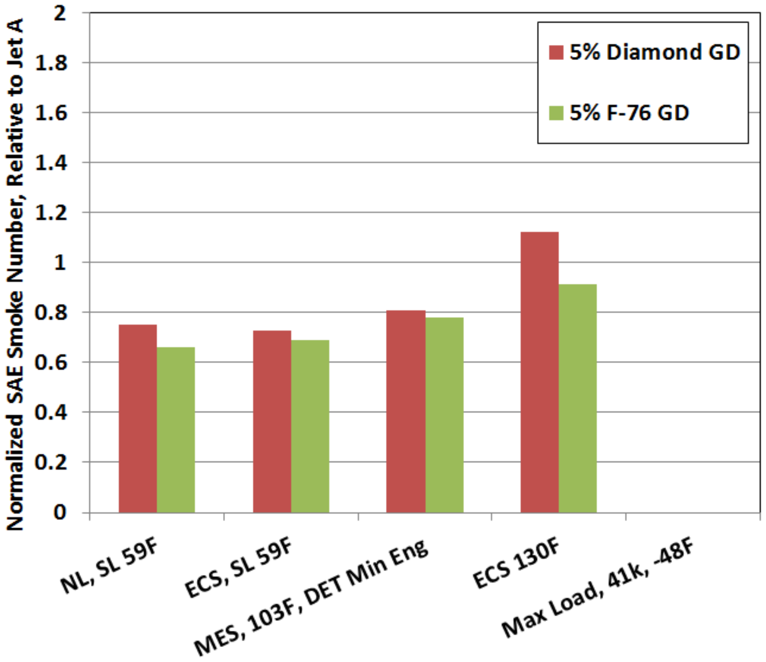


Figure 7 .Equivalent SAE Smoke Numbers Using Optical Smoke Meter at All Test Conditions.

Gaseous emissions were measured from fixed emission probes in the rig exhaust in accordance with SAE ARP1156, and reduced to SAE ARP1533 requirements.

Figure 8 shows the normalized NOx Emissions Index for the two GD blends, relative to the baseline Jet A results. The two GD blends have very similar NOx emissions relative to the baseline Jet A. These values are within test-to-test variation and measurement errors.

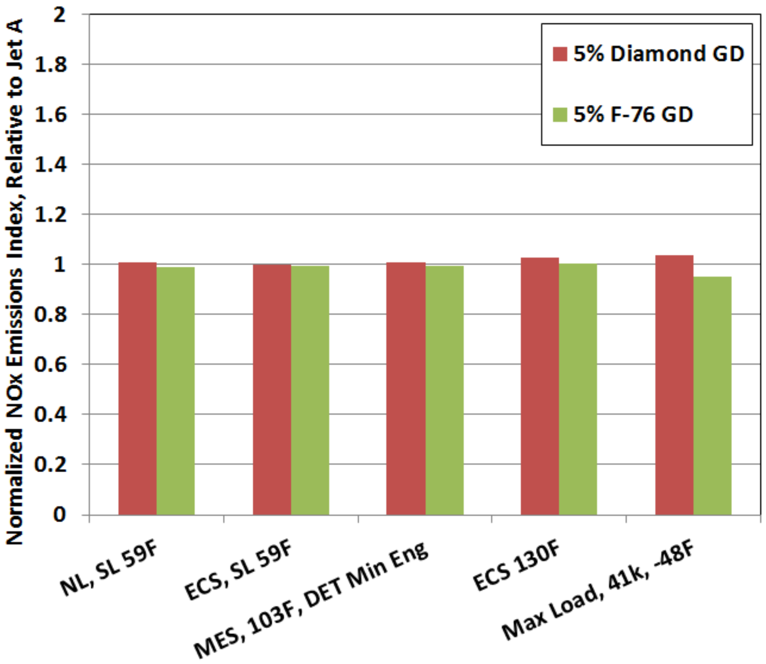


Figure 8. NOx Emissions Index at All Test Conditions.

Figure 9 shows the normalized results of the carbon monoxide (CO) and unburned hydrocarbon (UHC) measurements for the two GD blends. These emissions represent incomplete combustion with UHC being leftover fuel components and the CO being an incomplete combustion product. The two GD blends produced very similar CO and UHC emissions, relative to the Jet A baseline, with only significant productions occurring at low power and high altitude conditions.

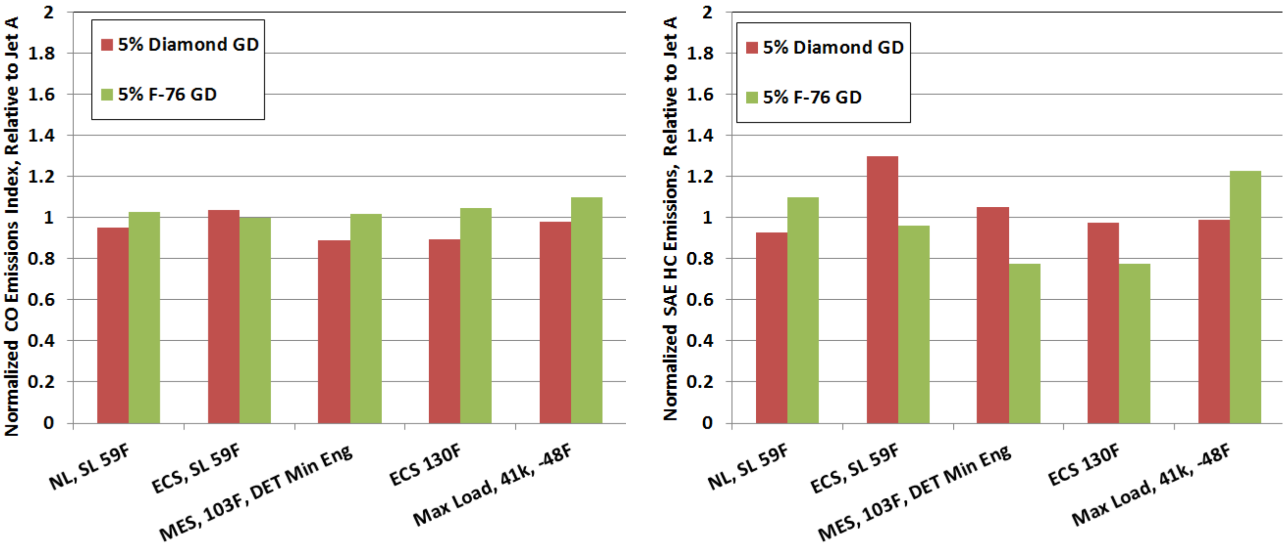


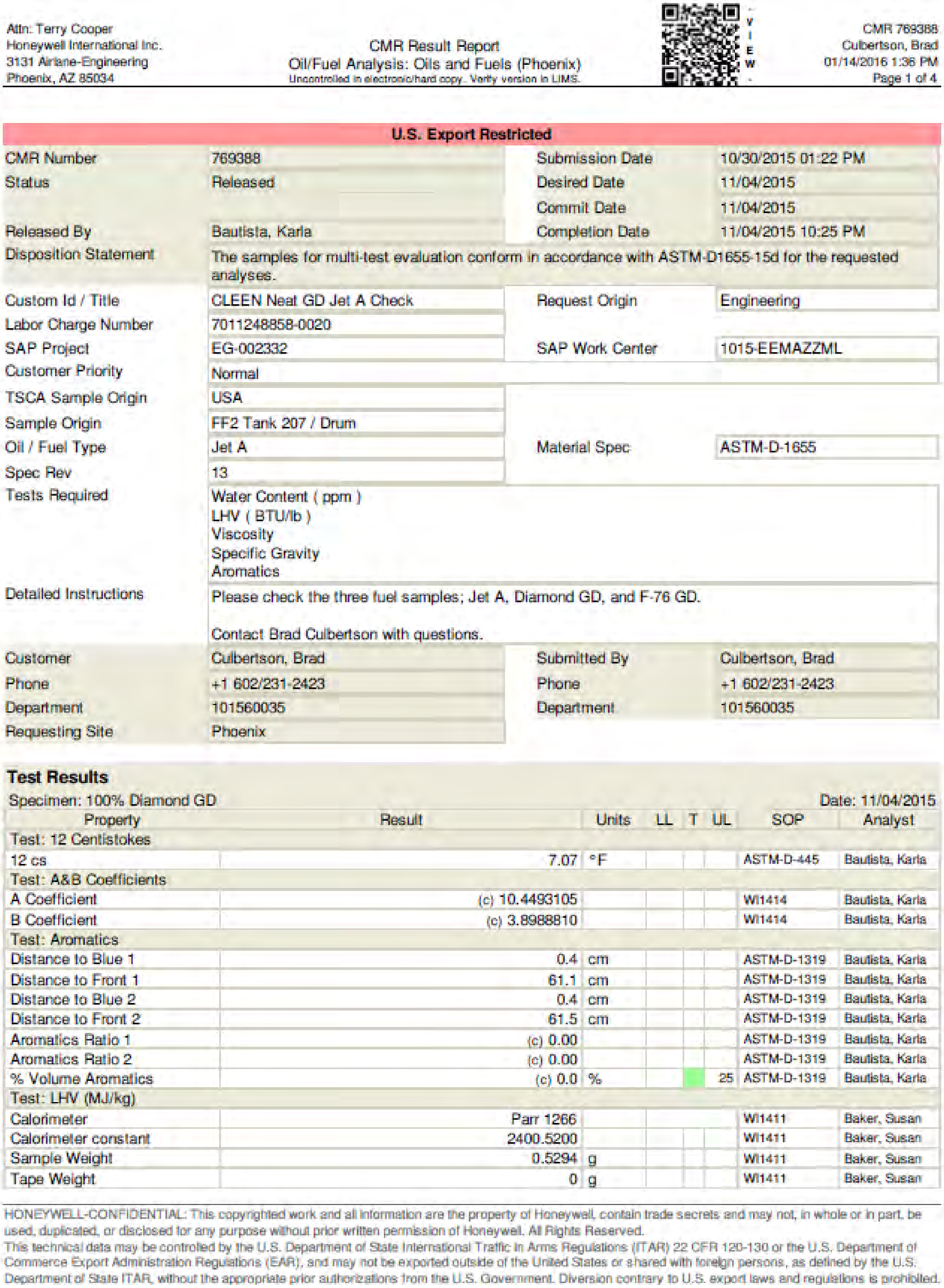
Figure 9. Emissions All Test Conditions a) CO Emissions Index and b) SAE UHC.

5.0 CONCLUSIONS

Two different GD fuels were blended to a 5 percent blend ratio with Jet A and tested to determine their impact on 131-9[B] APU combustion system performance and gaseous emissions and were compared to a baseline Jet A. Test results indicate that the 5 percent GD blends are acceptable and showed no adverse effects on combustion system performance or emissions.

Appendix 1. Chemical Analyses Results

(22 pages)



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Phoenix, AZ 85034

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CMR Number	769388	Submission Date	10/30/2015 01:22 PM
Status	Released	Desired Date	11/04/2015
		Commit Date	11/04/2015
Released By	Bautista, Karla	Completion Date	11/04/2015 10:25 PM
Disposition Statement	The samples for multi-test evaluation conform in accordance with ASTM-D1655-15d for the requested analyses.		
Custom Id / Title	CLEEN Neat GD Jet A Check	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	FF2 Tank 207 / Drum		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Specific Gravity Aromatics		
Detailed Instructions	Please check the three fuel samples; Jet A, Diamond GD, and F-76 GD. Contact Brad Culbertson with questions.		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 100% Diamond GD — Date: 11/04/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	7.07	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.4493105					WI1414	Bautista, Karla
B Coefficient	(c) 3.8988810					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	0.4	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	61.1	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	0.4	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	61.5	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.00					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.00					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 0.0	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Baker, Susan
Calorimeter constant	2400.5200					WI1411	Baker, Susan
Sample Weight	0.5294	g				WI1411	Baker, Susan
Tape Weight	0	g				WI1411	Baker, Susan

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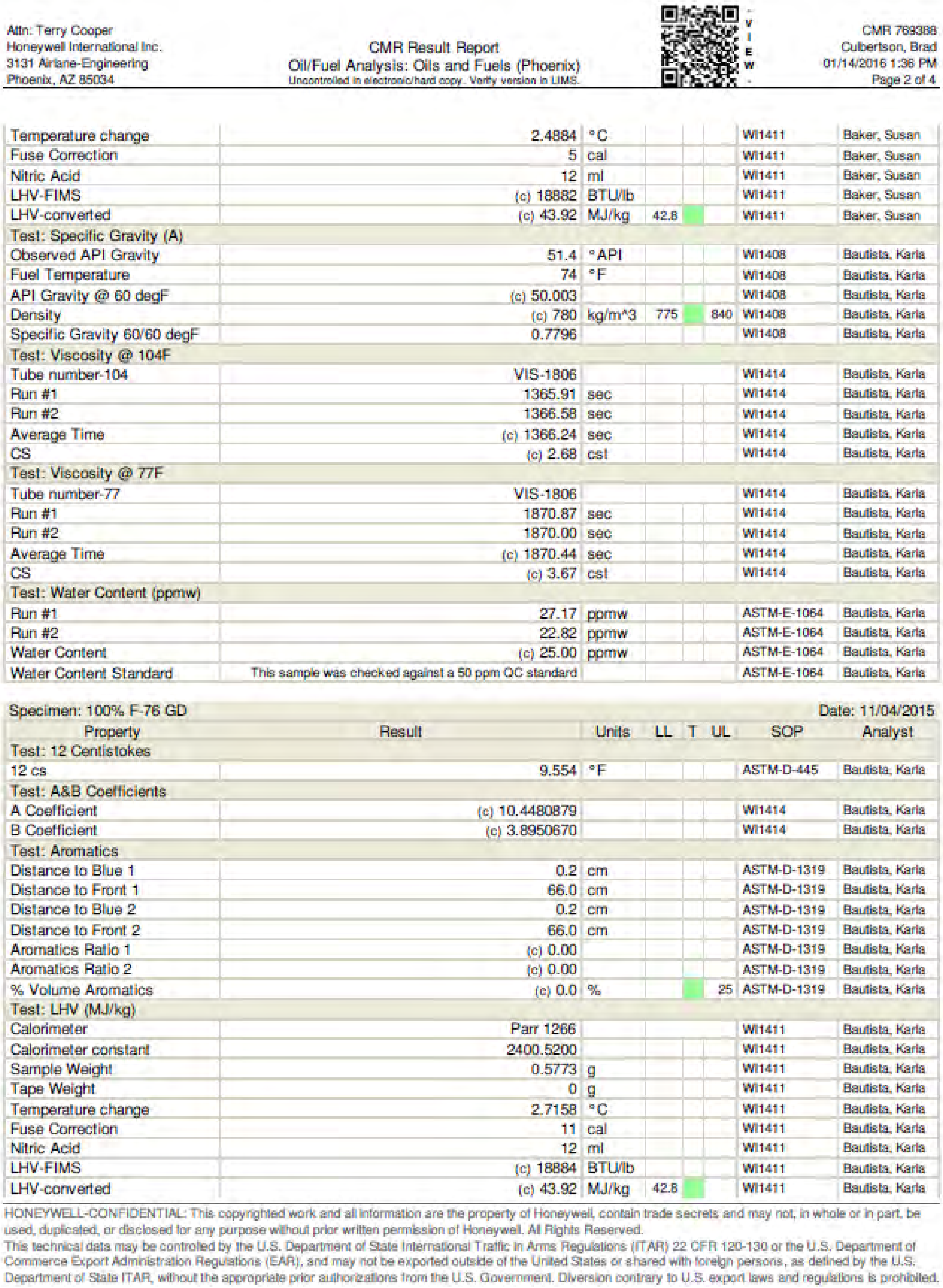
Pre-Blend/Pretest Analyses of Jet A, Diamond GD, and F-76 GD



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Temperature change	2.4884	°C				WI1411	Baker, Susan
Fuse Correction	5	cal				WI1411	Baker, Susan
Nitric Acid	12	ml				WI1411	Baker, Susan
LHV-FIMS	(c) 18882	BTU/lb				WI1411	Baker, Susan
LHV-converted	(c) 43.92	MJ/kg	42.8	🟩		WI1411	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	51.4	°API				WI1408	Bautista, Karla
Fuel Temperature	74	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF	(c) 50.003					WI1408	Bautista, Karla
Density	(c) 780	kg/m^3	775	🟩	840	WI1408	Bautista, Karla
Specific Gravity 60/60 degF	0.7796					WI1408	Bautista, Karla
Test: Viscosity @ 104F							
Tube number-104	VIS-1806					WI1414	Bautista, Karla
Run #1	1365.91	sec				WI1414	Bautista, Karla
Run #2	1366.58	sec				WI1414	Bautista, Karla
Average Time	(c) 1366.24	sec				WI1414	Bautista, Karla
CS	(c) 2.68	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	VIS-1806					WI1414	Bautista, Karla
Run #1	1870.87	sec				WI1414	Bautista, Karla
Run #2	1870.00	sec				WI1414	Bautista, Karla
Average Time	(c) 1870.44	sec				WI1414	Bautista, Karla
CS	(c) 3.67	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	27.17	ppmw				ASTM-E-1064	Bautista, Karla
Run #2	22.82	ppmw				ASTM-E-1064	Bautista, Karla
Water Content	(c) 25.00	ppmw				ASTM-E-1064	Bautista, Karla
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Bautista, Karla

Specimen: 100% F-76 GD — Date: 11/04/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	9.554	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.4480879					WI1414	Bautista, Karla
B Coefficient	(c) 3.8950670					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	0.2	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	66.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	0.2	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	66.0	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.00					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.00					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 0.0	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Bautista, Karla
Calorimeter constant	2400.5200					WI1411	Bautista, Karla
Sample Weight	0.5773	g				WI1411	Bautista, Karla
Tape Weight	0	g				WI1411	Bautista, Karla
Temperature change	2.7158	°C				WI1411	Bautista, Karla
Fuse Correction	11	cal				WI1411	Bautista, Karla
Nitric Acid	12	ml				WI1411	Bautista, Karla
LHV-FIMS	(c) 18884	BTU/lb				WI1411	Bautista, Karla
LHV-converted	(c) 43.92	MJ/kg	42.8	🟩		WI1411	Bautista, Karla

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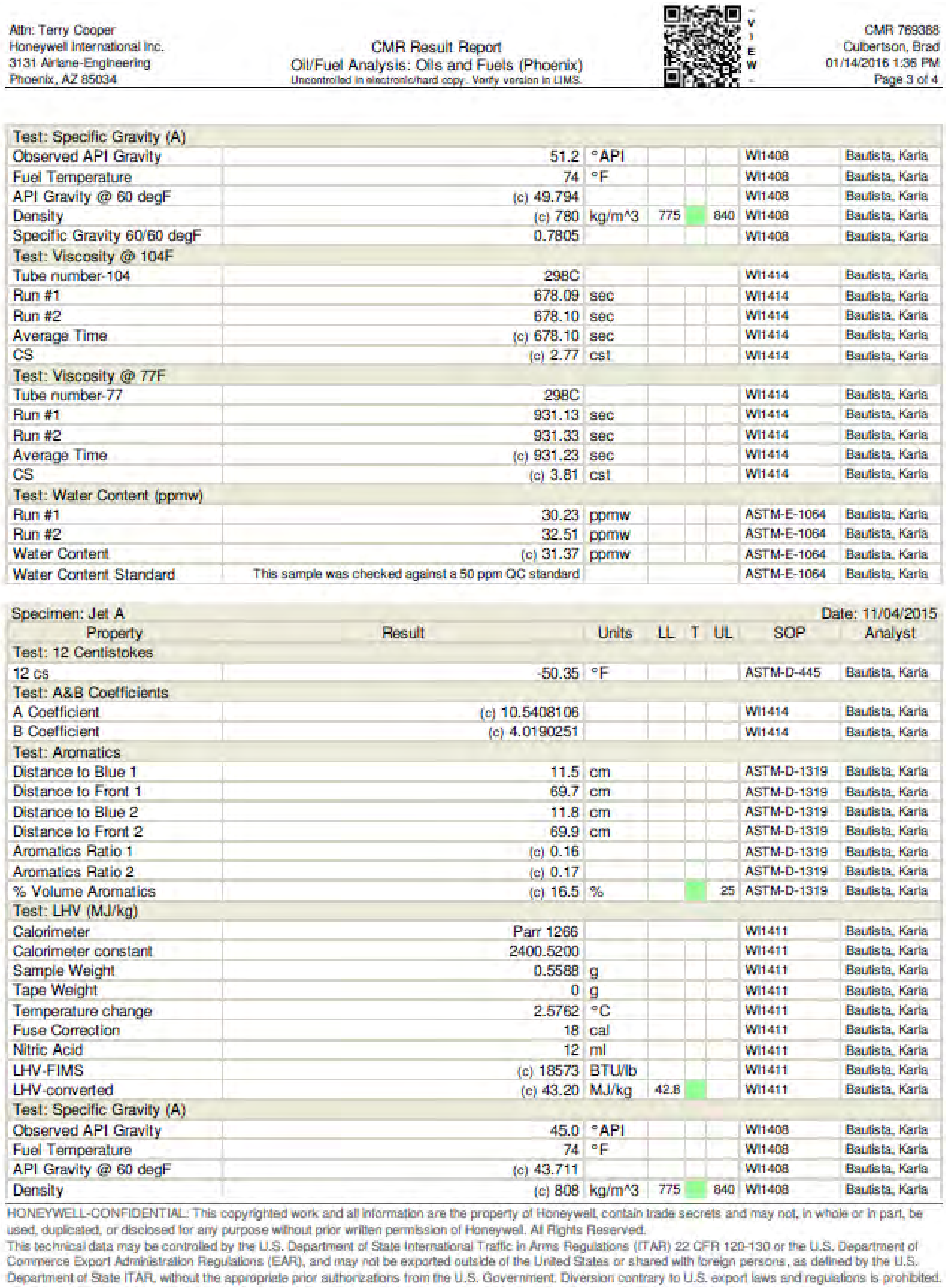
Pre-Blend/Pretest Analyses of Jet A, Diamond GD, and F-76 GD (Cont)



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Test: Specific Gravity (A)							
Observed API Gravity	51.2	°API				WI1408	Bautista, Karla
Fuel Temperature	74	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF	(c) 49.794					WI1408	Bautista, Karla
Density	(c) 780	kg/m^3	775	🟩	840	WI1408	Bautista, Karla
Specific Gravity 60/60 degF	0.7805					WI1408	Bautista, Karla
Test: Viscosity @ 104F							
Tube number-104	298C					WI1414	Bautista, Karla
Run #1	678.09	sec				WI1414	Bautista, Karla
Run #2	678.10	sec				WI1414	Bautista, Karla
Average Time	(c) 678.10	sec				WI1414	Bautista, Karla
CS	(c) 2.77	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	298C					WI1414	Bautista, Karla
Run #1	931.13	sec				WI1414	Bautista, Karla
Run #2	931.33	sec				WI1414	Bautista, Karla
Average Time	(c) 931.23	sec				WI1414	Bautista, Karla
CS	(c) 3.81	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	30.23	ppmw				ASTM-E-1064	Bautista, Karla
Run #2	32.51	ppmw				ASTM-E-1064	Bautista, Karla
Water Content	(c) 31.37	ppmw				ASTM-E-1064	Bautista, Karla
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Bautista, Karla

Specimen: Jet A Date: 11/04/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-50.35	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.5408106					WI1414	Bautista, Karla
B Coefficient	(c) 4.0190251					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.5	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	69.7	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.8	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	69.9	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.16					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.17					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 16.5	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Bautista, Karla
Calorimeter constant	2400.5200					WI1411	Bautista, Karla
Sample Weight	0.5588	g				WI1411	Bautista, Karla
Tape Weight	0	g				WI1411	Bautista, Karla
Temperature change	2.5762	°C				WI1411	Bautista, Karla
Fuse Correction	18	cal				WI1411	Bautista, Karla
Nitric Acid	12	ml				WI1411	Bautista, Karla
LHV-FIMS	(c) 18573	BTU/lb				WI1411	Bautista, Karla
LHV-converted	(c) 43.20	MJ/kg	42.8	🟩		WI1411	Bautista, Karla
Test: Specific Gravity (A)							
Observed API Gravity	45.0	°API				WI1408	Bautista, Karla
Fuel Temperature	74	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF	(c) 43.711					WI1408	Bautista, Karla
Density	(c) 808	kg/m^3	775	🟩	840	WI1408	Bautista, Karla

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Pre-Blend/Pretest Analyses of Jet A, Diamond GD, and F-76 GD (Cont)

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Specific Gravity 60/60 degF	0.8076					WI1408	Bautista, Karla
Test: Viscosity @ 104F							
Tube number-104	299C					WI1414	Baker, Susan
Run #1	310.46	sec				WI1414	Baker, Susan
Run #2	310.24	sec				WI1414	Baker, Susan
Average Time	(c) 310.35	sec				WI1414	Baker, Susan
CS	(c) 1.31	cst				WI1414	Baker, Susan
Test: Viscosity @ 77F							
Tube number-77	299C					WI1414	Baker, Susan
Run #1	389.01	sec				WI1414	Baker, Susan
Run #2	388.99	sec				WI1414	Baker, Susan
Average Time	(c) 389.00	sec				WI1414	Baker, Susan
CS	(c) 1.65	cst				WI1414	Baker, Susan
Test: Water Content (ppmw)							
Run #1	40.43	ppmw				ASTM-E-1064	Bautista, Karla
Run #2	40.05	ppmw				ASTM-E-1064	Bautista, Karla
Water Content	(c) 40.24	ppmw				ASTM-E-1064	Bautista, Karla
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Bautista, Karla

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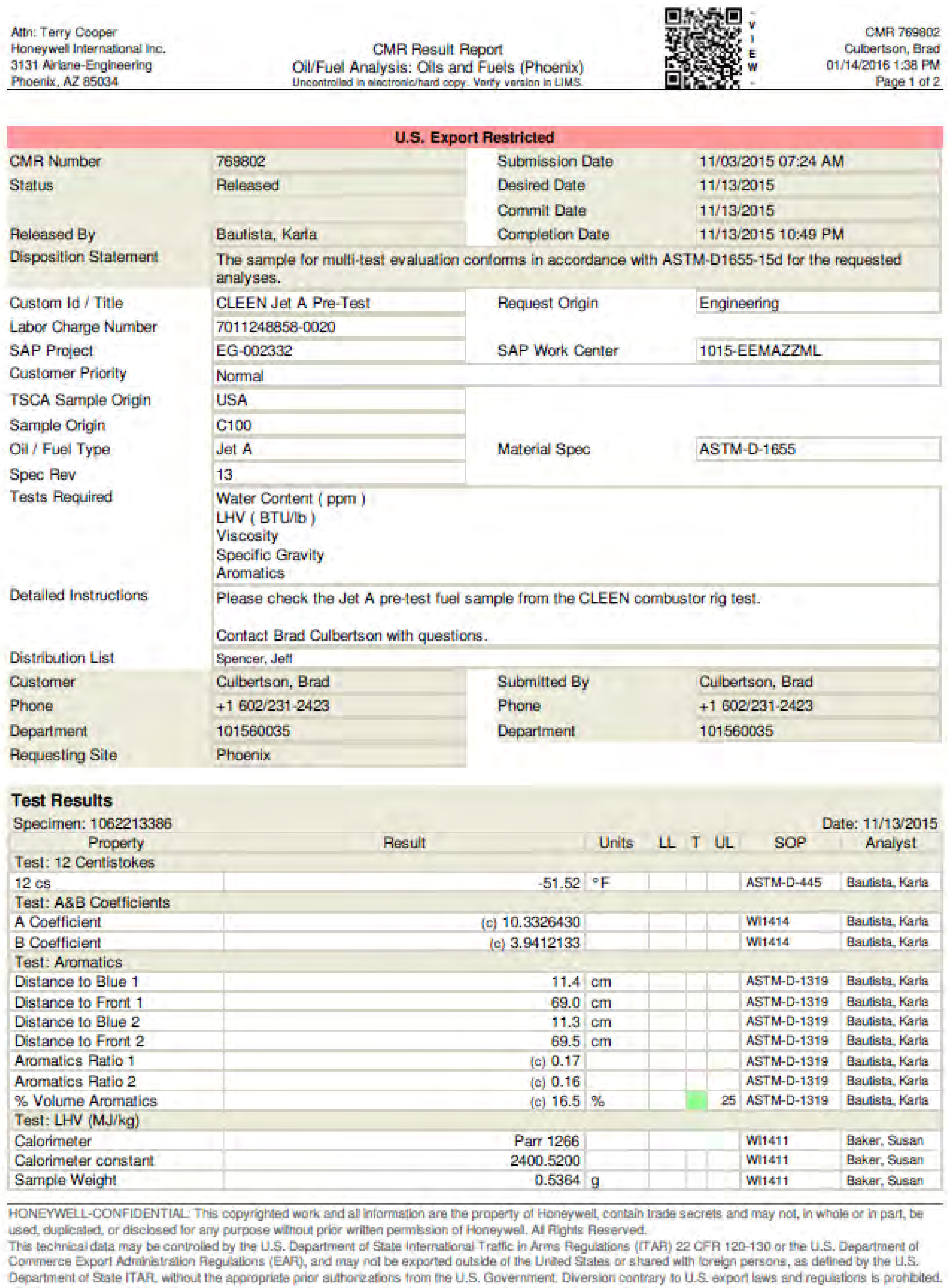
Pre-Blend/Pretest Analyses of Jet A, Diamond GD, and F-76 GD (Cont)



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 769802
Culbertson, Brad
01/14/2016 1:38 PM
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CMR Number	769802	Submission Date	11/03/2015 07:24 AM
Status	Released	Desired Date	11/13/2015
		Commit Date	11/13/2015
Released By	Bautista, Karla	Completion Date	11/13/2015 10:49 PM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the requested analyses.		
Custom Id / Title	CLEEN Jet A Pre-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Specific Gravity Aromatics		
Detailed Instructions	Please check the Jet A pre-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Spencer, Jeff		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213386 Date: 11/13/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-51.52	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.3326430					WI1414	Bautista, Karla
B Coefficient	(c) 3.9412133					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.4	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	69.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.3	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	69.5	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.17					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.16					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 16.5	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Baker, Susan
Calorimeter constant	2400.5200					WI1411	Baker, Susan
Sample Weight	0.5364	g				WI1411	Baker, Susan

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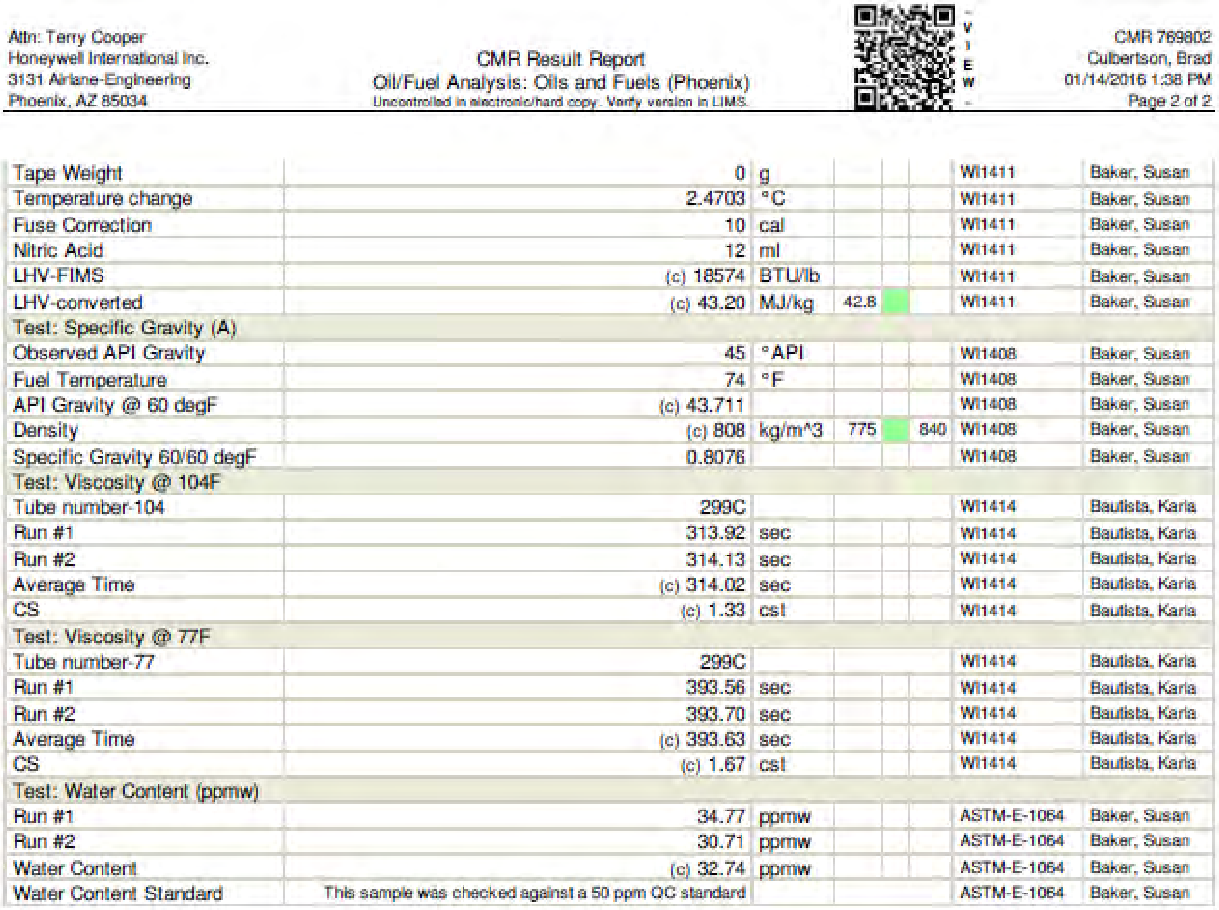
Performance Pretest Analyses of Jet A Baseline



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Phoenix, AZ 85034

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Page 2 of 2

Tape Weight	0	g				WI1411	Baker, Susan
Temperature change	2.4703	°C				WI1411	Baker, Susan
Fuse Correction	10	cal				WI1411	Baker, Susan
Nitric Acid	12	ml				WI1411	Baker, Susan
LHV-FIMS	(c) 18574	BTU/lb				WI1411	Baker, Susan
LHV-converted	(c) 43.20	MJ/kg	42.8	🟩		WI1411	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	45	°API				WI1408	Baker, Susan
Fuel Temperature	74	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 43.711					WI1408	Baker, Susan
Density	(c) 808	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8076					WI1408	Baker, Susan
Test: Viscosity @ 104F							
Tube number-104	299C					WI1414	Bautista, Karla
Run #1	313.92	sec				WI1414	Bautista, Karla
Run #2	314.13	sec				WI1414	Bautista, Karla
Average Time	(c) 314.02	sec				WI1414	Bautista, Karla
CS	(c) 1.33	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	299C					WI1414	Bautista, Karla
Run #1	393.56	sec				WI1414	Bautista, Karla
Run #2	393.70	sec				WI1414	Bautista, Karla
Average Time	(c) 393.63	sec				WI1414	Bautista, Karla
CS	(c) 1.67	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	34.77	ppmw				ASTM-E-1064	Baker, Susan
Run #2	30.71	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 32.74	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

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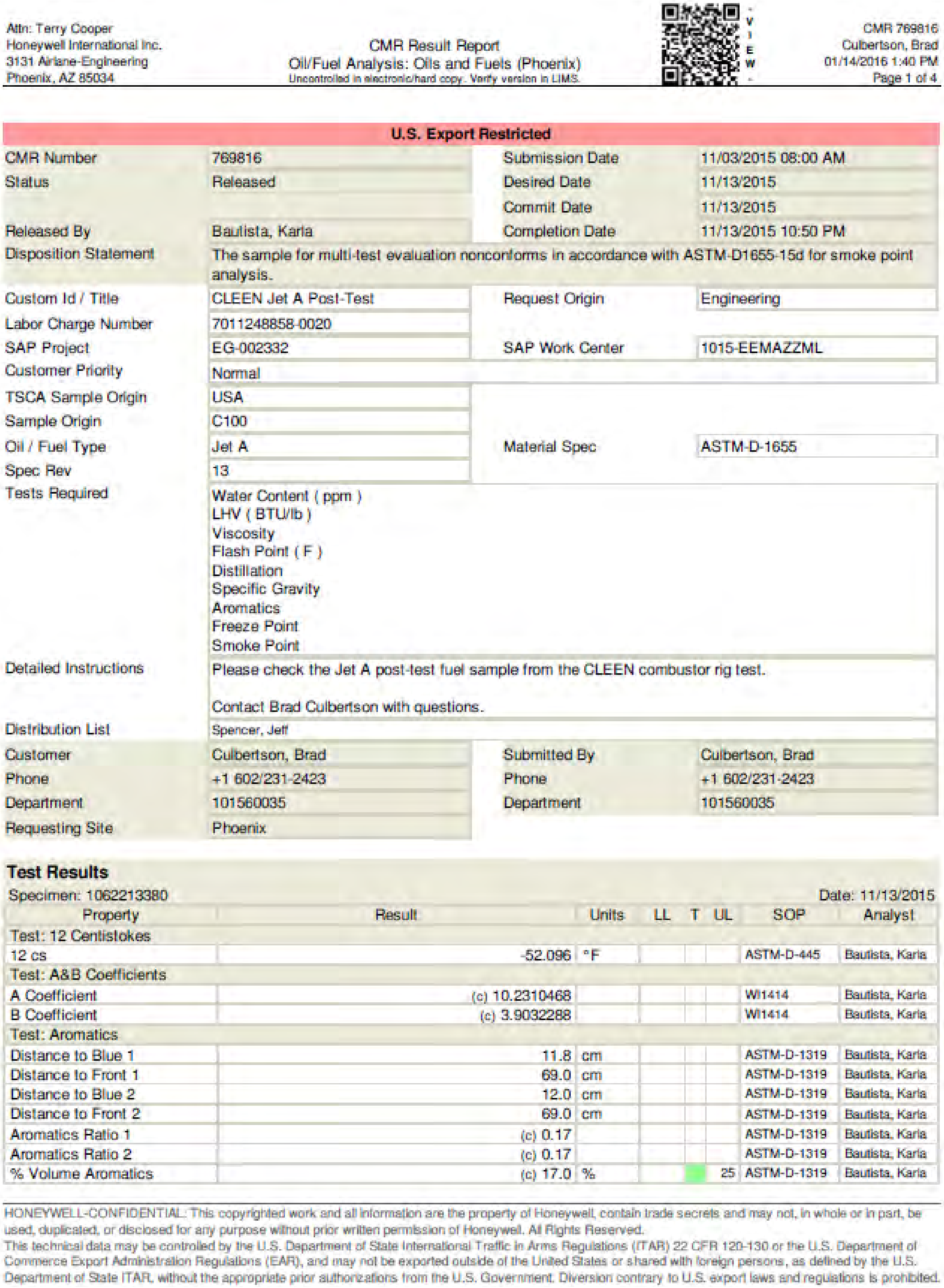
Performance Pretest Analyses of Jet A Baseline (Cont)



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 769816
Culbertson, Brad
01/14/2016 1:40 PM
Page 1 of 4

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CMR Number	769816	Submission Date	11/03/2015 08:00 AM
Status	Released	Desired Date	11/13/2015
		Commit Date	11/13/2015
Released By	Bautista, Karla	Completion Date	11/13/2015 10:50 PM
Disposition Statement	The sample for multi-test evaluation nonconforms in accordance with ASTM-D1655-15d for smoke point analysis.		
Custom Id / Title	CLEEN Jet A Post-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Flash Point (F) Distillation Specific Gravity Aromatics Freeze Point Smoke Point		
Detailed Instructions	Please check the Jet A post-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Spencer, Jeff		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213380 Date: 11/13/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-52.096	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.2310468					WI1414	Bautista, Karla
B Coefficient	(c) 3.9032288					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.8	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	69.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	12.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	69.0	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.17					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.17					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 17.0	%		🟩	25	ASTM-D-1319	Bautista, Karla

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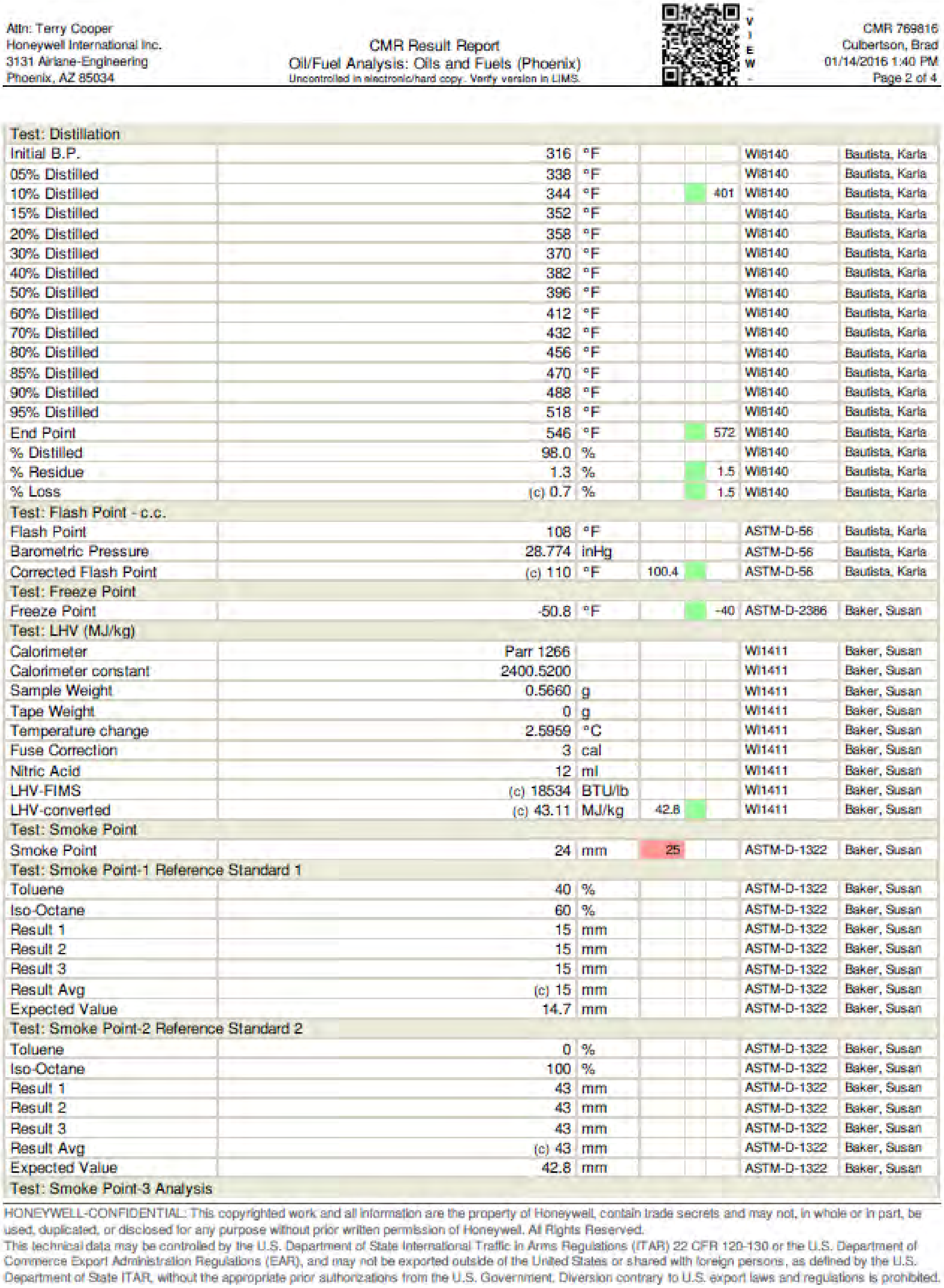
Performance Posttest Analyses of Jet A Baseline



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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Test: Distillation								
Initial B.P.		316	°F				WI8140	Bautista, Karla
05% Distilled		338	°F				WI8140	Bautista, Karla
10% Distilled		344	°F		🟩	401	WI8140	Bautista, Karla
15% Distilled		352	°F				WI8140	Bautista, Karla
20% Distilled		358	°F				WI8140	Bautista, Karla
30% Distilled		370	°F				WI8140	Bautista, Karla
40% Distilled		382	°F				WI8140	Bautista, Karla
50% Distilled		396	°F				WI8140	Bautista, Karla
60% Distilled		412	°F				WI8140	Bautista, Karla
70% Distilled		432	°F				WI8140	Bautista, Karla
80% Distilled		456	°F				WI8140	Bautista, Karla
85% Distilled		470	°F				WI8140	Bautista, Karla
90% Distilled		488	°F				WI8140	Bautista, Karla
95% Distilled		518	°F				WI8140	Bautista, Karla
End Point		546	°F		🟩	572	WI8140	Bautista, Karla
% Distilled		98.0	%				WI8140	Bautista, Karla
% Residue		1.3	%		🟩	1.5	WI8140	Bautista, Karla
% Loss		(c) 0.7	%		🟩	1.5	WI8140	Bautista, Karla
Test: Flash Point - c.c.								
Flash Point		108	°F				ASTM-D-56	Bautista, Karla
Barometric Pressure		28.774	inHg				ASTM-D-56	Bautista, Karla
Corrected Flash Point		(c) 110	°F	100.4	🟩		ASTM-D-56	Bautista, Karla
Test: Freeze Point								
Freeze Point		-50.8	°F		🟩	-40	ASTM-D-2386	Baker, Susan
Test: LHV (MJ/kg)								
Calorimeter		Parr 1266					WI1411	Baker, Susan
Calorimeter constant		2400.5200					WI1411	Baker, Susan
Sample Weight		0.5660	g				WI1411	Baker, Susan
Tape Weight		0	g				WI1411	Baker, Susan
Temperature change		2.5959	°C				WI1411	Baker, Susan
Fuse Correction		3	cal				WI1411	Baker, Susan
Nitric Acid		12	ml				WI1411	Baker, Susan
LHV-FIMS		(c) 18534	BTU/lb				WI1411	Baker, Susan
LHV-converted		(c) 43.11	MJ/kg	42.8	🟩		WI1411	Baker, Susan
Test: Smoke Point								
Smoke Point		24	mm	🟥 25			ASTM-D-1322	Baker, Susan
Test: Smoke Point-1 Reference Standard 1								
Toluene		40	%				ASTM-D-1322	Baker, Susan
Iso-Octane		60	%				ASTM-D-1322	Baker, Susan
Result 1		15	mm				ASTM-D-1322	Baker, Susan
Result 2		15	mm				ASTM-D-1322	Baker, Susan
Result 3		15	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 15	mm				ASTM-D-1322	Baker, Susan
Expected Value		14.7	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-2 Reference Standard 2								
Toluene		0	%				ASTM-D-1322	Baker, Susan
Iso-Octane		100	%				ASTM-D-1322	Baker, Susan
Result 1		43	mm				ASTM-D-1322	Baker, Susan
Result 2		43	mm				ASTM-D-1322	Baker, Susan
Result 3		43	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 43	mm				ASTM-D-1322	Baker, Susan
Expected Value		42.8	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-3 Analysis								

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Performance Posttest Analyses of Jet A Baseline (Cont)

Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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Culbertson, Brad
01/14/2016 1:40 PM
Page 3 of 4

Result 1	24	mm				ASTM-D-1322	Baker, Susan
Result 2	24	mm				ASTM-D-1322	Baker, Susan
Result 3	24	mm				ASTM-D-1322	Baker, Susan
Result Avg	(c) 24	mm				ASTM-D-1322	Baker, Susan
Corrected Avg	(c) 23.7	mm				ASTM-D-1322	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	44.2	°API				WI1408	Baker, Susan
Fuel Temperature	72	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 43.105					WI1408	Baker, Susan
Density	(c) 810	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8104					WI1408	Baker, Susan
Test: Viscosity @ 104F							
Tube number-104	E896					WI1414	Bautista, Karla
Run #1	647.37	sec				WI1414	Bautista, Karla
Run #2	647.80	sec				WI1414	Bautista, Karla
Average Time	(c) 647.58	sec				WI1414	Bautista, Karla
CS	(c) 1.34	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	E896					WI1414	Bautista, Karla
Run #1	813.05	sec				WI1414	Bautista, Karla
Run #2	813.76	sec				WI1414	Bautista, Karla
Average Time	(c) 813.40	sec				WI1414	Bautista, Karla
CS	(c) 1.68	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	52.03	ppmw				ASTM-E-1064	Baker, Susan
Run #2	53.66	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 52.84	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062213380

Oil and Fuel CMR #	769816
Material	Jet A
Material Specification	ASTM-D-1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	98.0		
Percent Residue	1.3		1.5
Percent Loss	0.7		1.5

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	316		
5%			
10%	344		401
15%	352		
20%	358		
30%	370		
40%	382		
50%	396		
60%	412		
70%	432		
80%	456		
85%	470		
90%	488		
95%	518		
100%	546		572

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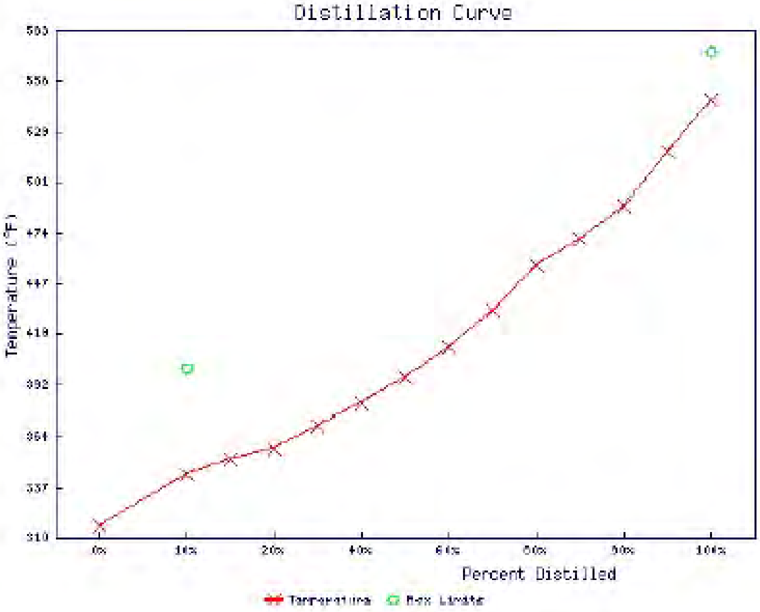
Performance Posttest Analyses of Jet A Baseline (Cont)



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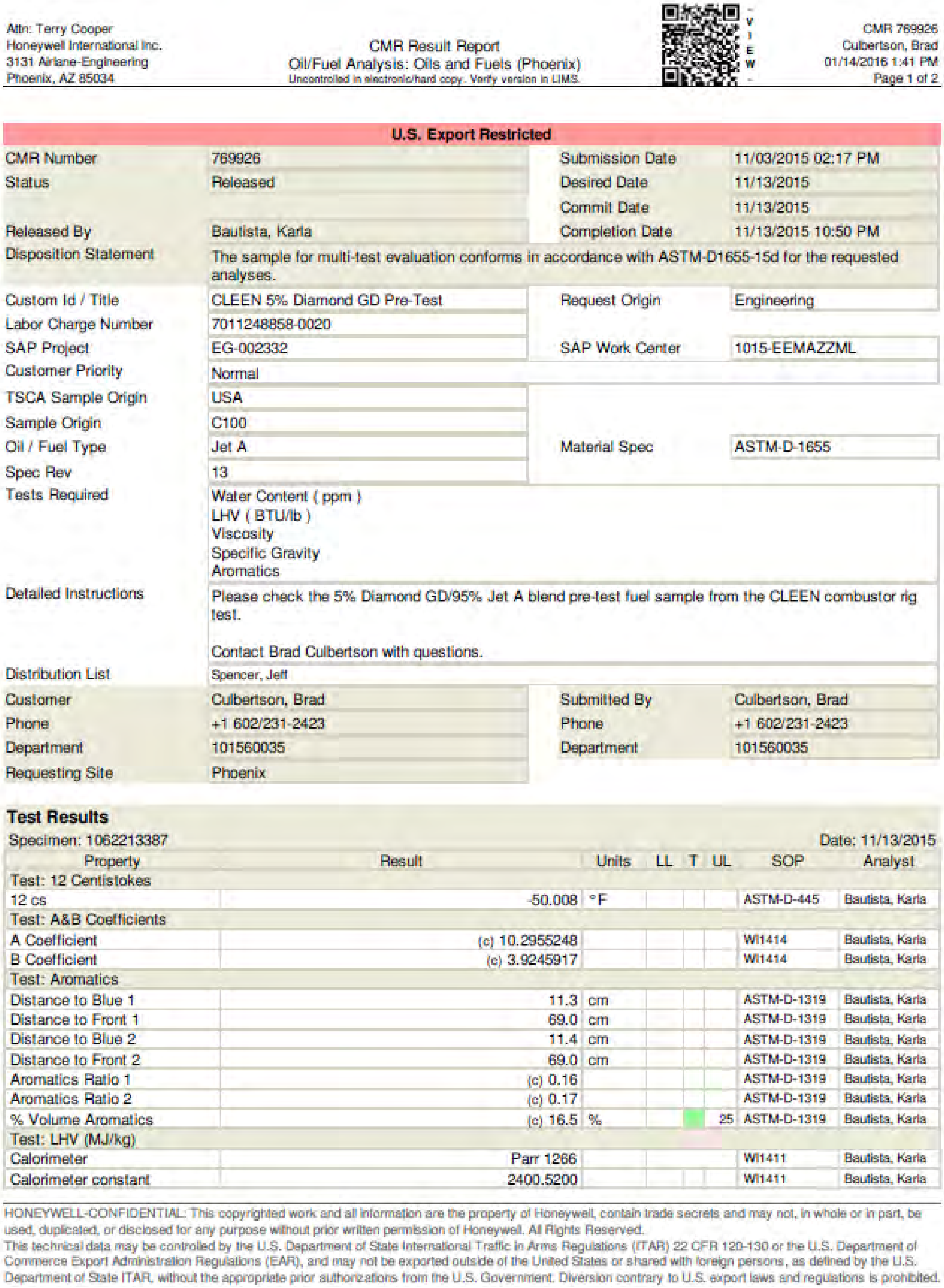
Performance Posttest Analyses of Jet A Baseline (Cont)



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 769926
Culbertson, Brad
01/14/2016 1:41 PM
Page 1 of 2

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CMR Number	769926	Submission Date	11/03/2015 02:17 PM
Status	Released	Desired Date	11/13/2015
		Commit Date	11/13/2015
Released By	Bautista, Karla	Completion Date	11/13/2015 10:50 PM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the requested analyses.		
Custom Id / Title	CLEEN 5% Diamond GD Pre-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Specific Gravity Aromatics		
Detailed Instructions	Please check the 5% Diamond GD/95% Jet A blend pre-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Spencer, Jeff		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213387 Date: 11/13/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-50.008	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.2955248					WI1414	Bautista, Karla
B Coefficient	(c) 3.9245917					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.3	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	69.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.4	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	69.0	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.16					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.17					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 16.5	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Bautista, Karla
Calorimeter constant	2400.5200					WI1411	Bautista, Karla

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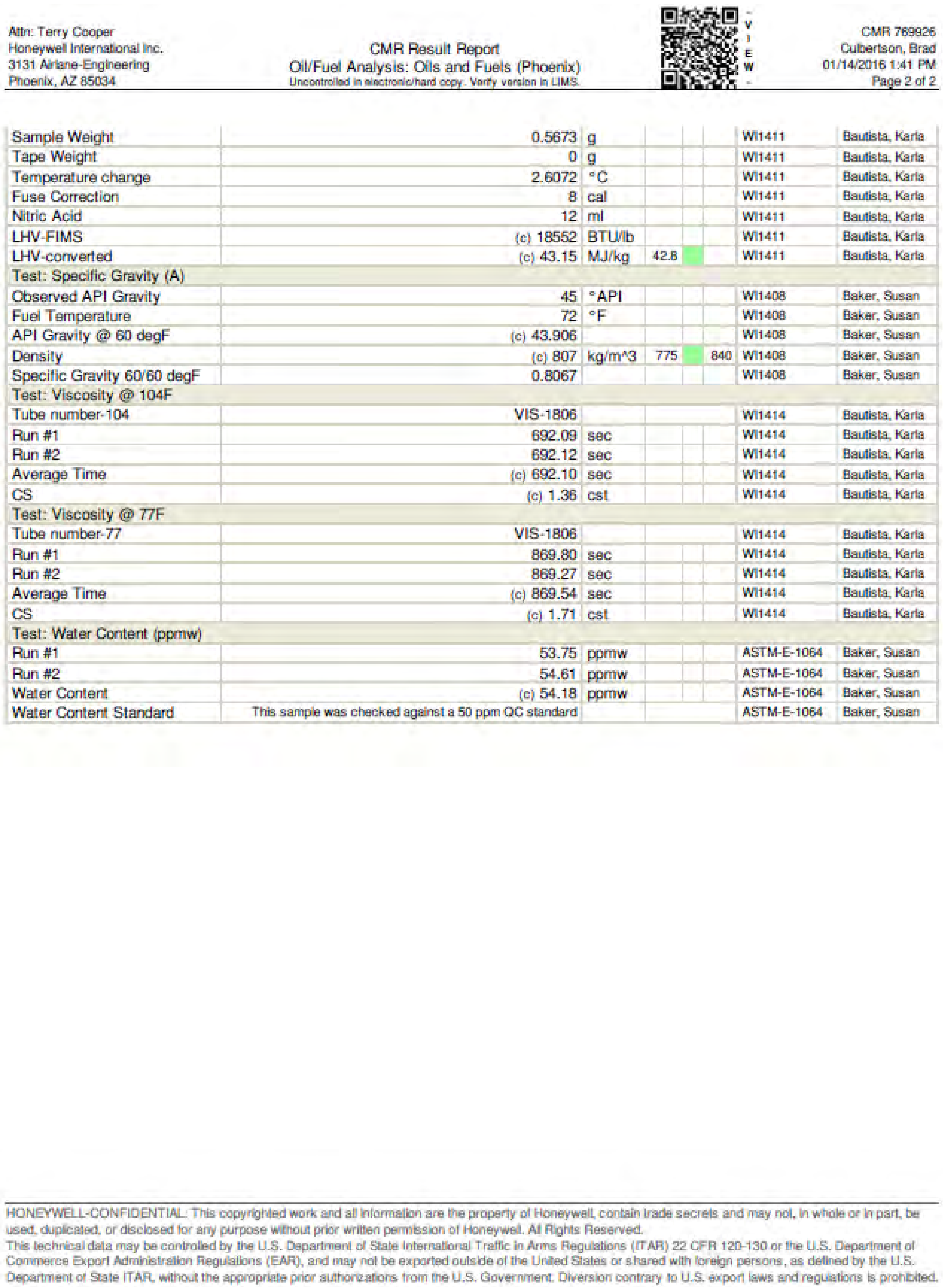
Performance Pretest Analyses of 5% Diamond Green Diesel



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 769926
Culbertson, Brad
01/14/2016 1:41 PM
Page 2 of 2

Sample Weight	0.5673	g				WI1411	Bautista, Karla
Tape Weight	0	g				WI1411	Bautista, Karla
Temperature change	2.6072	°C				WI1411	Bautista, Karla
Fuse Correction	8	cal				WI1411	Bautista, Karla
Nitric Acid	12	ml				WI1411	Bautista, Karla
LHV-FIMS	(c) 18552	BTU/lb				WI1411	Bautista, Karla
LHV-converted	(c) 43.15	MJ/kg	42.8	🟩		WI1411	Bautista, Karla
Test: Specific Gravity (A)							
Observed API Gravity	45	°API				WI1408	Baker, Susan
Fuel Temperature	72	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 43.906					WI1408	Baker, Susan
Density	(c) 807	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8067					WI1408	Baker, Susan
Test: Viscosity @ 104F							
Tube number-104	VIS-1806					WI1414	Bautista, Karla
Run #1	692.09	sec				WI1414	Bautista, Karla
Run #2	692.12	sec				WI1414	Bautista, Karla
Average Time	(c) 692.10	sec				WI1414	Bautista, Karla
CS	(c) 1.36	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	VIS-1806					WI1414	Bautista, Karla
Run #1	869.80	sec				WI1414	Bautista, Karla
Run #2	869.27	sec				WI1414	Bautista, Karla
Average Time	(c) 869.54	sec				WI1414	Bautista, Karla
CS	(c) 1.71	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	53.75	ppmw				ASTM-E-1064	Baker, Susan
Run #2	54.61	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 54.18	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

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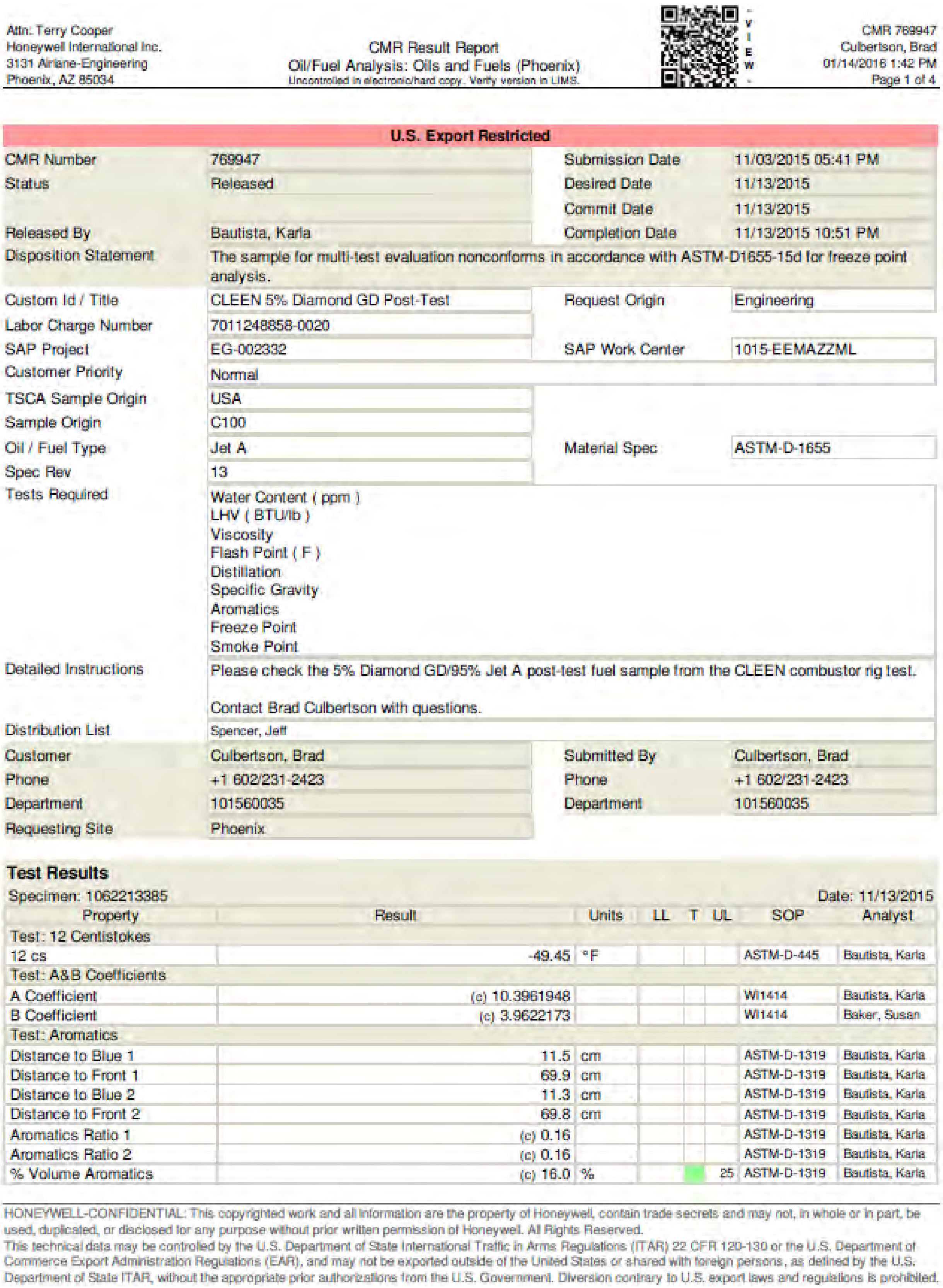
Performance Pretest Analyses of 5% Diamond Green Diesel (Cont)



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CMR Number	769947	Submission Date	11/03/2015 05:41 PM
Status	Released	Desired Date	11/13/2015
		Commit Date	11/13/2015
Released By	Bautista, Karla	Completion Date	11/13/2015 10:51 PM
Disposition Statement	The sample for multi-test evaluation nonconforms in accordance with ASTM-D1655-15d for freeze point analysis.		
Custom Id / Title	CLEEN 5% Diamond GD Post-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Flash Point (F) Distillation Specific Gravity Aromatics Freeze Point Smoke Point		
Detailed Instructions	Please check the 5% Diamond GD/95% Jet A post-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Spencer, Jeff		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213385 Date: 11/13/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-49.45	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.3961948					WI1414	Bautista, Karla
B Coefficient	(c) 3.9622173					WI1414	Baker, Susan
Test: Aromatics							
Distance to Blue 1	11.5	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	69.9	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.3	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	69.8	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.16					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.16					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 16.0	%		🟩	25	ASTM-D-1319	Bautista, Karla

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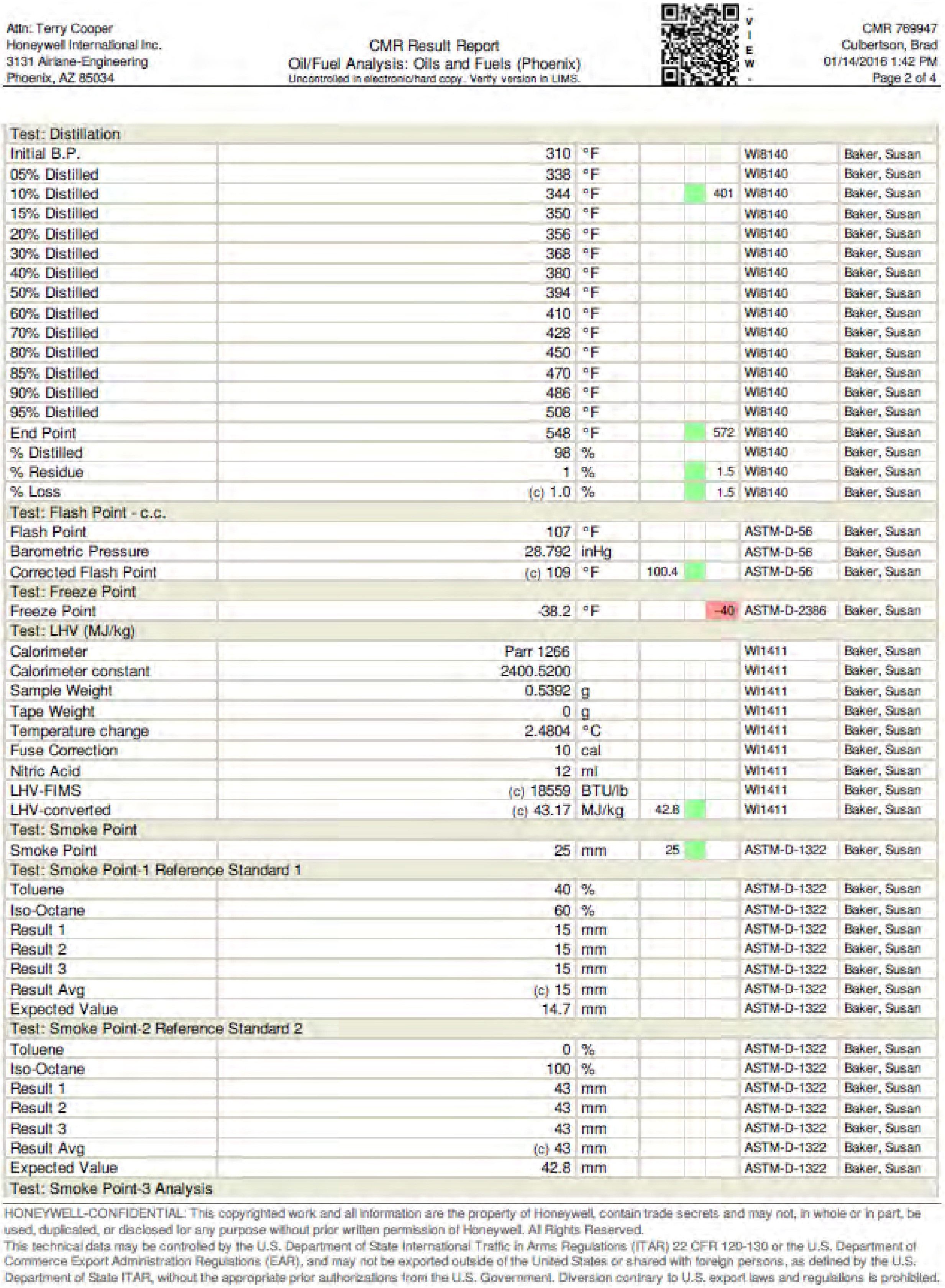
Performance Posttest Analyses of 5% Diamond Green Diesel



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Test: Distillation								
Initial B.P.		310	°F				WI8140	Baker, Susan
05% Distilled		338	°F				WI8140	Baker, Susan
10% Distilled		344	°F		🟩	401	WI8140	Baker, Susan
15% Distilled		350	°F				WI8140	Baker, Susan
20% Distilled		356	°F				WI8140	Baker, Susan
30% Distilled		368	°F				WI8140	Baker, Susan
40% Distilled		380	°F				WI8140	Baker, Susan
50% Distilled		394	°F				WI8140	Baker, Susan
60% Distilled		410	°F				WI8140	Baker, Susan
70% Distilled		428	°F				WI8140	Baker, Susan
80% Distilled		450	°F				WI8140	Baker, Susan
85% Distilled		470	°F				WI8140	Baker, Susan
90% Distilled		486	°F				WI8140	Baker, Susan
95% Distilled		508	°F				WI8140	Baker, Susan
End Point		548	°F		🟩	572	WI8140	Baker, Susan
% Distilled		98	%				WI8140	Baker, Susan
% Residue		1	%		🟩	1.5	WI8140	Baker, Susan
% Loss		(c) 1.0	%		🟩	1.5	WI8140	Baker, Susan
Test: Flash Point - c.c.								
Flash Point		107	°F				ASTM-D-56	Baker, Susan
Barometric Pressure		28.792	inHg				ASTM-D-56	Baker, Susan
Corrected Flash Point		(c) 109	°F	100.4	🟩		ASTM-D-56	Baker, Susan
Test: Freeze Point								
Freeze Point		-38.2	°F			🟥 -40	ASTM-D-2386	Baker, Susan
Test: LHV (MJ/kg)								
Calorimeter		Parr 1266					WI1411	Baker, Susan
Calorimeter constant		2400.5200					WI1411	Baker, Susan
Sample Weight		0.5392	g				WI1411	Baker, Susan
Tape Weight		0	g				WI1411	Baker, Susan
Temperature change		2.4804	°C				WI1411	Baker, Susan
Fuse Correction		10	cal				WI1411	Baker, Susan
Nitric Acid		12	ml				WI1411	Baker, Susan
LHV-FIMS		(c) 18559	BTU/lb				WI1411	Baker, Susan
LHV-converted		(c) 43.17	MJ/kg	42.8	🟩		WI1411	Baker, Susan
Test: Smoke Point								
Smoke Point		25	mm	25	🟩		ASTM-D-1322	Baker, Susan
Test: Smoke Point-1 Reference Standard 1								
Toluene		40	%				ASTM-D-1322	Baker, Susan
Iso-Octane		60	%				ASTM-D-1322	Baker, Susan
Result 1		15	mm				ASTM-D-1322	Baker, Susan
Result 2		15	mm				ASTM-D-1322	Baker, Susan
Result 3		15	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 15	mm				ASTM-D-1322	Baker, Susan
Expected Value		14.7	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-2 Reference Standard 2								
Toluene		0	%				ASTM-D-1322	Baker, Susan
Iso-Octane		100	%				ASTM-D-1322	Baker, Susan
Result 1		43	mm				ASTM-D-1322	Baker, Susan
Result 2		43	mm				ASTM-D-1322	Baker, Susan
Result 3		43	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 43	mm				ASTM-D-1322	Baker, Susan
Expected Value		42.8	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-3 Analysis								

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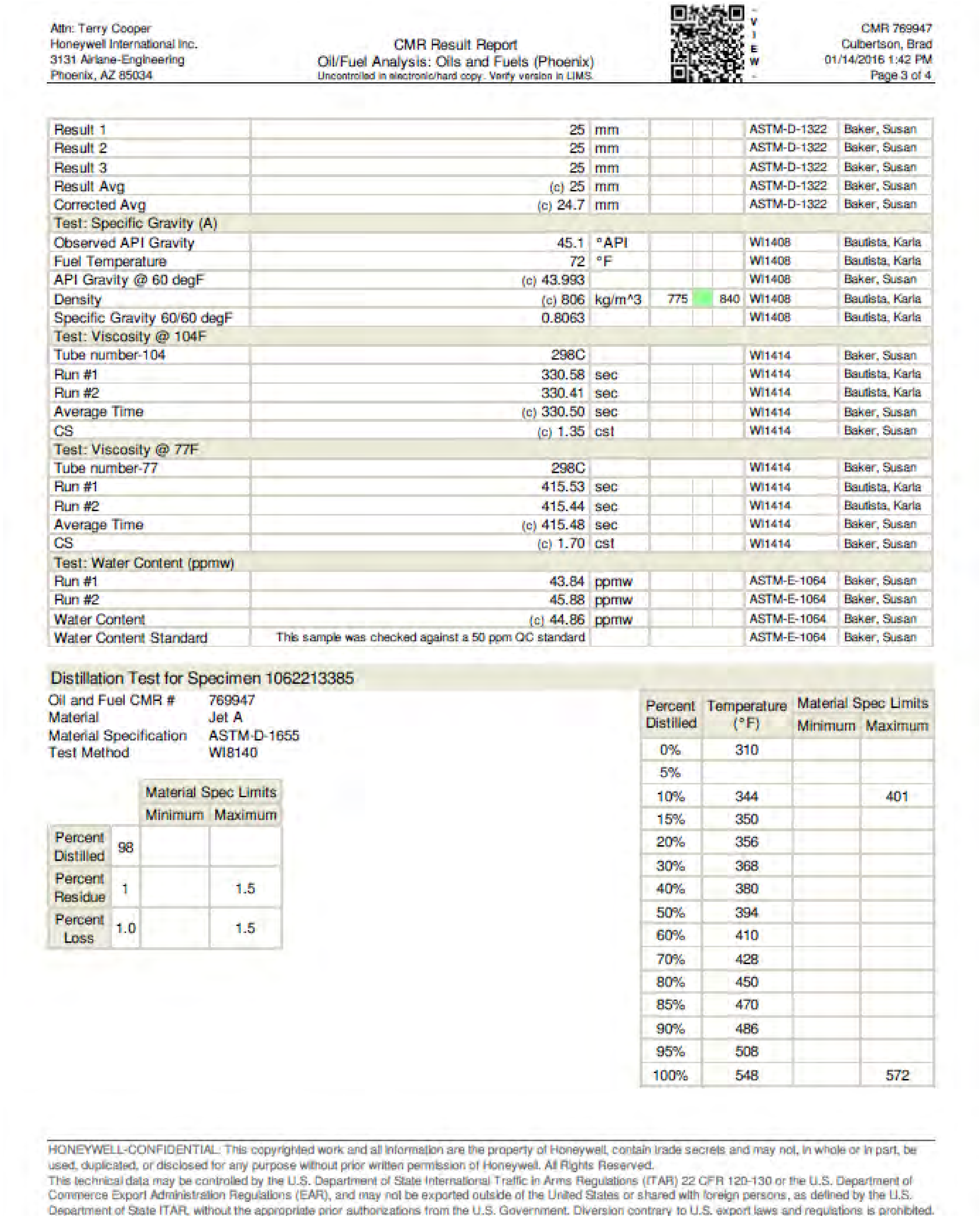
Performance Posttest Analyses of 5% Diamond Green Diesel (Cont)



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Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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Result 1	25	mm				ASTM-D-1322	Baker, Susan
Result 2	25	mm				ASTM-D-1322	Baker, Susan
Result 3	25	mm				ASTM-D-1322	Baker, Susan
Result Avg	(c) 25	mm				ASTM-D-1322	Baker, Susan
Corrected Avg	(c) 24.7	mm				ASTM-D-1322	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	45.1	°API				WI1408	Bautista, Karla
Fuel Temperature	72	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF	(c) 43.993					WI1408	Baker, Susan
Density	(c) 806	kg/m^3	775	🟩	840	WI1408	Bautista, Karla
Specific Gravity 60/60 degF	0.8063					WI1408	Bautista, Karla
Test: Viscosity @ 104F							
Tube number-104	298C					WI1414	Baker, Susan
Run #1	330.58	sec				WI1414	Bautista, Karla
Run #2	330.41	sec				WI1414	Bautista, Karla
Average Time	(c) 330.50	sec				WI1414	Baker, Susan
CS	(c) 1.35	cst				WI1414	Baker, Susan
Test: Viscosity @ 77F							
Tube number-77	298C					WI1414	Baker, Susan
Run #1	415.53	sec				WI1414	Bautista, Karla
Run #2	415.44	sec				WI1414	Bautista, Karla
Average Time	(c) 415.48	sec				WI1414	Baker, Susan
CS	(c) 1.70	cst				WI1414	Baker, Susan
Test: Water Content (ppmw)							
Run #1	43.84	ppmw				ASTM-E-1064	Baker, Susan
Run #2	45.88	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 44.86	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062213385

Oil and Fuel CMR #	769947
Material	Jet A
Material Specification	ASTM-D-1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	98		
Percent Residue	1		1.5
Percent Loss	1.0		1.5

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	310		
5%			
10%	344		401
15%	350		
20%	356		
30%	368		
40%	380		
50%	394		
60%	410		
70%	428		
80%	450		
85%	470		
90%	486		
95%	508		
100%	548		572

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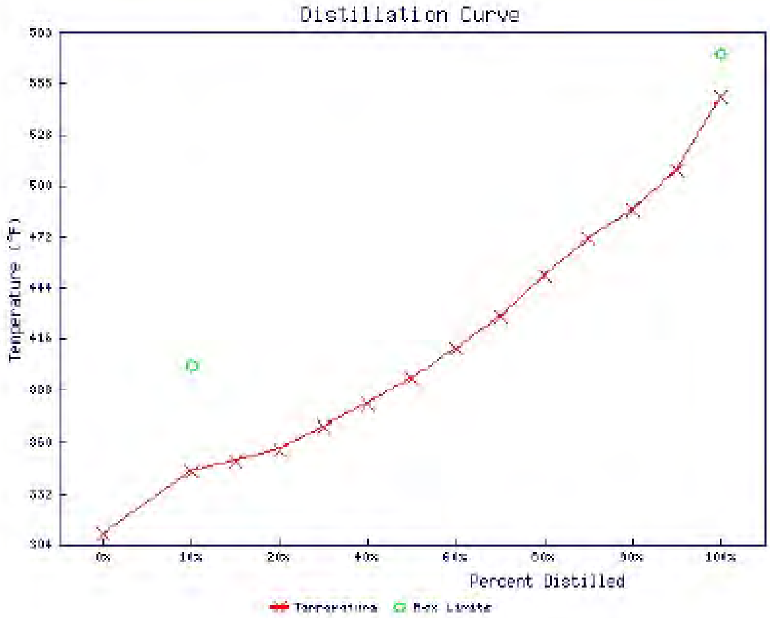
Performance Posttest Analyses of 5% Diamond Green Diesel (Cont)



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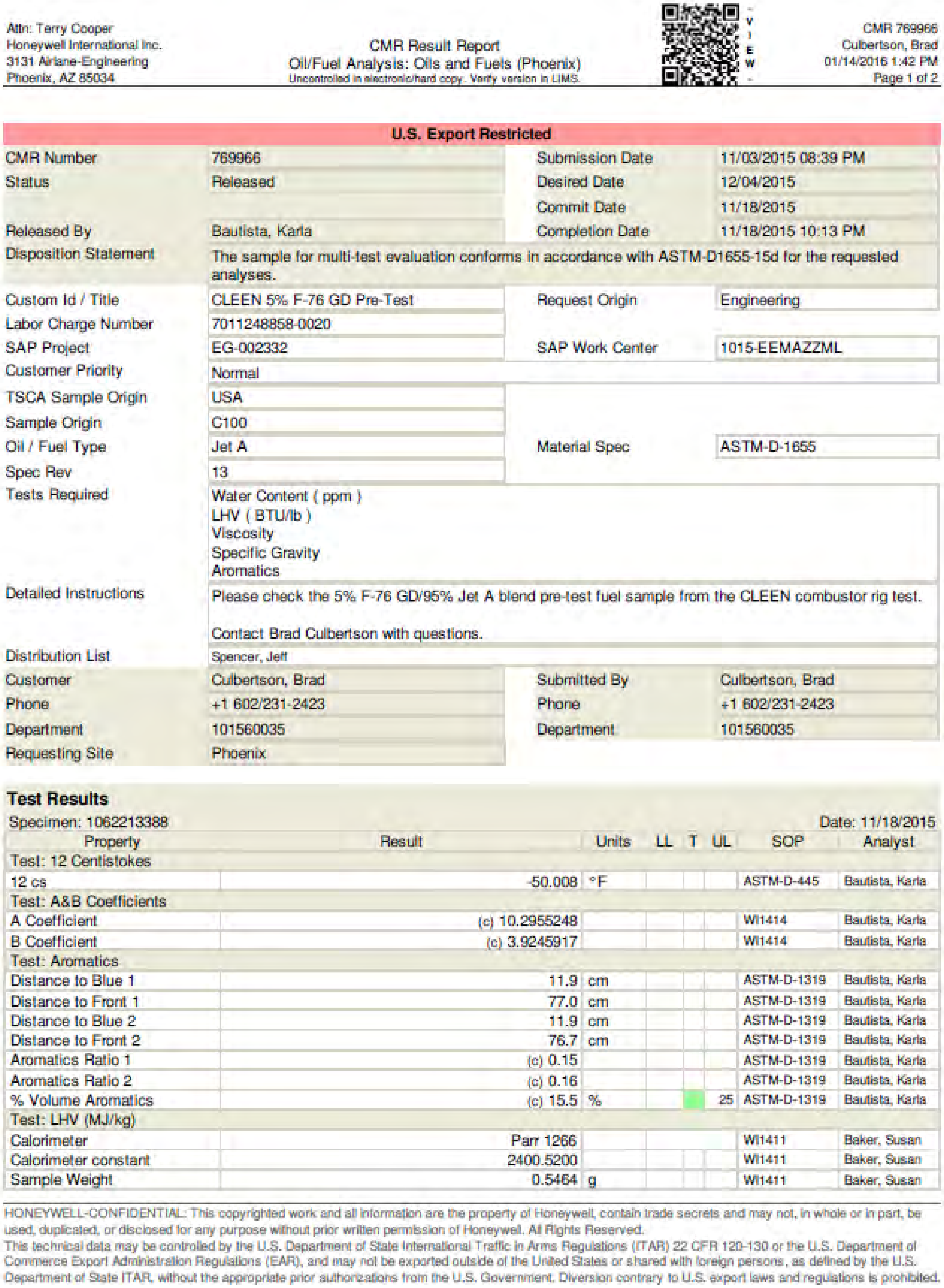
Performance Posttest Analyses of 5% Diamond Green Diesel (Cont)



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Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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Culbertson, Brad
01/14/2016 1:42 PM
Page 1 of 2

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CMR Number	769966	Submission Date	11/03/2015 08:39 PM
Status	Released	Desired Date	12/04/2015
		Commit Date	11/18/2015
Released By	Bautista, Karla	Completion Date	11/18/2015 10:13 PM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the requested analyses.		
Custom Id / Title	CLEEN 5% F-76 GD Pre-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Specific Gravity Aromatics		
Detailed Instructions	Please check the 5% F-76 GD/95% Jet A blend pre-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Spencer, Jeff		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213388 Date: 11/18/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-50.008	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.2955248					WI1414	Bautista, Karla
B Coefficient	(c) 3.9245917					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.9	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	77.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.9	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	76.7	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.15					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.16					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 15.5	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: LHV (MJ/kg)							
Calorimeter	Parr 1266					WI1411	Baker, Susan
Calorimeter constant	2400.5200					WI1411	Baker, Susan
Sample Weight	0.5464	g				WI1411	Baker, Susan

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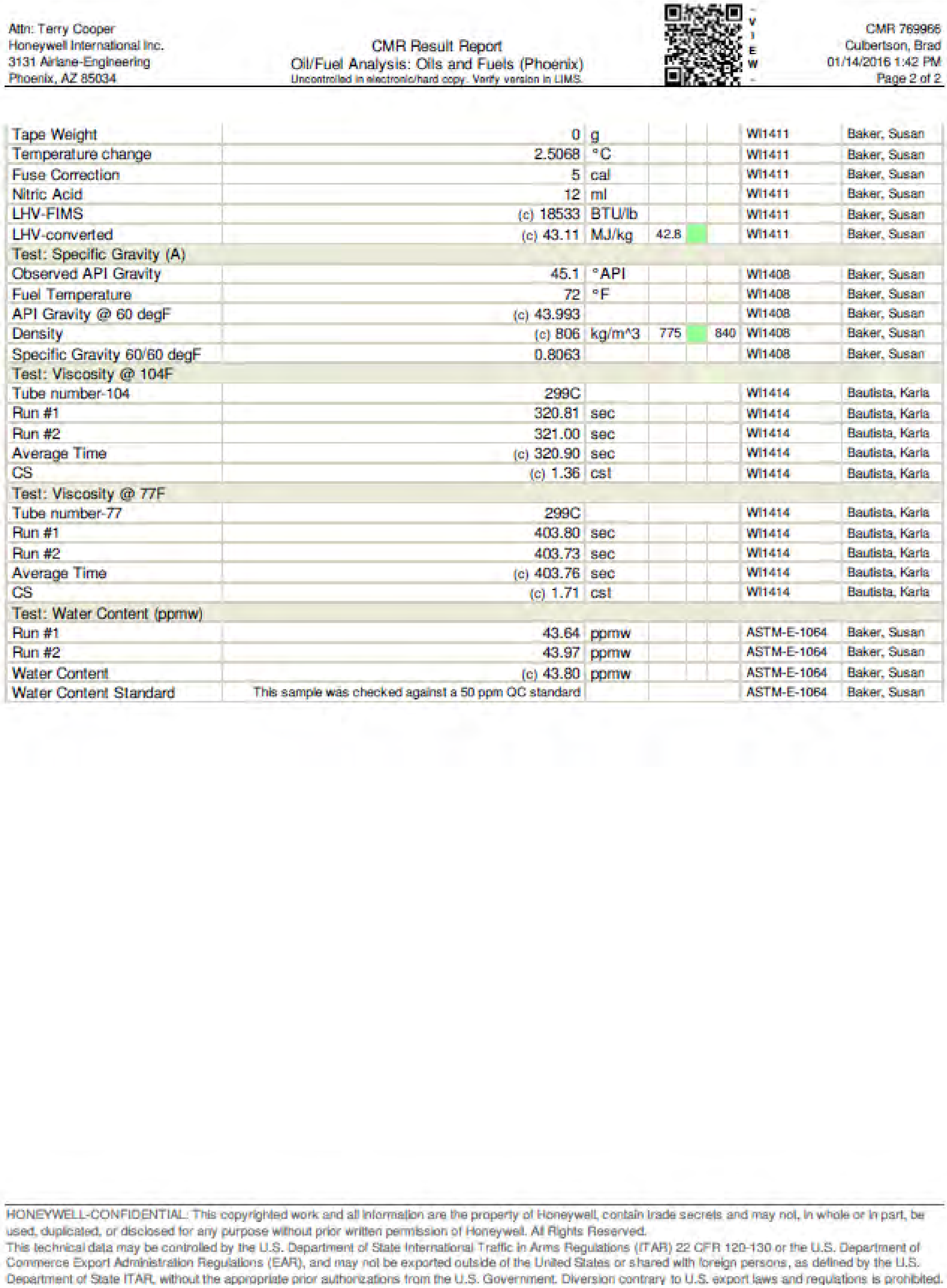
Performance Pretest Analyses of 5% F-76 Green Diesel



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Tape Weight	0	g				WI1411	Baker, Susan
Temperature change	2.5068	°C				WI1411	Baker, Susan
Fuse Correction	5	cal				WI1411	Baker, Susan
Nitric Acid	12	ml				WI1411	Baker, Susan
LHV-FIMS	(c) 18533	BTU/lb				WI1411	Baker, Susan
LHV-converted	(c) 43.11	MJ/kg	42.8	🟩		WI1411	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	45.1	°API				WI1408	Baker, Susan
Fuel Temperature	72	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 43.993					WI1408	Baker, Susan
Density	(c) 806	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8063					WI1408	Baker, Susan
Test: Viscosity @ 104F							
Tube number-104	299C					WI1414	Bautista, Karla
Run #1	320.81	sec				WI1414	Bautista, Karla
Run #2	321.00	sec				WI1414	Bautista, Karla
Average Time	(c) 320.90	sec				WI1414	Bautista, Karla
CS	(c) 1.36	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	299C					WI1414	Bautista, Karla
Run #1	403.80	sec				WI1414	Bautista, Karla
Run #2	403.73	sec				WI1414	Bautista, Karla
Average Time	(c) 403.76	sec				WI1414	Bautista, Karla
CS	(c) 1.71	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	43.64	ppmw				ASTM-E-1064	Baker, Susan
Run #2	43.97	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 43.80	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

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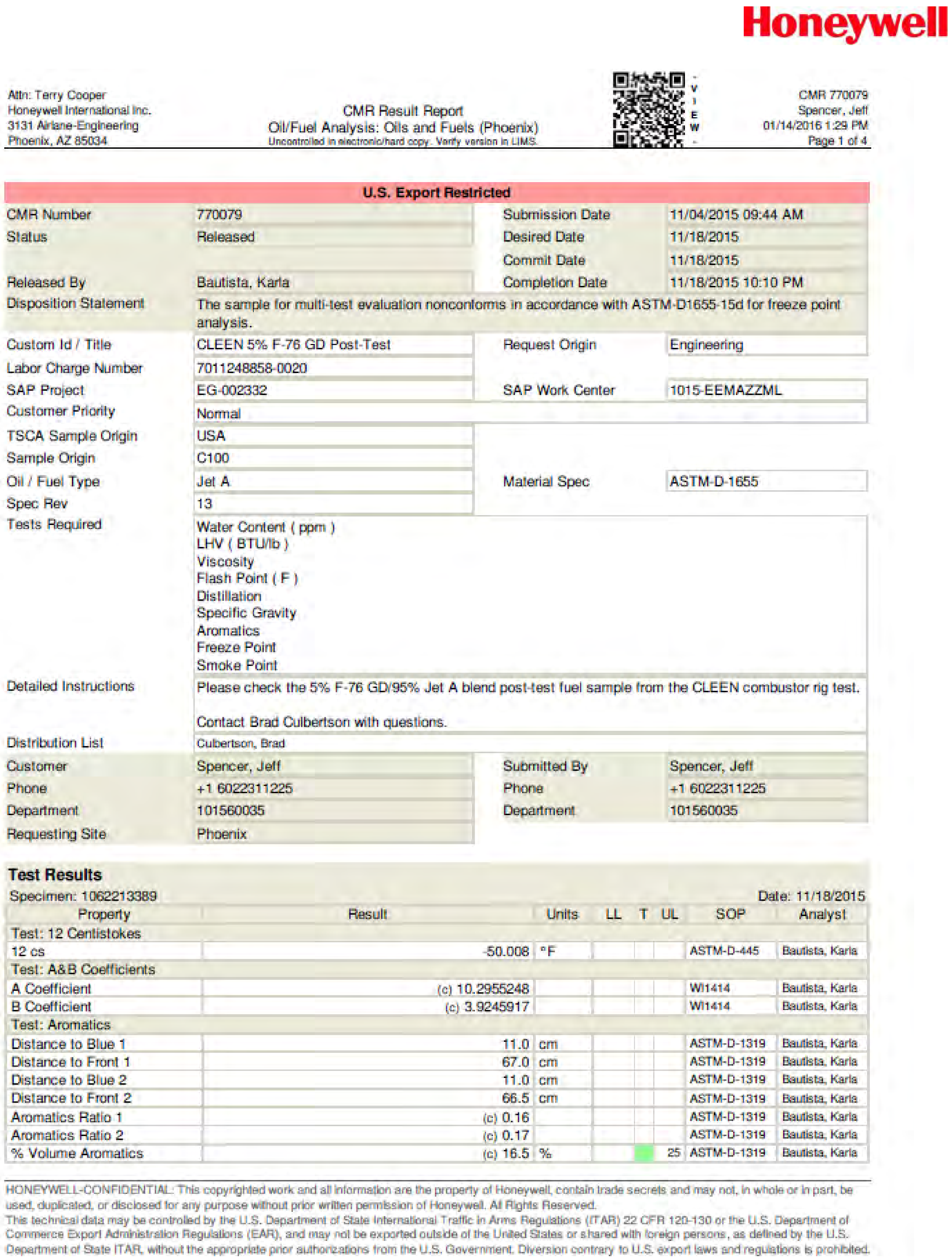
Performance Pretest Analyses of 5% F-76 Green Diesel (Cont)



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Phoenix, AZ 85034

CMR Result Report
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CMR 770079
Spencer, Jeff
01/14/2016 1:29 PM
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CMR Number	770079	Submission Date	11/04/2015 09:44 AM
Status	Released	Desired Date	11/18/2015
		Commit Date	11/18/2015
Released By	Bautista, Karla	Completion Date	11/18/2015 10:10 PM
Disposition Statement	The sample for multi-test evaluation nonconforms in accordance with ASTM-D1655-15d for freeze point analysis.		
Custom Id / Title	CLEEN 5% F-76 GD Post-Test	Request Origin	Engineering
Labor Charge Number	7011248858-0020		
SAP Project	EG-002332	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	C100		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	13		
Tests Required	Water Content (ppm) LHV (BTU/lb) Viscosity Flash Point (F) Distillation Specific Gravity Aromatics Freeze Point Smoke Point		
Detailed Instructions	Please check the 5% F-76 GD/95% Jet A blend post-test fuel sample from the CLEEN combustor rig test. Contact Brad Culbertson with questions.		
Distribution List	Culbertson, Brad		
Customer	Spencer, Jeff	Submitted By	Spencer, Jeff
Phone	+1 6022311225	Phone	+1 6022311225
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062213389 Date: 11/18/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-50.008	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.2955248					WI1414	Bautista, Karla
B Coefficient	(c) 3.9245917					WI1414	Bautista, Karla
Test: Aromatics							
Distance to Blue 1	11.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	67.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	11.0	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	66.5	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.16					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.17					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 16.5	%		🟩	25	ASTM-D-1319	Bautista, Karla

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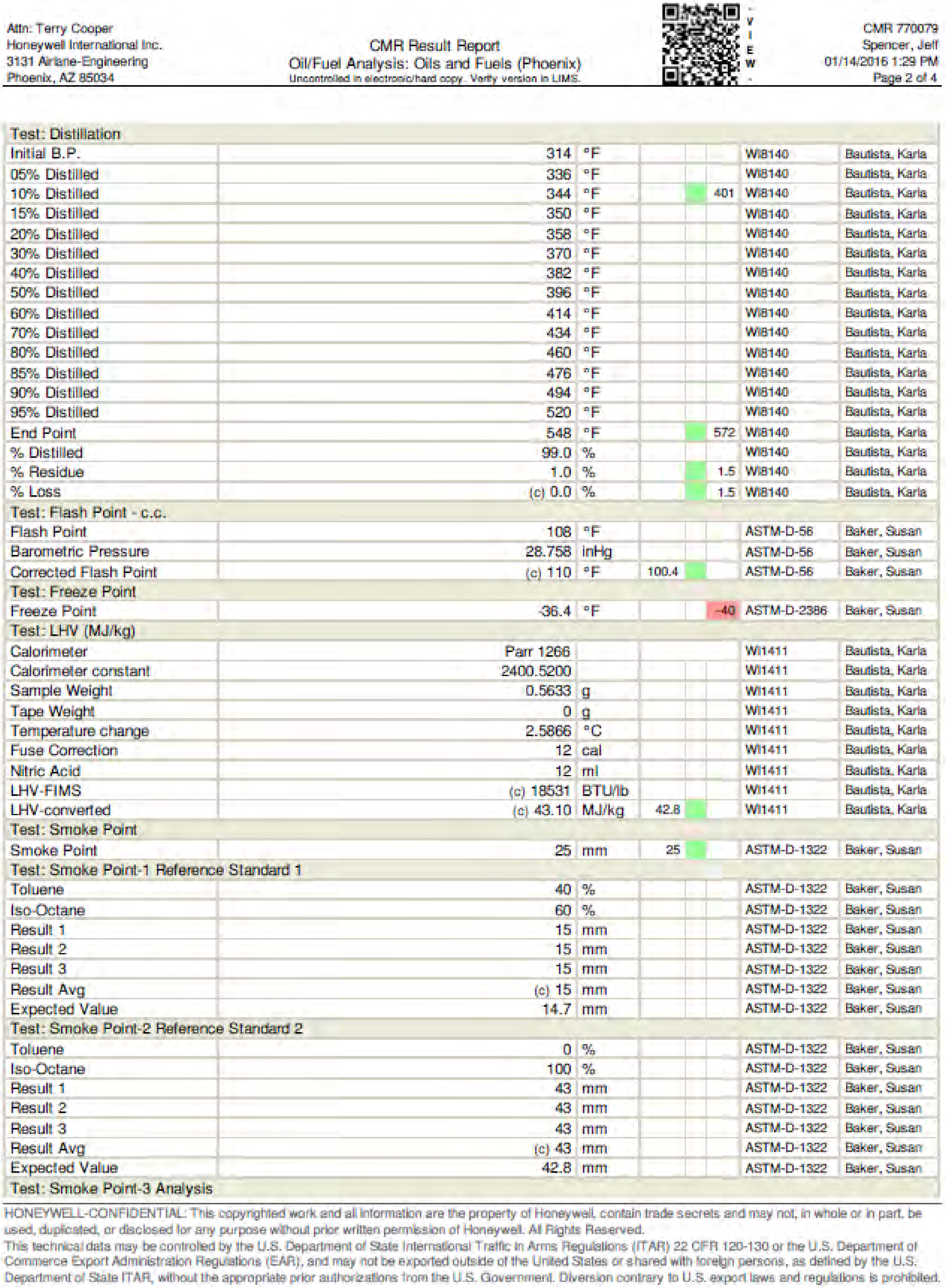
Performance Posttest Analyses of 5% F-76 Green Diesel



Attn: Terry Cooper
Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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Test: Distillation								
Initial B.P.		314	°F				WI8140	Bautista, Karla
05% Distilled		336	°F				WI8140	Bautista, Karla
10% Distilled		344	°F		🟩	401	WI8140	Bautista, Karla
15% Distilled		350	°F				WI8140	Bautista, Karla
20% Distilled		358	°F				WI8140	Bautista, Karla
30% Distilled		370	°F				WI8140	Bautista, Karla
40% Distilled		382	°F				WI8140	Bautista, Karla
50% Distilled		396	°F				WI8140	Bautista, Karla
60% Distilled		414	°F				WI8140	Bautista, Karla
70% Distilled		434	°F				WI8140	Bautista, Karla
80% Distilled		460	°F				WI8140	Bautista, Karla
85% Distilled		476	°F				WI8140	Bautista, Karla
90% Distilled		494	°F				WI8140	Bautista, Karla
95% Distilled		520	°F				WI8140	Bautista, Karla
End Point		548	°F		🟩	572	WI8140	Bautista, Karla
% Distilled		99.0	%				WI8140	Bautista, Karla
% Residue		1.0	%		🟩	1.5	WI8140	Bautista, Karla
% Loss		(c) 0.0	%		🟩	1.5	WI8140	Bautista, Karla
Test: Flash Point - c.c.								
Flash Point		108	°F				ASTM-D-56	Baker, Susan
Barometric Pressure		28.758	inHg				ASTM-D-56	Baker, Susan
Corrected Flash Point		(c) 110	°F	100.4	🟩		ASTM-D-56	Baker, Susan
Test: Freeze Point								
Freeze Point		-36.4	°F			🟥 -40	ASTM-D-2386	Baker, Susan
Test: LHV (MJ/kg)								
Calorimeter		Parr 1266					WI1411	Bautista, Karla
Calorimeter constant		2400.5200					WI1411	Bautista, Karla
Sample Weight		0.5633	g				WI1411	Bautista, Karla
Tape Weight		0	g				WI1411	Bautista, Karla
Temperature change		2.5866	°C				WI1411	Bautista, Karla
Fuse Correction		12	cal				WI1411	Bautista, Karla
Nitric Acid		12	ml				WI1411	Bautista, Karla
LHV-FIMS		(c) 18531	BTU/lb				WI1411	Bautista, Karla
LHV-converted		(c) 43.10	MJ/kg	42.8	🟩		WI1411	Bautista, Karla
Test: Smoke Point								
Smoke Point		25	mm	25	🟩		ASTM-D-1322	Baker, Susan
Test: Smoke Point-1 Reference Standard 1								
Toluene		40	%				ASTM-D-1322	Baker, Susan
Iso-Octane		60	%				ASTM-D-1322	Baker, Susan
Result 1		15	mm				ASTM-D-1322	Baker, Susan
Result 2		15	mm				ASTM-D-1322	Baker, Susan
Result 3		15	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 15	mm				ASTM-D-1322	Baker, Susan
Expected Value		14.7	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-2 Reference Standard 2								
Toluene		0	%				ASTM-D-1322	Baker, Susan
Iso-Octane		100	%				ASTM-D-1322	Baker, Susan
Result 1		43	mm				ASTM-D-1322	Baker, Susan
Result 2		43	mm				ASTM-D-1322	Baker, Susan
Result 3		43	mm				ASTM-D-1322	Baker, Susan
Result Avg		(c) 43	mm				ASTM-D-1322	Baker, Susan
Expected Value		42.8	mm				ASTM-D-1322	Baker, Susan
Test: Smoke Point-3 Analysis								

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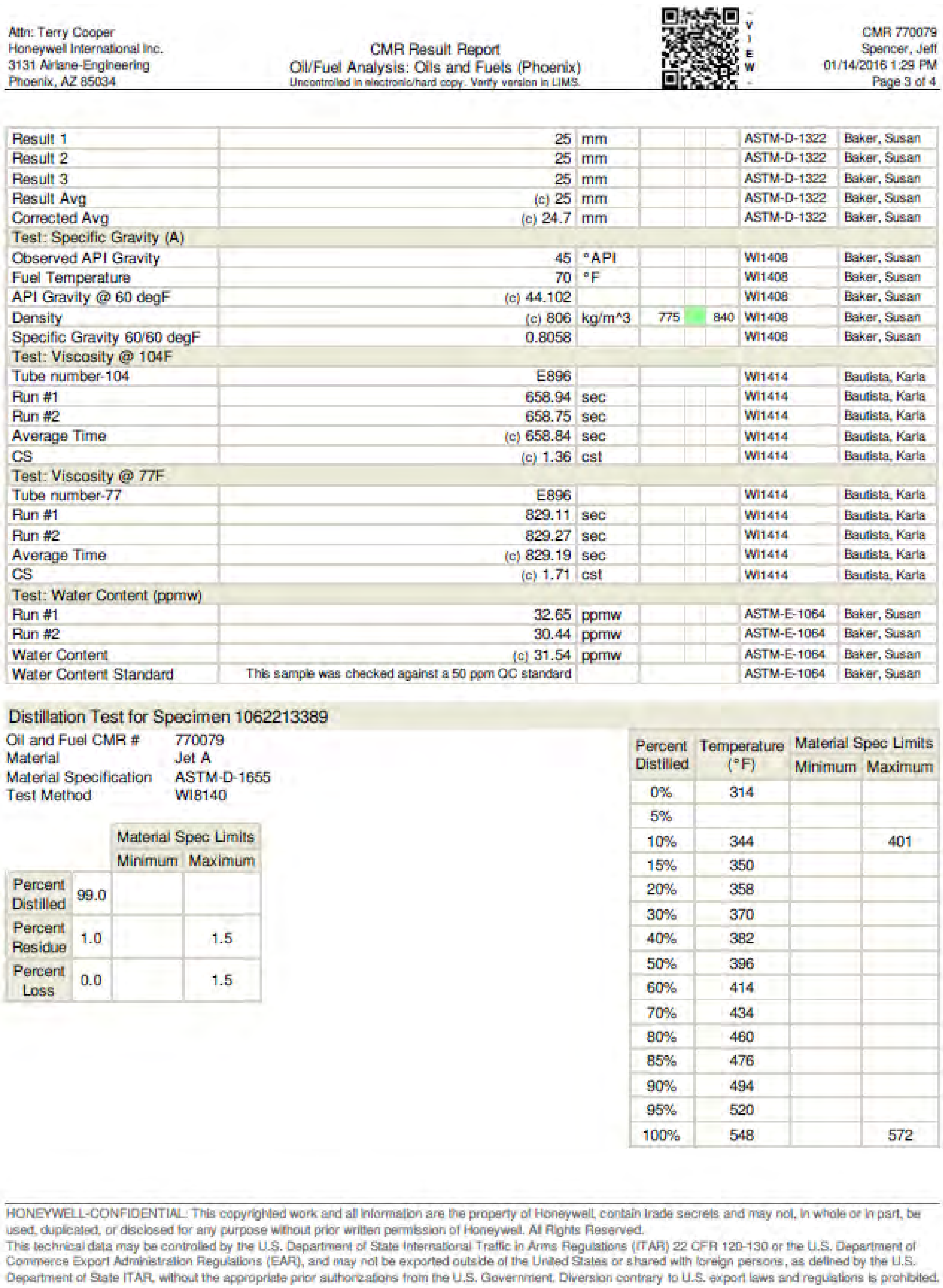
Performance Posttest Analyses of 5% F-76 Green Diesel (Cont)



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CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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VIEW

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01/14/2016 1:29 PM
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Result 1	25	mm				ASTM-D-1322	Baker, Susan
Result 2	25	mm				ASTM-D-1322	Baker, Susan
Result 3	25	mm				ASTM-D-1322	Baker, Susan
Result Avg	(c) 25	mm				ASTM-D-1322	Baker, Susan
Corrected Avg	(c) 24.7	mm				ASTM-D-1322	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	45	°API				WI1408	Baker, Susan
Fuel Temperature	70	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 44.102					WI1408	Baker, Susan
Density	(c) 806	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8058					WI1408	Baker, Susan
Test: Viscosity @ 104F							
Tube number-104	E896					WI1414	Bautista, Karla
Run #1	658.94	sec				WI1414	Bautista, Karla
Run #2	658.75	sec				WI1414	Bautista, Karla
Average Time	(c) 658.84	sec				WI1414	Bautista, Karla
CS	(c) 1.36	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F							
Tube number-77	E896					WI1414	Bautista, Karla
Run #1	829.11	sec				WI1414	Bautista, Karla
Run #2	829.27	sec				WI1414	Bautista, Karla
Average Time	(c) 829.19	sec				WI1414	Bautista, Karla
CS	(c) 1.71	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	32.65	ppmw				ASTM-E-1064	Baker, Susan
Run #2	30.44	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 31.54	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062213389

Oil and Fuel CMR #	770079
Material	Jet A
Material Specification	ASTM-D-1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	99.0		
Percent Residue	1.0		1.5
Percent Loss	0.0		1.5

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	314		
5%			
10%	344		401
15%	350		
20%	358		
30%	370		
40%	382		
50%	396		
60%	414		
70%	434		
80%	460		
85%	476		
90%	494		
95%	520		
100%	548		572

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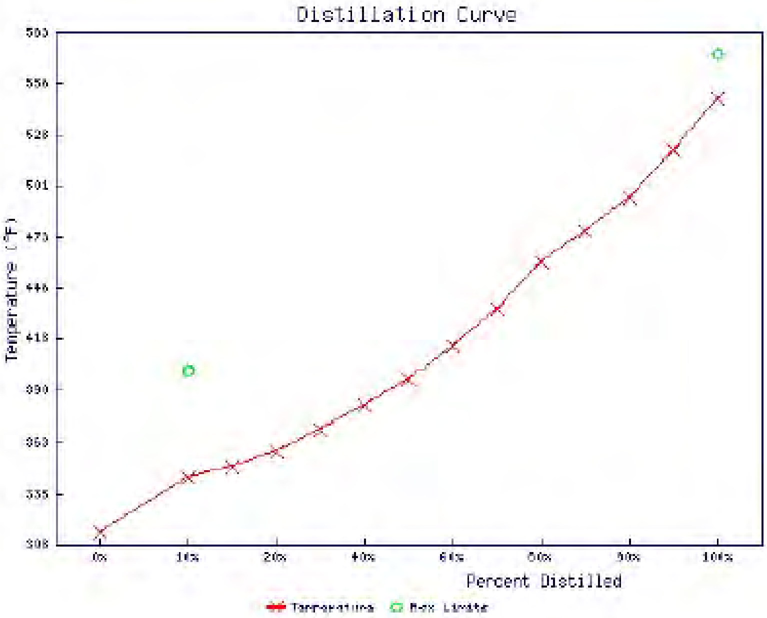
Performance Posttest Analyses of 5% F-76 Green Diesel (Cont)



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Performance Posttest Analyses of 5% F-76 Green Diesel (Cont)

Appendix 2. Combustor Exit Temperature Contour Plots

(5 pages)

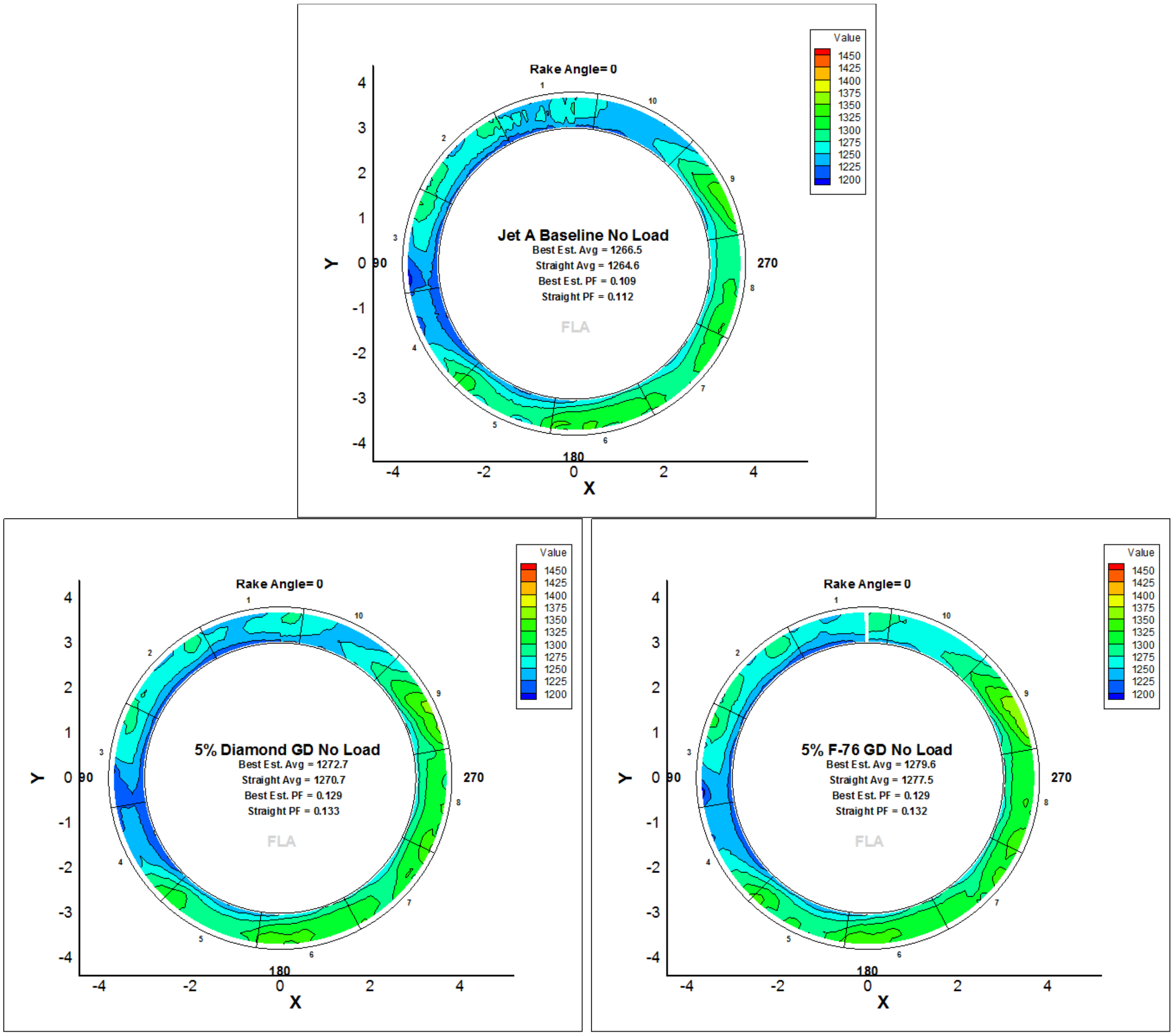

Figure 2–1. No Load Temperature Contour Plots.

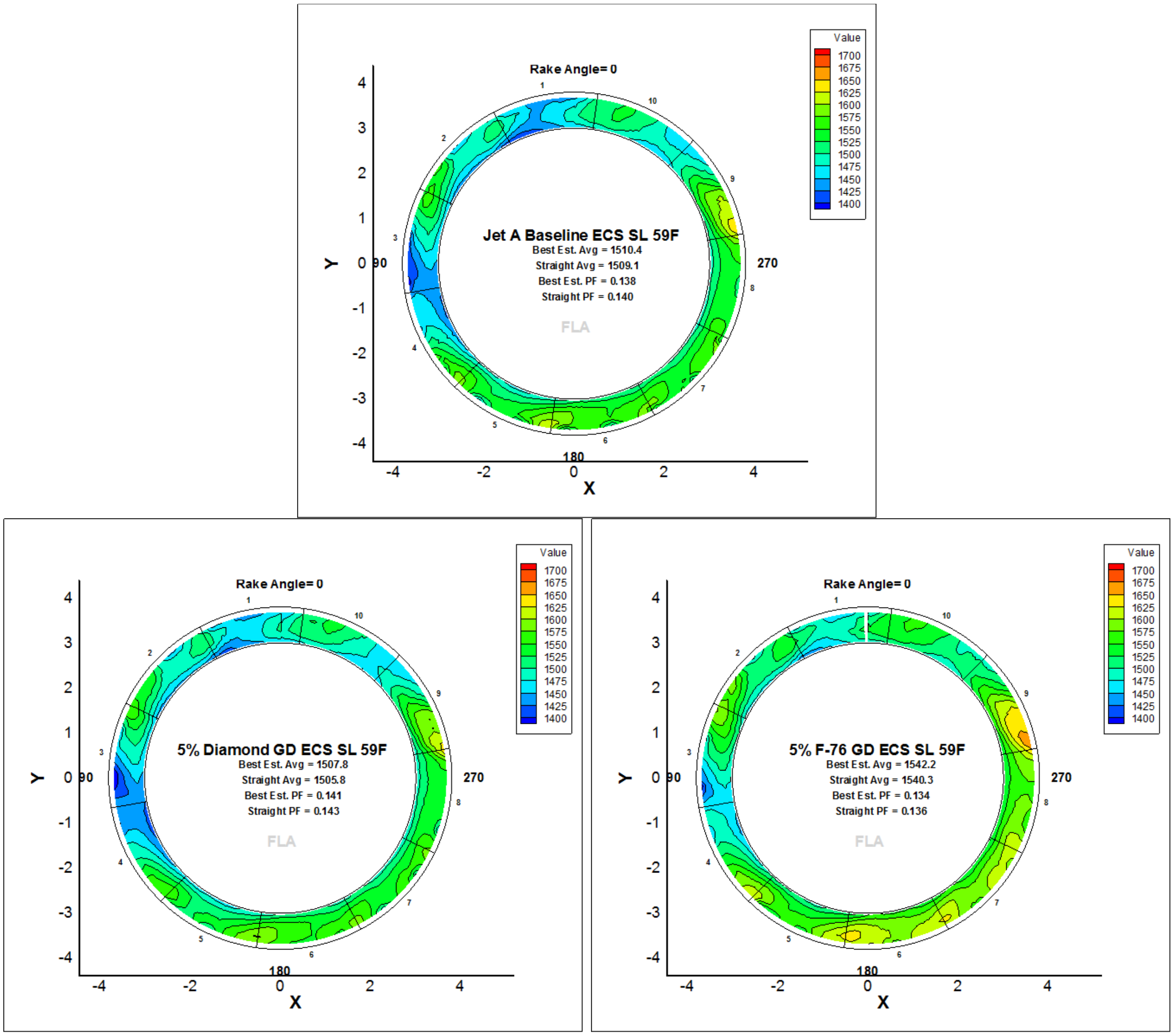

Figure 2–2. ECS SL 59°F Temperature Contour Plots.

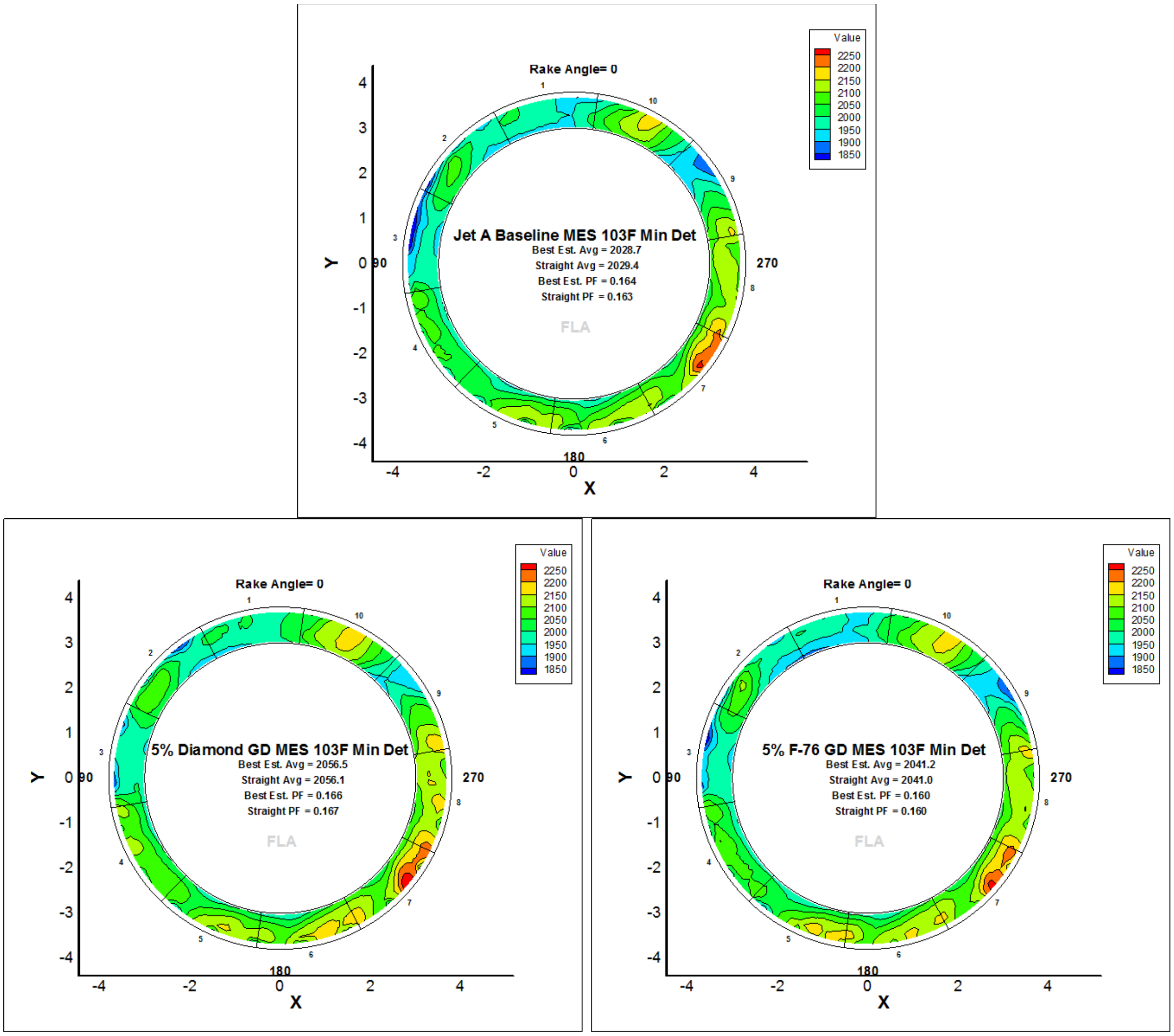

Figure 2–3. MES 103°F Minimum Deteriorated Temperature Contour Plots.

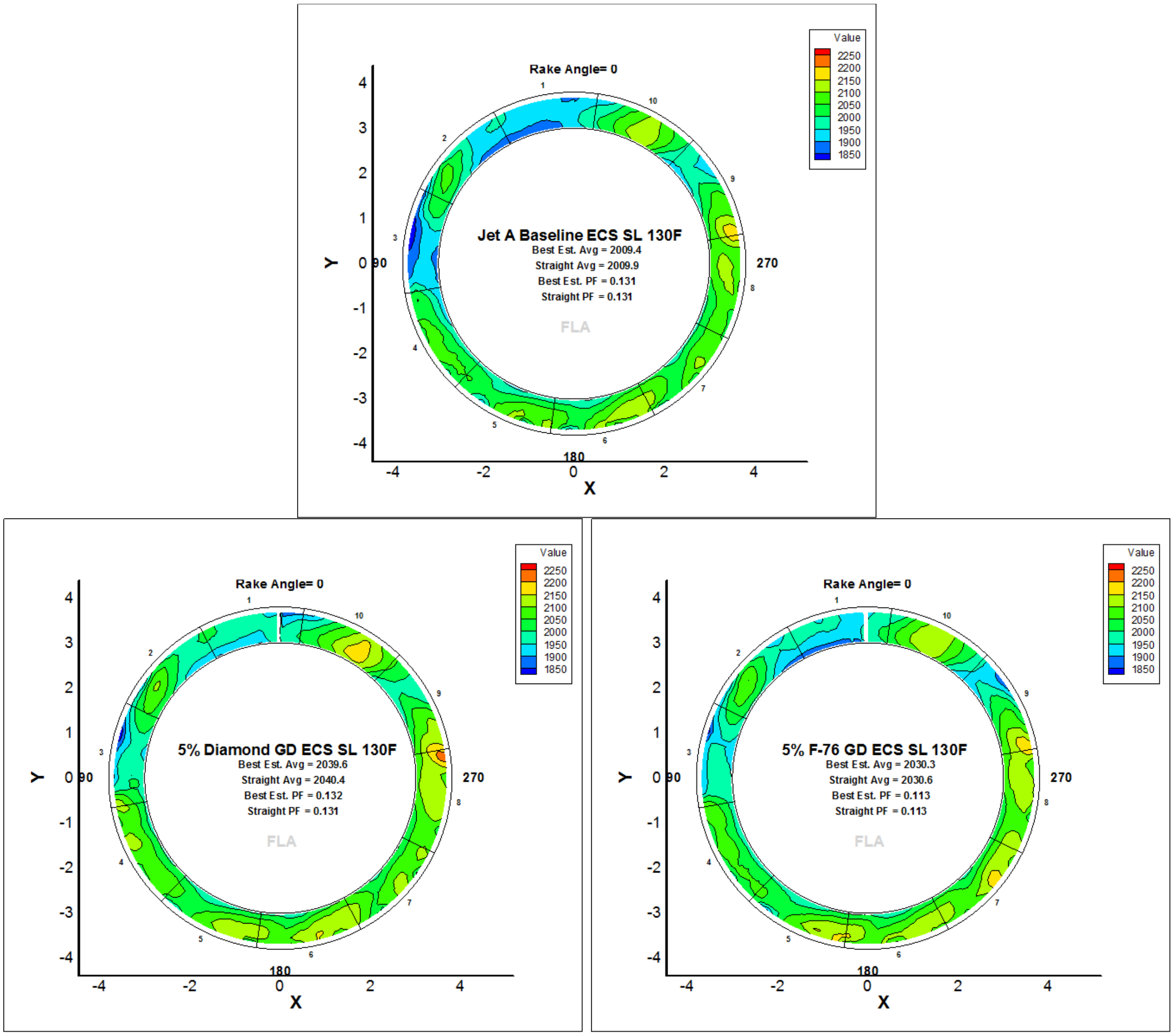

Figure 2–4. ECS SL 130°F Temperature Contour Plots.

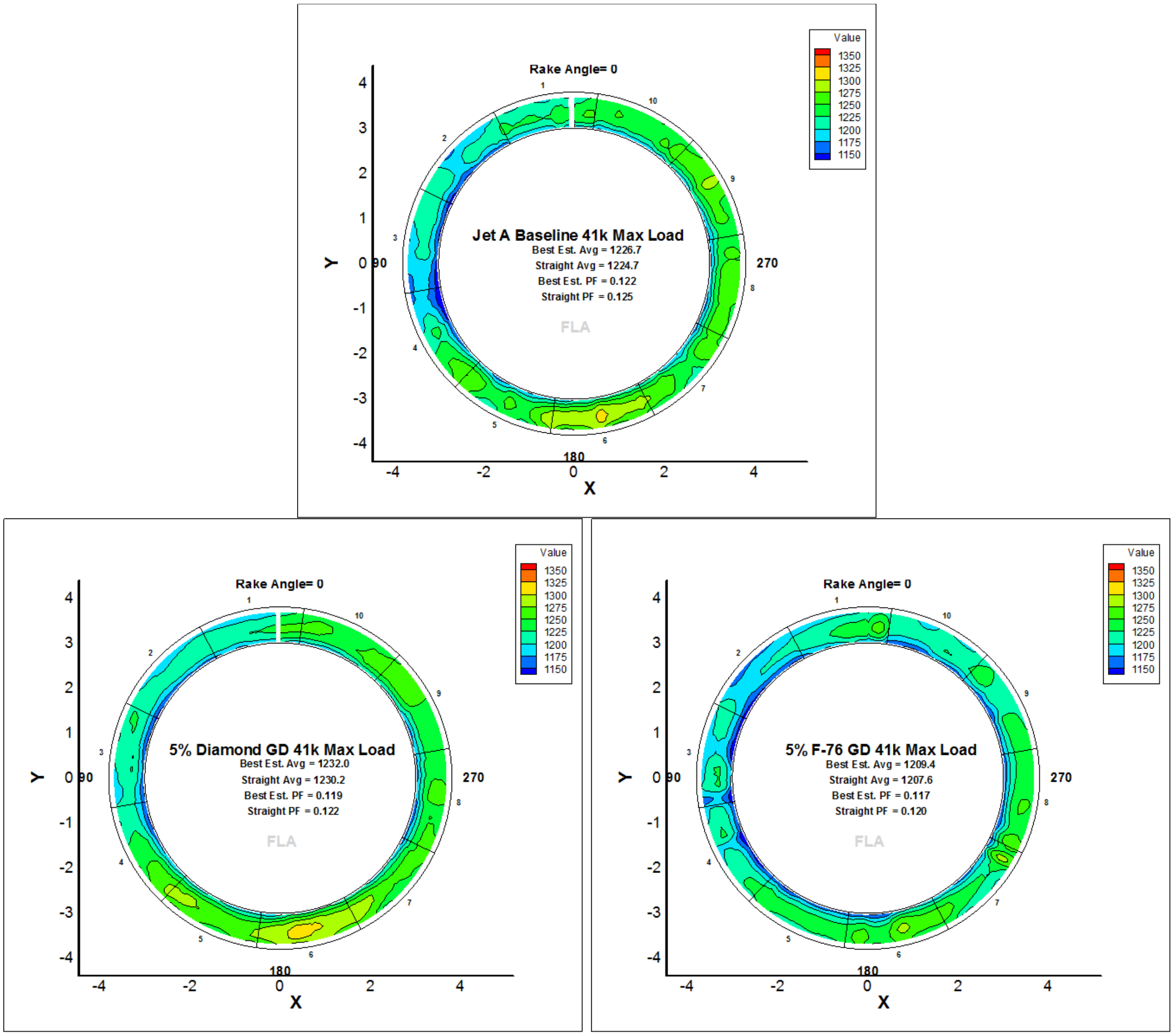

Figure 2–5. 41k Maximum Load Temperature Contour Plots.

Honeywell

Appendix 3. Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development Program
Test Report to Determine the Effects of Alternative Fuel Blends on APU Cold and Altitude Starting
Public Version
(Honeywell Document 21-15850)

(34 pages)

Honeywell Aerospace
111 S. 34th St., P.O. Box 52181
Phoenix, AZ 85072-2181

Honeywell

CAGE 99193

CONTINUOUS LOWER ENERGY, EMISSIONS AND NOISE (CLEEN) TECHNOLOGIES DEVELOPMENT PROGRAM

TEST REPORT TO DETERMINE THE EFFECTS OF ALTERNATIVE FUEL BLENDS ON APU COLD AND ALTITUDE STARTING

PUBLIC VERSION

21-15850

MARCH 24, 2016

Approved By: ______________________
Thomas F. Johnson, Program Manager
Alternative Fuel Evaluation Program

Approved By: Eric Blatt
Eric Blatt, Program Manager
CLEEN Technologies Development Program

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ENGINEERING - Release - 25 Mar 2016 11:29:31 MST - Printed on 28 Mar 2016

REVISION HISTORY

Rev	By	Approved	Date	Revision Summary
—	LAQ	T. Johnson E. Blatt	March 24, 2016	Initial issue.

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LIST OF ACRONYMS

Acronym	**Definition**
APU	Auxiliary Power Unit
CLEEN	Continuous Lower Energy, Emissions and Noise
ECS	Environmental Control System
EGT	Exhaust Gas Temperature
FAA	Federal Aviation Administration
GD	Green Diesel
LACC-1	Large Altitude Cold Chamber - 1
MES	Main Engine Starting
RTL	Ready-To-Load
SK	Synthetic Kerosene

1.0 INTRODUCTION

This document, prepared by Honeywell Aerospace, Phoenix, Arizona (hereinafter referred to as Honeywell), presents the results from tests performed in order to determine the effect of alternative fuel blends on a 131-9[A] auxiliary power unit (APU) starting.

Testing the alternative fuel was part of the Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development Program, Federal Aviation Administration (FAA) Agreement No. DTFAWA-10-C-00040. This test report will be submitted to the FAA for review in accordance with contract data requirements.

This is a development test in support of alternative fuel evaluations. The objective of this test is to determine if select alternative fuels negatively impact APU cold and altitude starting. For the purpose of the alternative fuel testing, a Honeywell development 131-9[A] APU [serial number (S/N) D-3207] was the test asset and unit under test.

1.1 Miscellaneous Information

APU Project Engineers:	Matt Greenman, (602) 231-2984
Engine P/N:	3800708-1
Engine S/N:	D-3207
Test Type:	Development Test
Work Request Numbers:	614199 – CLEEN I Start Testing
Advanced Technology Project Engineer:	Tom Johnson (602) 231-3509
Combustion Engineer:	Brad Culbertson (602) 231-2423

1.2 Test Location

All of the testing was conducted at Honeywell Aerospace in Phoenix, AZ. The APU was installed into the Large Altitude Cold Chamber - 1 (LACC-1) facility for the cold and altitude start testing.

1.3 Referenced Documents

Document Number	Title
ASTM D1655	Standard Specification for Aviation Turbine Fuels
MIL-PRF-23699	Lubricating Oil, Aircraft Turbine Engine, Synthetic Base, NATO Code Numbers: O-152, O-154, O-156, O-167
21-15784A	Test Report Evaluation of 100 Percent CHCJ-5 Fuel in the 131-9 APU Combustor Rig
31-13939D	Acceptance Test Procedure for the 131-9[A] Auxiliary Power Unit P/N 3800708-1 for the Airbus A319/A320/A321 Aircraft
31-12048A-3F	Model Specification for the 131-9[A] Gas Turbine Auxiliary Power Unit P/N 3800708-1, Category I (Essential)

2.0 OBJECTIVES AND SUCCESS CRITERIA

This testing was conducted to determine the effect of two different alternative fuels. The first alternative fuel was a 50/50 blend of Virent Synthetic Kerosene (SK) and Jet A. The second alternative fuel was a blend containing 2 percent Diamond Green Diesel (GD) and 98 percent Jet A. The evaluations attempted to determine the effect of either alternative fuel blend on cold and altitude starting of the 131-9[A] APU, used in the Airbus A320 aircraft. The 131-9[A] APU has a reverse flow annular combustion system that is representative of other APUs that use a reverse flow annular combustion system. The fuel system is designed with dual-orifice atomizers which help to provide sufficient atomization at difficult starting regimes, such as cold temperatures and high altitudes.

The neat Virent SK was provided by the FAA and produced by Virent. The neat Diamond GD was supplied by the Boeing Company and was produced by Valero Energy.

The test results with the two alternative fuel blends were compared to results from baseline testing conducted using conventional petroleum-derived Jet A fuel. The following fuels were used during the testing:

- Baseline – ASTM D1655, Jet A
- Alternate – 50/50 Blend of Virent Synthetic Kerosene (SK) and Jet A
- Alternate – Blend of 2 percent Diamond Green Diesel and 98 percent Jet A

3.0 TEST EQUIPMENT

3.1 Test Item Description

Model 131-9[A] APU S/N D-3207 is a development asset of Honeywell and has been used for various development programs throughout its history.

The 131-9[A] APU was designed to provide main engine starting power, air to the aircraft environmental control system (ECS), and electrical power generation. The 131-9[A] series APU delivers compressed (bleed) air, shaft power, or a combination of both for the A320 family (Figure 1). The 131-9[A] is a single-shaft, constant speed, load-compressor APU. The engine has a single radial engine compressor, a reverse-flow annular combustor, and a two-stage axial turbine. The bleed air is extracted from a radial load compressor.

Figure 1. 131-9[A] APU Used in the Airbus A320 Aircraft.

Figure 2 shows a cut-out of a 131-9[A] APU which illustrates the engine and load compressor flow paths. The engine compressor provides air to the combustor and turbine stages, whereas load compressor air is extracted for aircraft uses such as ECS or main engine starting (MES).

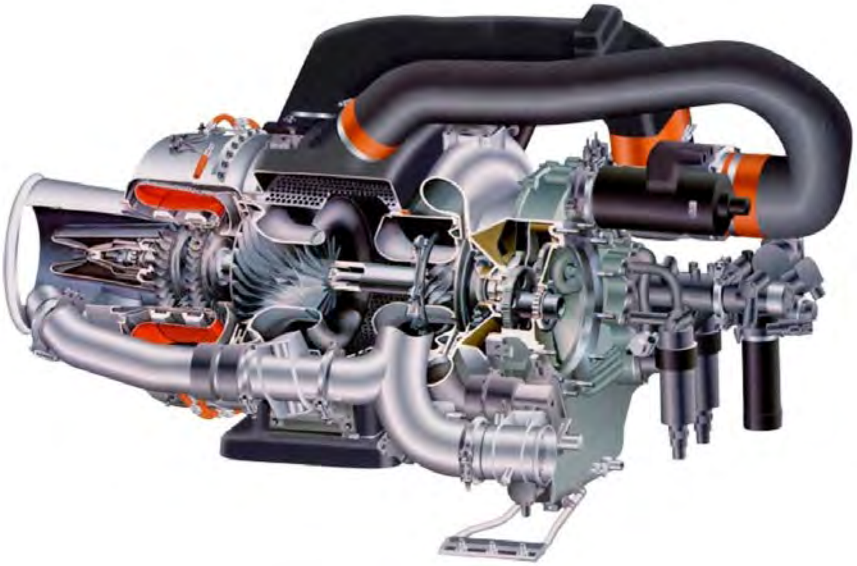


Figure 2. 131-9[A] APU.

3.2 Test Cell Configuration

The 131-9[A] APU was installed in LACC-1, shown in Figure 3, in order to evaluate the effect of the alternative fuel blends on cold and altitude starting.

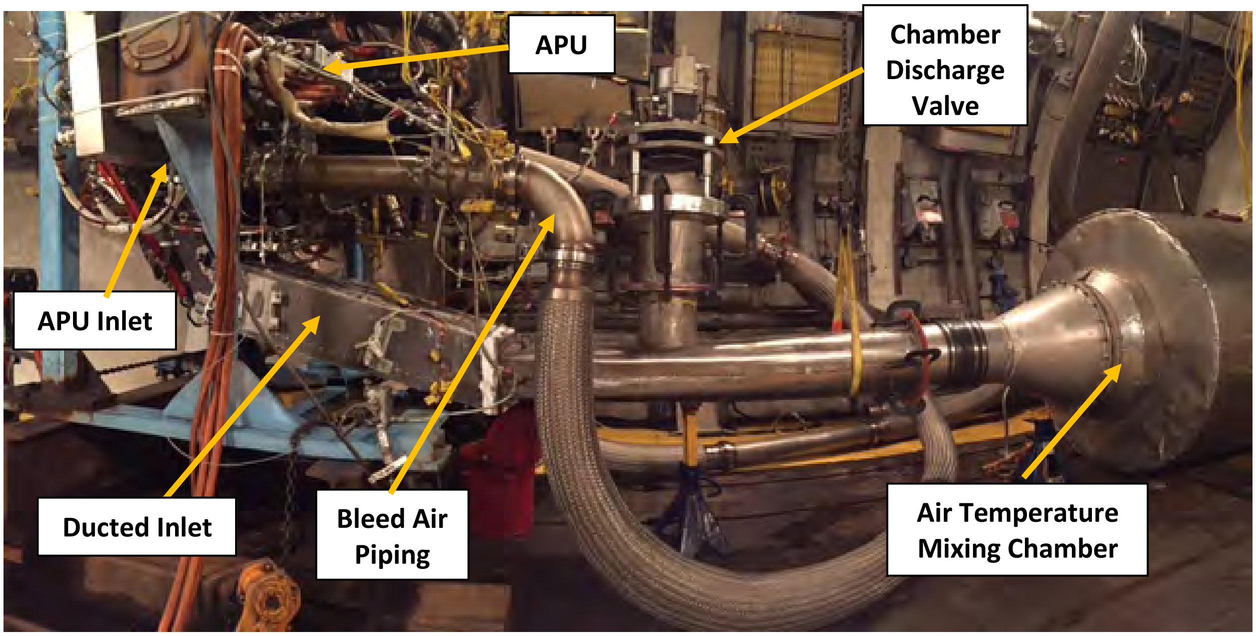


Figure 3. 131-9[A] Setup in the Honeywell Large Altitude Control Chamber 1 (LACC-1).

The LACC-1 test setup used a simulated aircraft installation including the generator and electric starter. The battery cart system, used to provide DC electricity to the starter, was installed outside the chamber and provided electric power for each start.

Altitude, air inlet temperature, air inlet pressure, exhaust pressure conditioning and variation were controlled manually by a test cell technician, by controlling airflow valves, ejectors, and ram air (pressure delta between APU inlet and exhaust). Ram air delta pressure was manually controlled and is read in inches H_2O at the test cell control panel.

For start test evaluations, a cold box, constructed of insulating foam panels, was installed around the APU to create an enclosure to cold soak the engine. Liquid nitrogen was injected into the enclosure during cold soaks to simulate various compartment temperatures. Liquid nitrogen injection was temperature controlled, with fans inside the cold box to prevent stratification.

3.3 Fuels

The specific gravity of the test fuels were very similar. The Honeywell-Phoenix Jet A fuel specific gravity was 0.818, the Virent 50/50 blend was 0.819, and the 2 percent Diamond GD blend was 0.817. Other fuel properties of the three fuels are shown in Table 1. Once delivered to the test cell, the fuel drums were placed outside the altitude chamber on a spill pallet, shown in Figure 4. Safety requirements were closely followed, including properly grounding the drums, installation of a flame arrestor, and wearing applicable personal protection equipment.

Table 1. Critical Fuel Properties

	Jet A Baseline	50% Virent SK Blend	2% Diamond GD Blend
	CMR 776649	CMR 776015	CMR 776201
Density, kg/m^3	0.818	0.819	0.817
Viscosity at 25°C, cSt	1.80	1.90	1.83
Viscosity at 40°C, cSt	1.42	1.49	1.44
12cSt Temperature, °C (1)	-42.4	-39.9	-41.4
Freeze Point, °C	-43.0	-48.0	-41.0
Calculated			

The Jet A fuel was provided from the laboratory fuel system and was plumbed to the test cell via flexible lines, which can be seen in Figure 4. Between fuel evaluations, the subsequent fuel was thoroughly flushed through the fuel system. The APU was operated with the fuel for approximately ten minutes prior to sampling the fuel at the APU fuel control inlet. Fuel samples were submitted to the Honeywell Chemistry Laboratory and analyzed for freeze point, specific gravity, and viscosity to ensure the fuel system had been sufficiently purged.

To ensure the fuel was properly conditioned to the test point temperature, a long copper coil was installed inside the altitude chamber so that the fuel used to start the APU was exposed to the same environmental conditions as the APU even though the fuel drums were placed outside the altitude tank.

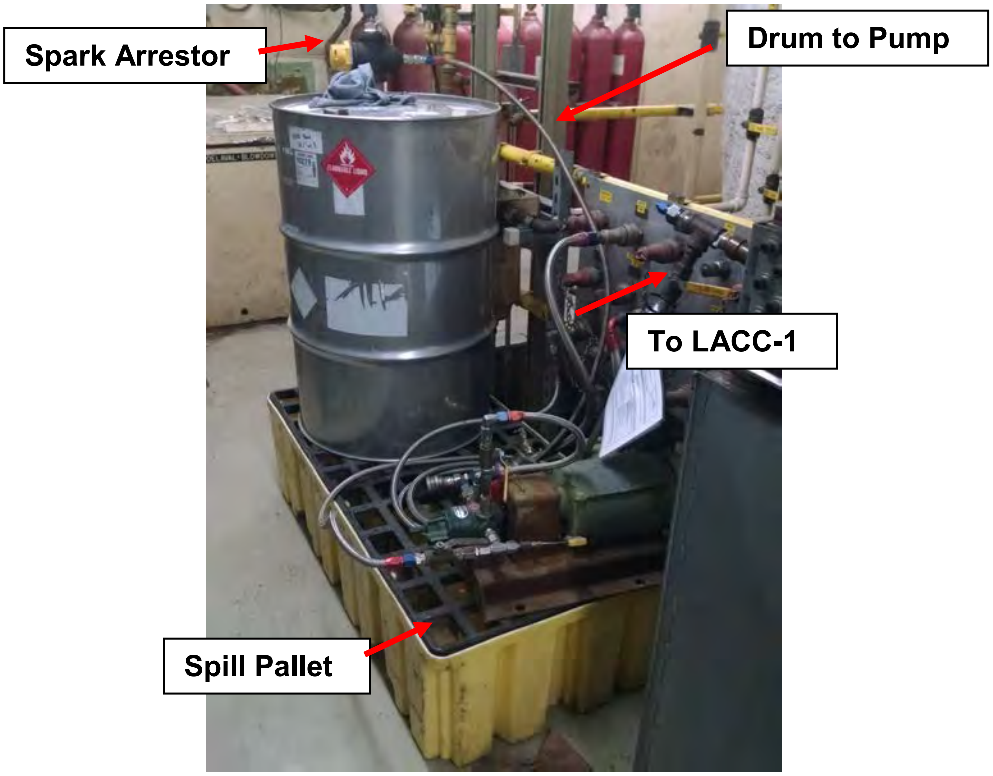


Figure 4. 55-Gallon Drum Setup Outside Altitude Tank.

3.4 Lubricant

The engine was serviced with MIL-PRF-23699 lubricant prior to operation. This oil is suitable for starts down to temperatures of -40°F.

3.5 Battery Start Settings

The APU DC starter was supplied power from the laboratory battery cart system. The curves shown in Figure 5 were used to start the APU, based on the condition being evaluated. Starts were performed with DC input power only. All three base level starts (C1, C2, and C3) utilized curve 4, the high altitude cold day condition (C4) used curve 6*, while the high altitude hot day condition (C5) used curve 7.

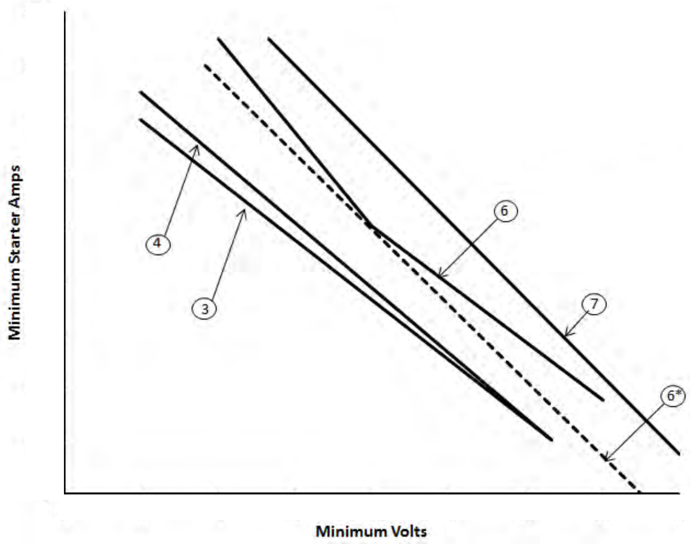


Figure 5. 131-9[A] DC Power Supply Characteristics.

4.0 INSTRUMENTATION AND DATA ACQUISITION

4.1 Instrumentation

The instrumentation and recording requirements were used for all APU operation during testing. APU operation, from startup to shutdown, was monitored continuously. Performance data was recorded for APU health checks.

In addition to the standard instrumentation found in Table 2 of ATP 31-13939, the special instrumentation listed in Table 3 was included for this fuel evaluation.

All digital sample rates were recorded at laboratory maximum frequency, 10 Hz, or as required by cognizant engineer. APU health checks performed at steady-state conditions were recorded at 1 Hz. Start evaluations were recorded at 10 Hz.

A special instrumented inlet rake conforming to the 131-9[A] inlet was installed in the inlet plenum. The rake has total pressures and temperatures, and static pressures.

Table 2. Starting Test Instrumentation Requirements.

Parameter	Units	Range
APU Speed	rpm	0-50,000
Lab Exhaust Gas Temperature (EGT)	F	-100-2000
Fuel Torque Motor Current	mA	0-300
Fuel Flow	lb/hr	0-500
Fuel Inlet Pressure	psig	0-100
Fuel Inlet Temperature	F	-100-350
Primary Fuel Nozzle ∆P	psid	0-500
Secondary Fuel Nozzle ∆P	psid	0-500
Oil Pressure	psig	0-100
Oil Discharge Temperature	F	-100-350
Oil Sump Temperature	F	-100-350
APU Inlet Total Temperature (inlet rake Qty 21)	F	-100-200
APU Inlet Total Pressure (inlet rake Qty 21)	psia	0-10
APU Inlet Static Pressure (inlet rake Qty 18)	psia	0-10
Ambient Temperature (LN2 Box)	F	-100-200
Tail Pipe Exit Pressure (PS9)	psia	0-15
APU ∆P (PT1-PS9)	in H20	0-30
Oil Cooler Air Inlet Pressure (PTOCL2)	psia	0-15
Oil Cooler Air Inlet Temperature (TOCL2)	F	-100-200
Oil Cooler Oil Inlet Temperature	F	-100-350
Oil Cooler Oil Outlet Temperature	F	-100-350
Oil Flow	gpm	0-10
Engine Compressor Discharge Temperature	F	-100-1000
Engine Compressor Discharge Total Pressure	psia	0-150
Cooling Fan Inlet Duct Temperature	F	-100 - 200
Cooling Fan Inlet Duct Static Pressure (Qty 6)	psig	+/-5
Mixing Chamber Temperature	F	-100 - 200
Mixing Chamber Total Pressure	psig	+/-5
Mixing Chamber Static Pressure	psig	+/-5
Bellmouth Static Pressure	psig	+/-5
Load Compressor Static pressure	psig	+/-5

5.0 TEST PROCEDURE

5.1.1 Test Description and Sequence

The alternative fuel evaluations using a 131-9[A] APU consisted of performing start attempts with conventional petroleum-derived Jet A fuel as a baseline and the two alternative fuels under test at ambient and cold conditions at base level and high altitudes.

5.2 Altitude Test Point Conditions

The cold and altitude start testing consisted of environmentally conditioning the APU in the LACC-1 altitude test facility to demonstrate the engine starting with the baseline Jet A fuel and the two alternative fuel blends. Once stable environmental conditions (oil temperature, inlet temperature, fuel temperature, etc.) were obtained, an engine start was attempted. An overview of the simulated test conditions is presented in Figure 6, which defines the ground and in-flight envelope of the 131-9[A] APU. Test conditions were evaluated in the order which most efficiently utilized LACC-1 and other laboratory capabilities (not necessarily in the order C1, C2, etc.). The test conditions (C1 through C5) in Figure 6 were chosen as those that represent the normal and "worst case" starting conditions for the 131-9[A] engine.

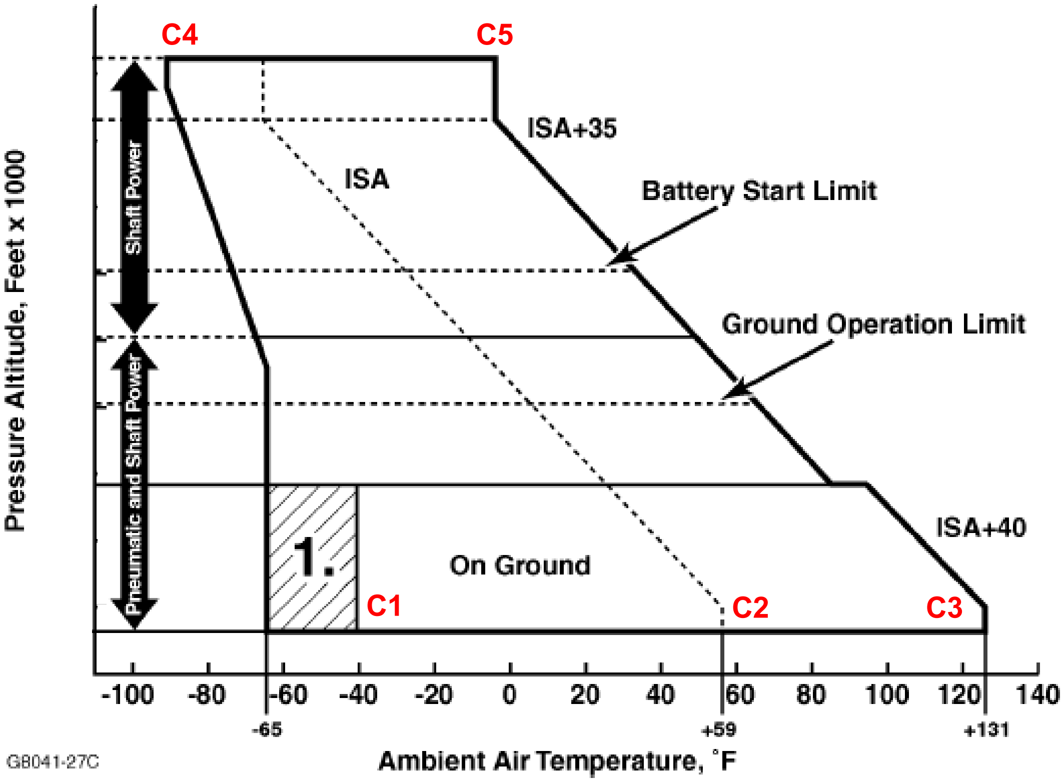


Figure 6. Temperature and Altitude Test Conditions.

The start attempts were performed at each condition (C1 through C5) with all three fuels under test, the Jet A baseline, 50 percent Virent blend, and 2 percent Diamond GD blend.

Base level conditions (C1, C2, and C3) were conducted with APU ram air of less than 2 inH_2O. Conditions at 39,000 feet (C4 and C5) were conducted approximately 1.9 inH_2O APU ram inlet air pressure. Ram conditions were maintained as best as possible during the start. As the APU accelerates and requires more air to rotate, the cell technician supplies the air to the engine necessary to maintain the desired ram pressure, so minor fluctuations were expected.

5.3 Performance Test

APU performance health checks were performed prior to initiating start evaluations, and at the conclusion of the start evaluations. Table 4 lists the results of the pre- and posttest APU health checks. The concern with difficult start conditions, like C4 and C5, is that the long hot starts could potentially damage the hot section of the APU. Over the course of time, the hot section damage would exhibit itself in degraded engine performance. However, the health checks performed before and after testing showed no signs of engine performance degradation.

Table 3. 131-9[A] APU Engine Performance Health Checks.

Description	Units	Pretest 12/5/2015	Posttest 12/22/2015
Barometric Pressure	psia	14.3	14.1
Inlet Temperature	°F	67.4	67.9
EGT (Corrected)	°F	1010	1013
EGT (Unit)	°F	948	943

5.4 Cold and Altitude Starting

Start evaluations consisted of five test conditions, shown in Table 4. Type II oil per MIL-PRF-23699 was used for cold soaks down to minus (-) 40°F. For each start test point, the APU was thermally conditioned, as described in Section 3.2. Cold soaks were sustained until the bulk oil sump and fuel temperatures reached the specified values ±2°F (minimum fuel temperature was limited by 12cSt maximum fuel viscosity).

During the start transient, temperature conditioned fuel and air were introduced into the APU. The inlet air and fuel temperatures at the values specified in Table 4. Start times, ignition delay times, and maximum EGTs during the start transient were calculated from the data for each start. Start time was calculated from the first sign of engine rotation to 99 percent full speed. Ignition delay time was calculated from the first sign of torque motor actuation (torque motor current greater than zero) to the first sign of exhaust gas temperature increase.

Table 4. 131-9[A] APU Start Test Points.

Ground Starts														
	Aircraft Conditions									Test Cell Conditions				
Test Condition Number	Altitude	Mach No	Ambient Temp	Ambient Pressure	A/C Total Temp	A/C Total Pressure	Exhaust Static Pressure	Oil Temp ± 2	Fuel Temp ± 2 12cSt Max	APU Inlet Temp, T1	Battery Curve	Cell Altitude	APU DP ± 2.0	APU Exit Static Pressure
	ft		°F	psia	°F	psia	psia	°F	°F	°F		ft	inH2O	psia
C1	1100	0	-40	14.7	-40	14.7	14.7	-40	-40	-40	4	amb	0	amb
C2	1100	0	amb	14.7	amb	amb	14.7	amb	amb	59	4	amb	0	amb
C3	1100	0	131	14.7	131	14.7	14.7	amb	amb	131	4	amb	0	amb

In-Flight Starts														
	Aircraft Conditions									Test Cell Conditions				
Test Condition Number	Altitude	Mach No	Ambient Temp	Ambient Pressure	A/C Total Temp	A/C Total Pressure	Exhaust Static Pressure	Oil Temp ± 2	Fuel Temp ± 2 12cSt Max	APU Inlet Temp, T1	Battery Curve	Cell Altitude	APU DP ± 0.4	APU Exit Static Pressure
	ft		°F	psia	°F	psia	psia	°F	°F	°F		ft	inH2O	psia
C4	39000	0.76	-94.0	2.85	-51.8-	3.18	3.11	-40	-40	-40.0	6*	37000	1.93	3.11
C5	39000	0.84	-6.7	2.85	57.2	3.26	3.19	57	57	57.2	7	37000	1.87	3.19

5.4.1 Cold and Altitude Starting Results

Cold and altitude start tests were performed using a 131-9[A] APU with Jet A and the two alternative fuel blends. The figures below illustrate that the blended fuels had no noticeable effect on APU starting. Figure 7 through Figure 9 show the normalized start times, normalized ignition delay times, and the normalized maximum unit EGTs, relative to the baseline Jet A, during the thermally conditioned start attempts (no hot-restarts), respectively.

The start times were similar for the two alternative fuels, with some minor variation from the baseline Jet A depending on test condition. The start time data appears to contain only minor test-to-test variation, with the exception of condition C1, where the Jet A baseline required a longer time to accelerate to ready-to-load (RTL). Comparing the start plots in Figure 10, it appears that for the Jet A start the APU accelerated slowly initially, and fuel was not injected until well after start initiation. Once the fuel was introduced, the start trace appears as normal.

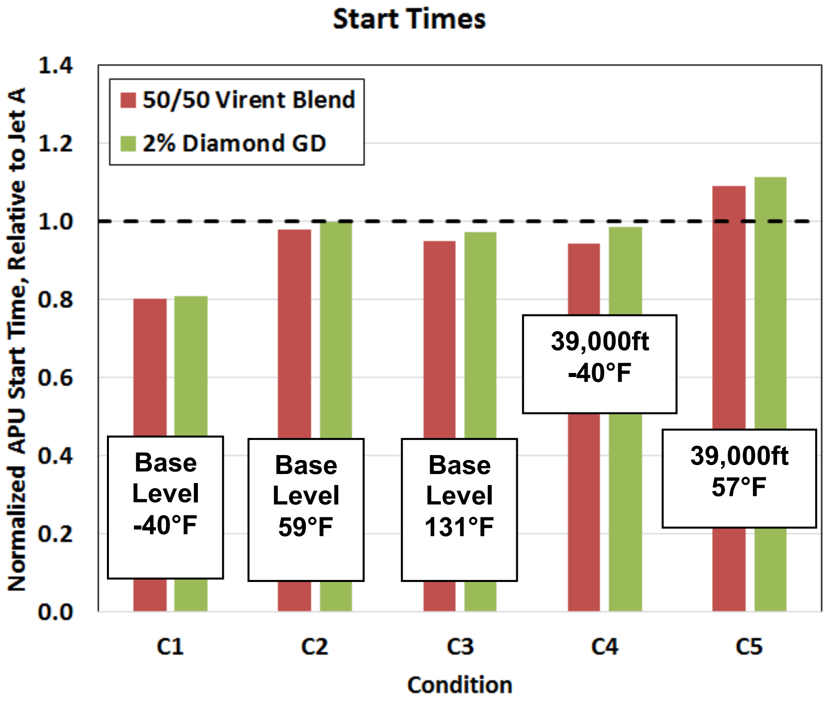


Figure 7. 131-9[A] APU Start Times.

Ignition delay times were comparable for the two alternative fuels, with only slight variations with the baseline Jet A fuel depending on test condition. Figure 8 shows the normalized ignition delay times of the Virent blend and Diamond GD blend, relative to the baseline Jet A. The ignition delay times were rather short, so small differences appear to be large when normalized. The differences in ignition delay time between the fuels under test and the baseline Jet A were determined to be within a reasonable amount of test-to-test variation.

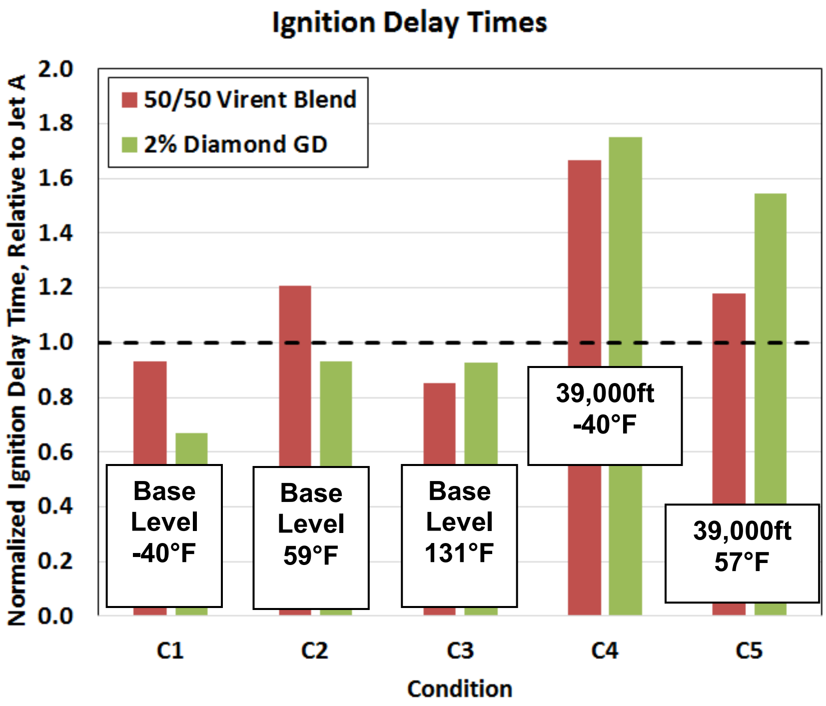


Figure 8. 131-9[A] APU Ignition Delay Times.

The maximum unit EGTs during the start transients were similar between the two alternative fuels under test and the baseline Jet A, as seen in the normalized plot of Figure 9.

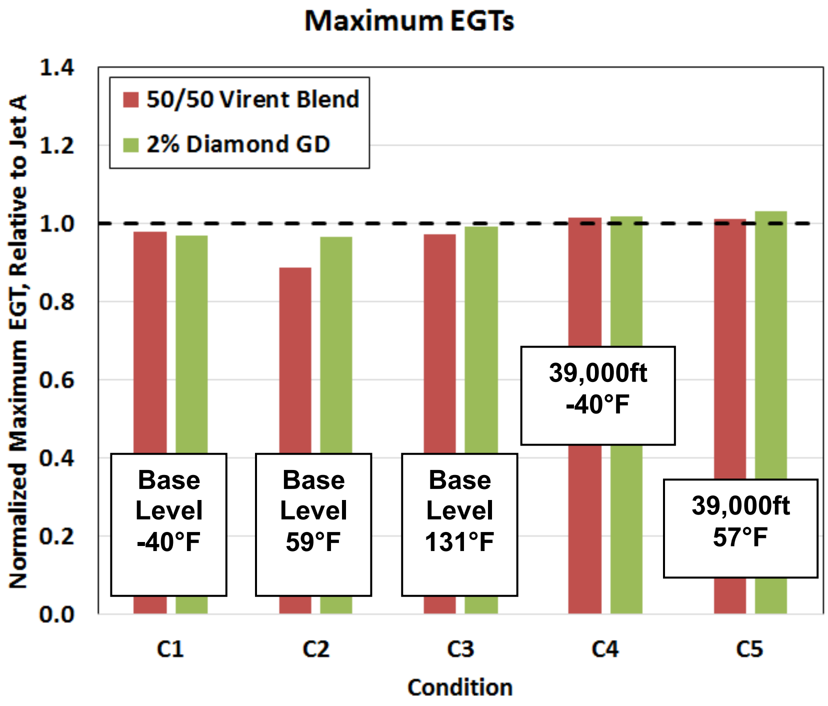
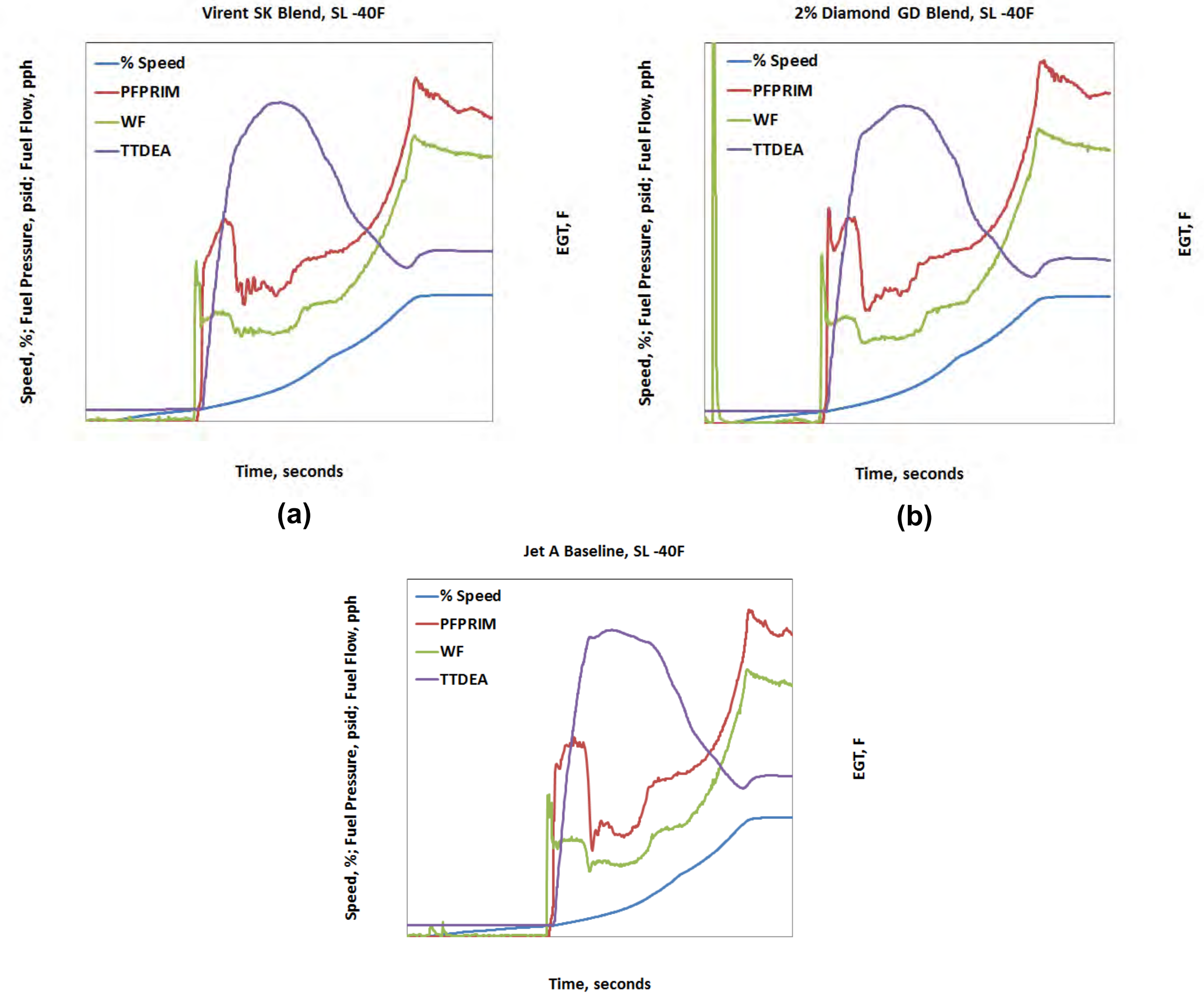


Figure 9. 131-9[A] APU Maximum Unit EGTs.

The below figures display the start transients with the three fuels. The traces include APU speed, in percent (% speed), primary fuel pressure, in psid (PFPRIM), fuel flow, in lb/hr (WF), and APU unit exhaust gas temperature thermocouple, in °F (TTDEA).

Figure 10 shows the start results for the -40°F ambient temperature start attempts at base level (condition C1). APU speed was stable after the acceleration from start for all three fuels. As noted previously, the APU acceleration was sluggish for the Jet A baseline start attempt, which delayed the fuel introduction. Once the fuel was introduced, the start transient appears to be normal. Since the acceleration was sluggish, the battery curve for the DC starter was double-checked, the battery curve was confirmed to be Curve 4. The soak temperature was also double-checked; overly viscous oil caused by excessively cold conditions (MIL-PRF-23699 limited to -40°F minimum) could also cause sluggish acceleration. The oil temperature was confirmed to be -39.6°F. Since the battery curve was set correctly and the oil was not soaked to an excessively cold temperature, the start attempt for the baseline Jet A fuel was deemed acceptable.

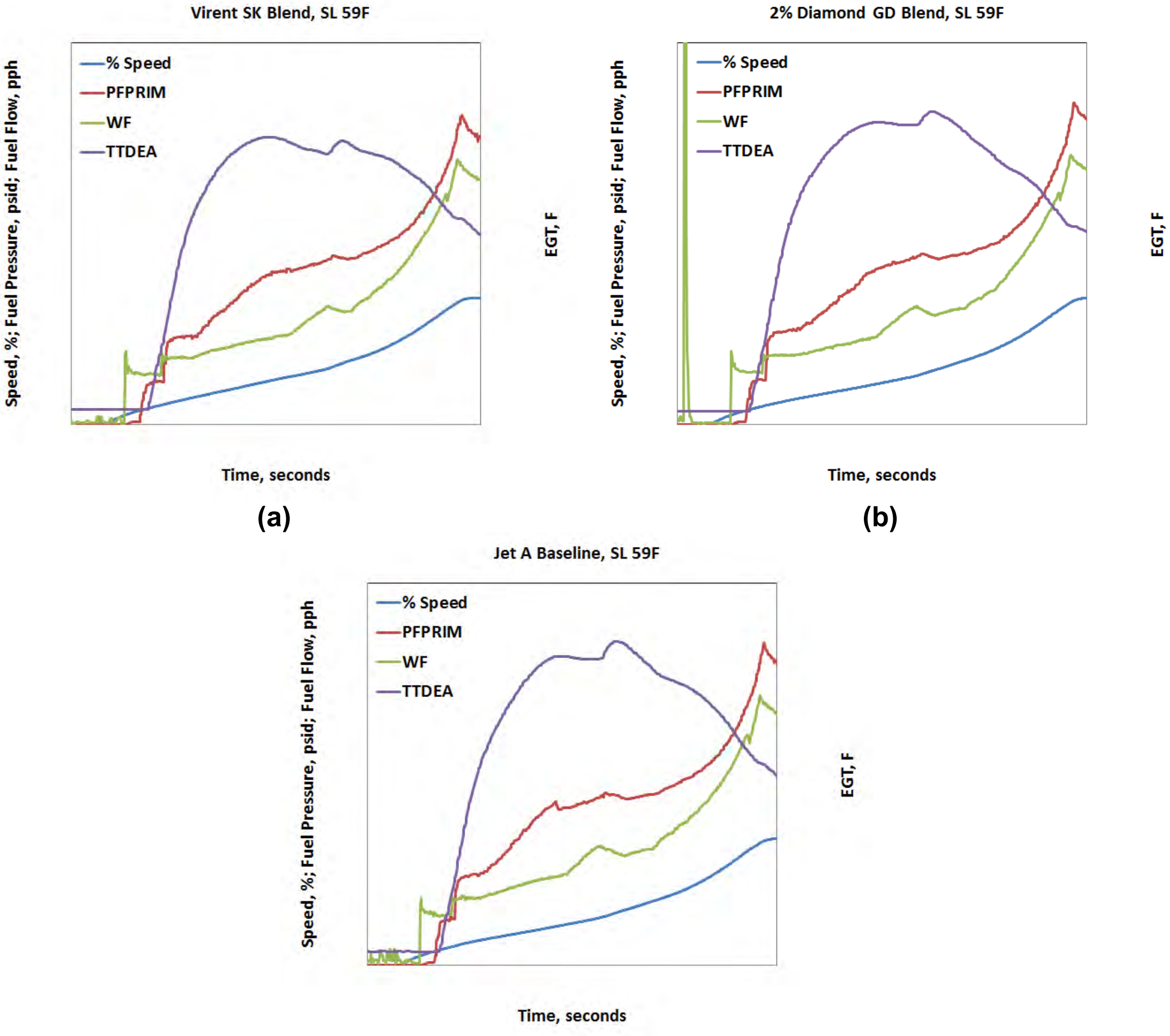


(a) (b)

(c)

Figure 10. Starts at Base Level -40°F Ambient (C1) Condition with a) 50/50 Virent Blend, b) 2% Diamond GD Blend, and c) Jet A Baseline.

Figure 11 shows the start results for the 59°F ambient temperature start attempt at base level (condition C2). The start traces appear nearly identical. APU speed was stable after the acceleration from start for all fuels.



Virent SK Blend, SL 59F

2% Diamond GD Blend, SL 59F

Jet A Baseline, SL 59F

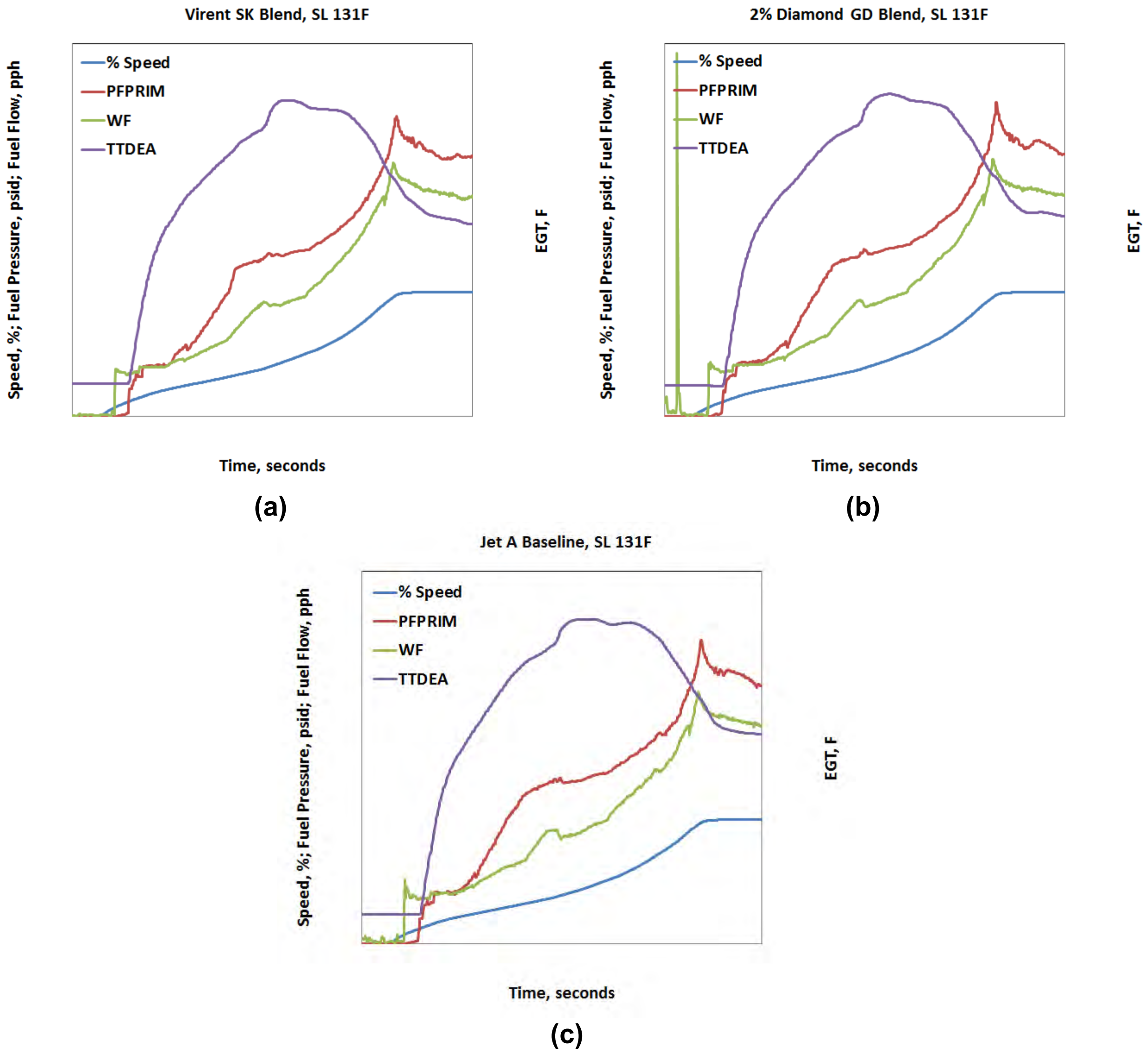
(a)

(b)

(c)

Figure 11. Starts at Base Level 59°F Ambient (C2) Condition with a) 50/50 Virent Blend, b) 2% Diamond GD Blend, and c) Jet A Baseline.

Figure 12 shows the start results for the 131°F ambient temperature start attempts at base level (condition C3). Again, the traces appear nearly identical. APU speed was stable after the acceleration from start for all fuels.



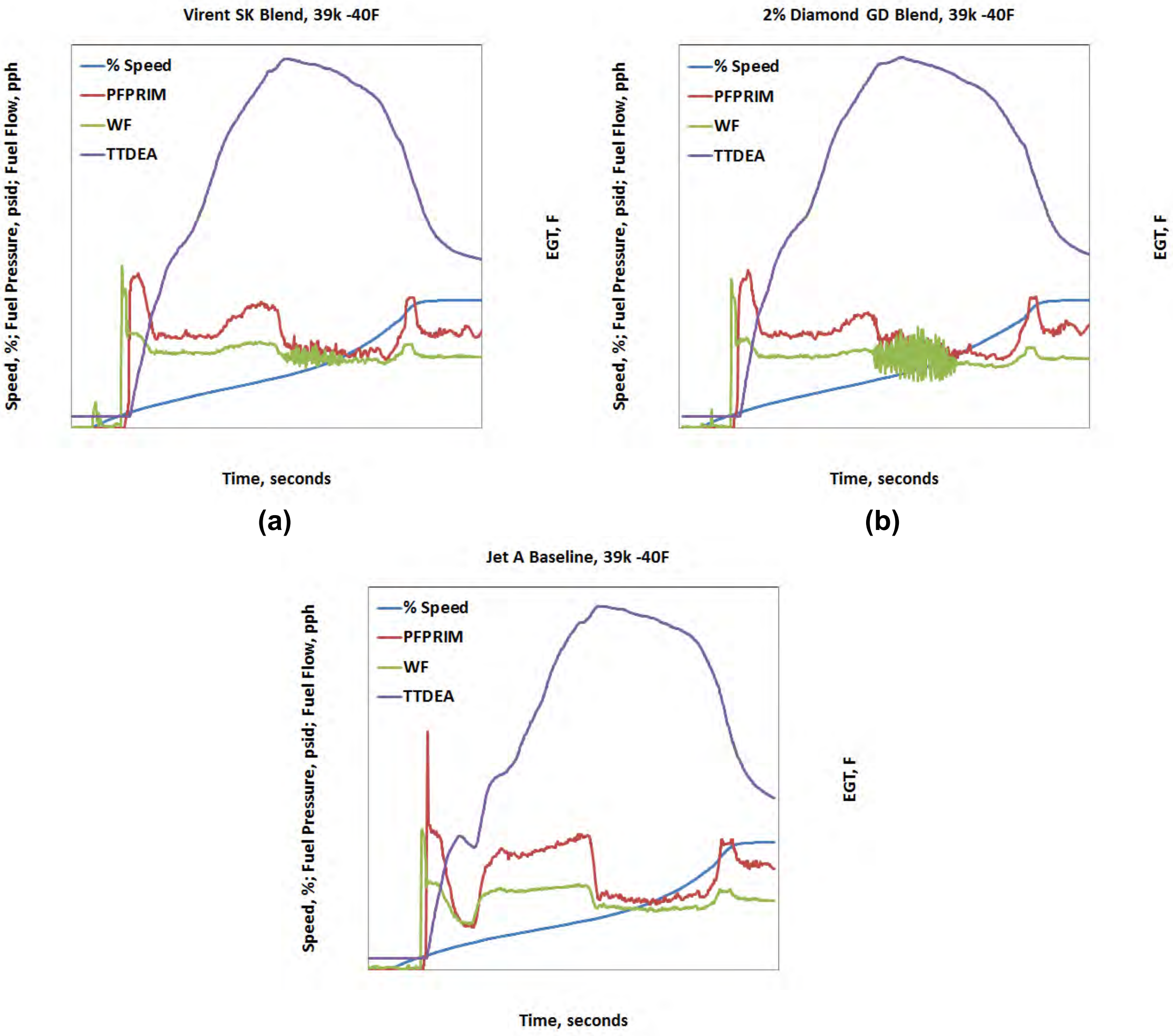
(a)

(b)

(c)

Figure 12. Starts at Base Level 131°F Ambient (C3) Condition with a) 50/50 Virent Blend, b) 2% Diamond GD Blend, and c) Jet A Baseline.

Figure 13 shows the start results for the -40°F ambient temperature start attempts at 39,000 feet altitude (Condition C4). APU speed was stable after the acceleration from start for all fuels.

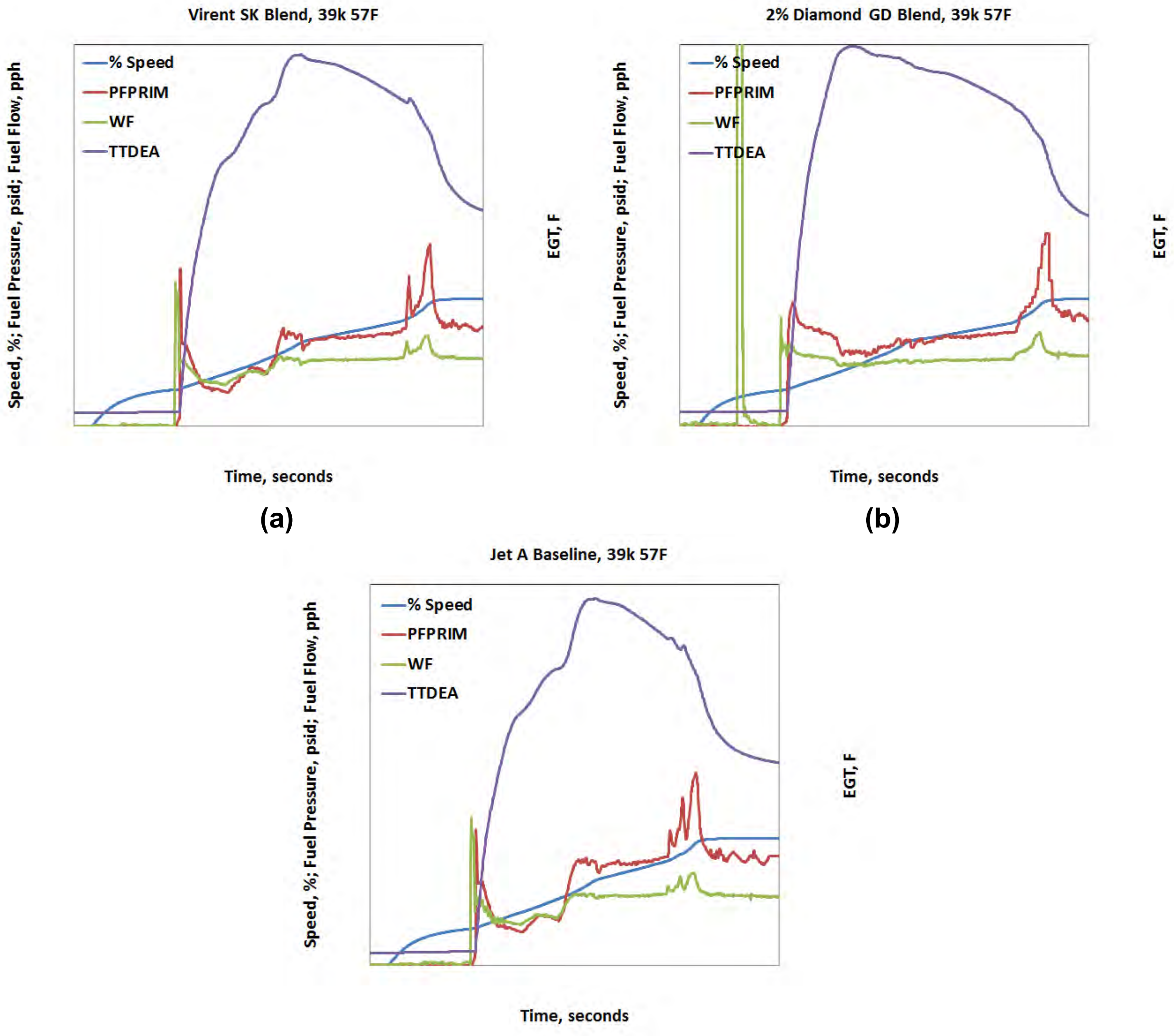


(a) (b)

(c)

Figure 13. Starts at 39,000 feet -40°F Ambient (C4) Condition with a) 50/50 Virent Blend, b) 2% Diamond GD Blend, and c) Jet A Baseline.

Figure 14 shows the start results for the 57°F ambient temperature start attempts at 39,000 feet altitude (condition C5). APU speed was stable after the acceleration from start for all fuels.



(a) (b)

(c)

Figure 14. Starts at 39,000 feet 57°F Ambient (C5) Condition with a) 50/50 Virent Blend, b) 2% Diamond GD Blend, and c) Jet A Baseline.

6.0 TEST SUMMARY

APU cold and altitude start tests were completed in order to evaluate a 50 percent blend of Virent SK and conventional petroleum derived Jet A and a blend of 2 percent Diamond GD and 98 percent conventional petroleum derived Jet A. A 131-9[A] APU (S/N D-3207) was used for all testing and started successfully with the baseline Jet A fuel and the two alternative fuel blends at all conditions. No fuel impact on APU starting was observed. No deterioration of APU performance was observed.

The 131-9[A] APU was started over the following flight envelope and temperatures:

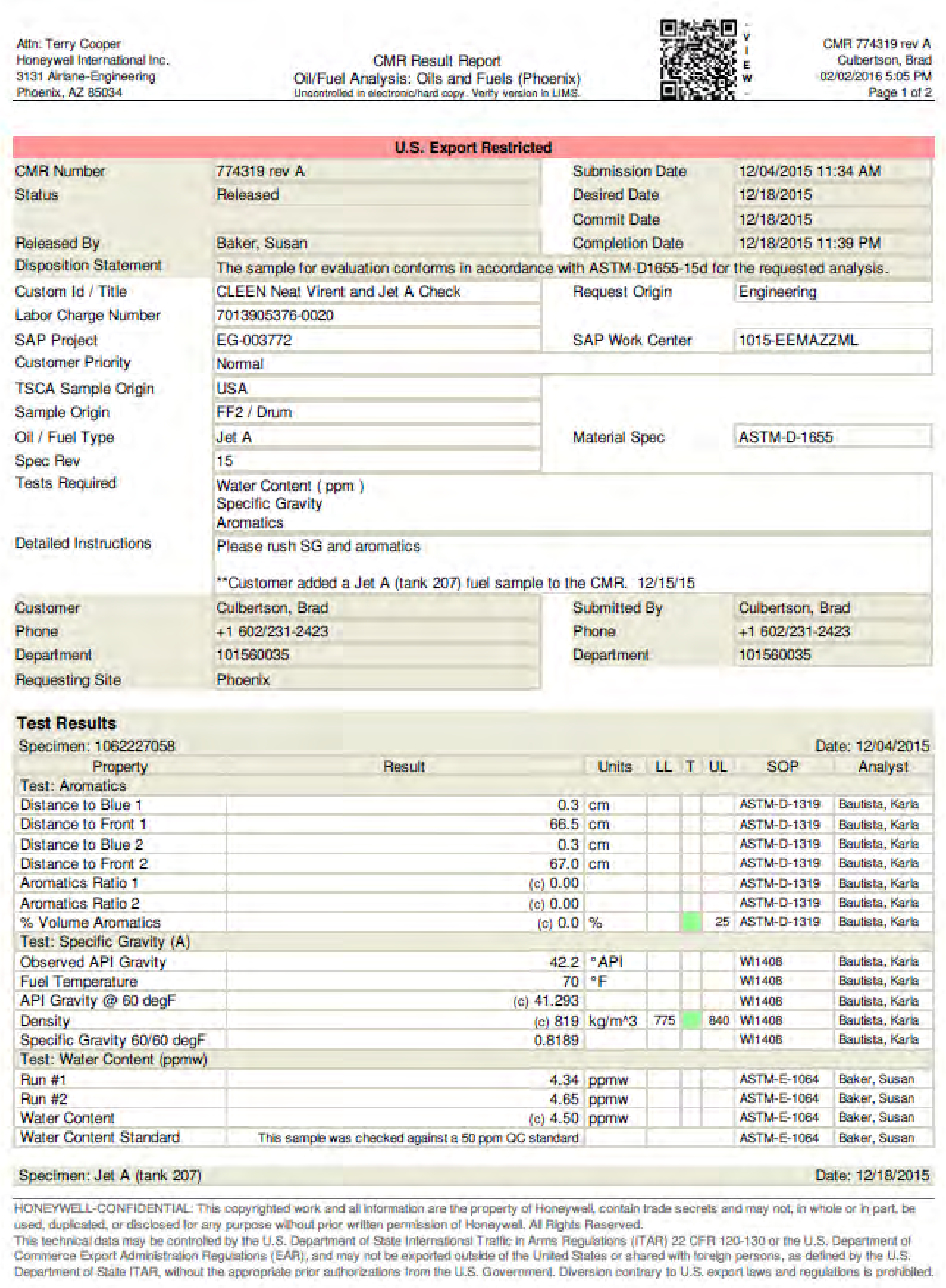
- Phoenix base level to 39,000 feet altitude
- Hot (131°F) and cold (-40°F) day

Start times and ignition delay times for the alternative fuels were comparable to the Jet A baseline. The maximum EGTs during the start transient for the two alternative fuel blends were similar to the baseline Jet A. APU speeds were stable after the accelerations from start.

The 131-9[A] APU performance was checked before and after the start evaluation. Posttest performance results indicated no APU degradation over the course of testing. There was no adverse effect of either the 50 percent Virent SK blend or the 2 percent Diamond GD blend on the starting of the 131-9[A] APU. No APU performance degradation was observed from the successful start attempts.

Appendix 1. Chemical Analysis Results

(11 pages)



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Phoenix, AZ 85034

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CMR 774319 rev A
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02/02/2016 5:05 PM
Page 1 of 2

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CMR Number	774319 rev A	Submission Date	12/04/2015 11:34 AM
Status	Released	Desired Date	12/18/2015
		Commit Date	12/18/2015
Released By	Baker, Susan	Completion Date	12/18/2015 11:39 PM
Disposition Statement	The sample for evaluation conforms in accordance with ASTM-D1655-15d for the requested analysis.		
Custom Id / Title	CLEEN Neat Virent and Jet A Check	Request Origin	Engineering
Labor Charge Number	7013905376-0020		
SAP Project	EG-003772	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	FF2 / Drum		
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	15		
Tests Required	Water Content (ppm) Specific Gravity Aromatics		
Detailed Instructions	Please rush SG and aromatics **Customer added a Jet A (tank 207) fuel sample to the CMR. 12/15/15		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062227058 Date: 12/04/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: Aromatics							
Distance to Blue 1	0.3	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 1	66.5	cm				ASTM-D-1319	Bautista, Karla
Distance to Blue 2	0.3	cm				ASTM-D-1319	Bautista, Karla
Distance to Front 2	67.0	cm				ASTM-D-1319	Bautista, Karla
Aromatics Ratio 1	(c) 0.00					ASTM-D-1319	Bautista, Karla
Aromatics Ratio 2	(c) 0.00					ASTM-D-1319	Bautista, Karla
% Volume Aromatics	(c) 0.0	%		🟩	25	ASTM-D-1319	Bautista, Karla
Test: Specific Gravity (A)							
Observed API Gravity	42.2	°API				WI1408	Bautista, Karla
Fuel Temperature	70	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF	(c) 41.293					WI1408	Bautista, Karla
Density	(c) 819	kg/m^3	775	🟩	840	WI1408	Bautista, Karla
Specific Gravity 60/60 degF	0.8189					WI1408	Bautista, Karla
Test: Water Content (ppmw)							
Run #1	4.34	ppmw				ASTM-E-1064	Baker, Susan
Run #2	4.65	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 4.50	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

Specimen: Jet A (tank 207) Date: 12/18/2015

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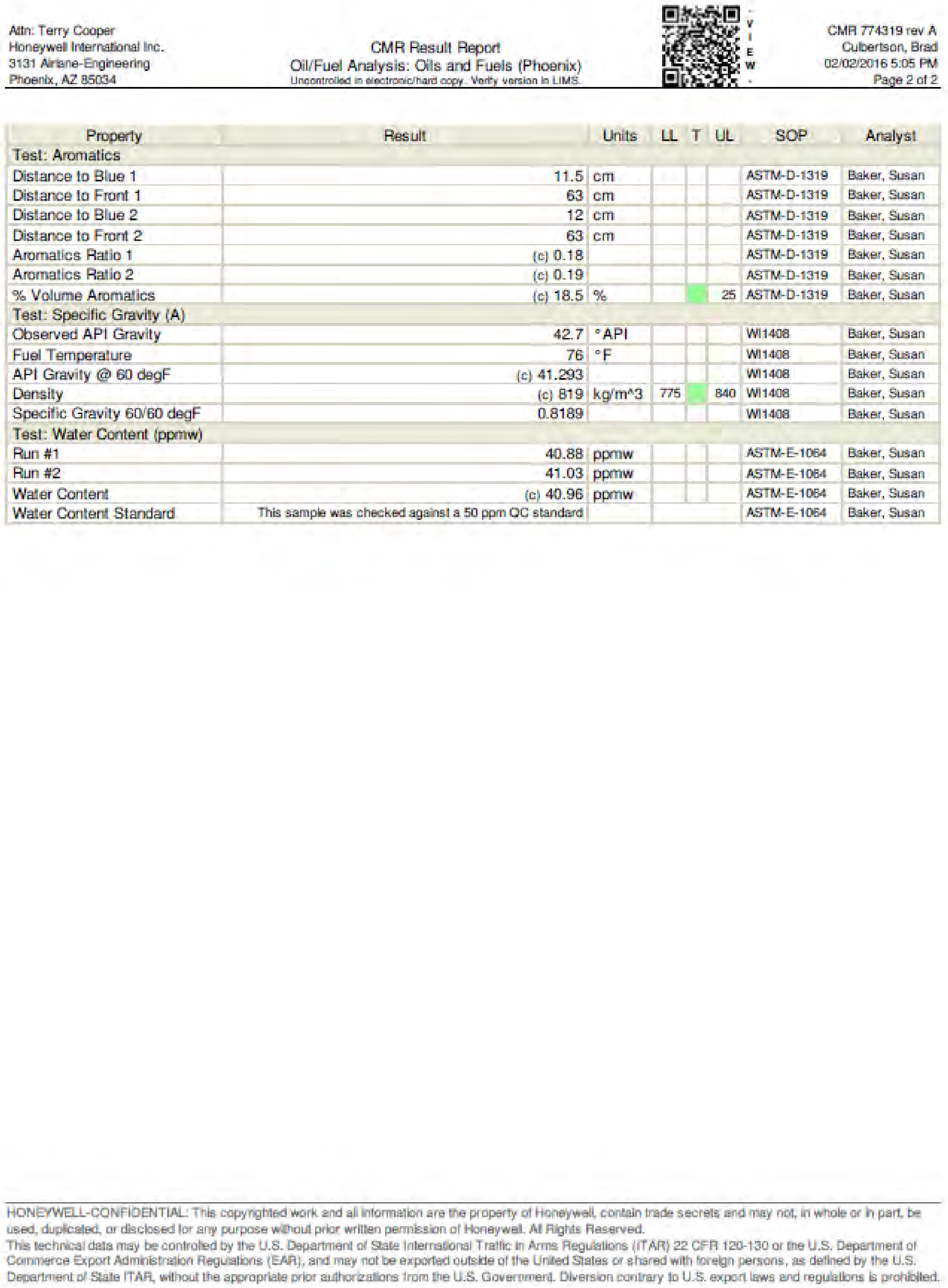

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02/02/2016 5:05 PM
Page 2 of 2

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: Aromatics							
Distance to Blue 1	11.5	cm				ASTM-D-1319	Baker, Susan
Distance to Front 1	63	cm				ASTM-D-1319	Baker, Susan
Distance to Blue 2	12	cm				ASTM-D-1319	Baker, Susan
Distance to Front 2	63	cm				ASTM-D-1319	Baker, Susan
Aromatics Ratio 1	(c) 0.18					ASTM-D-1319	Baker, Susan
Aromatics Ratio 2	(c) 0.19					ASTM-D-1319	Baker, Susan
% Volume Aromatics	(c) 18.5	%		🟩	25	ASTM-D-1319	Baker, Susan
Test: Specific Gravity (A)							
Observed API Gravity	42.7	°API				WI1408	Baker, Susan
Fuel Temperature	76	°F				WI1408	Baker, Susan
API Gravity @ 60 degF	(c) 41.293					WI1408	Baker, Susan
Density	(c) 819	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF	0.8189					WI1408	Baker, Susan
Test: Water Content (ppmw)							
Run #1	40.88	ppmw				ASTM-E-1064	Baker, Susan
Run #2	41.03	ppmw				ASTM-E-1064	Baker, Susan
Water Content	(c) 40.96	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard					ASTM-E-1064	Baker, Susan

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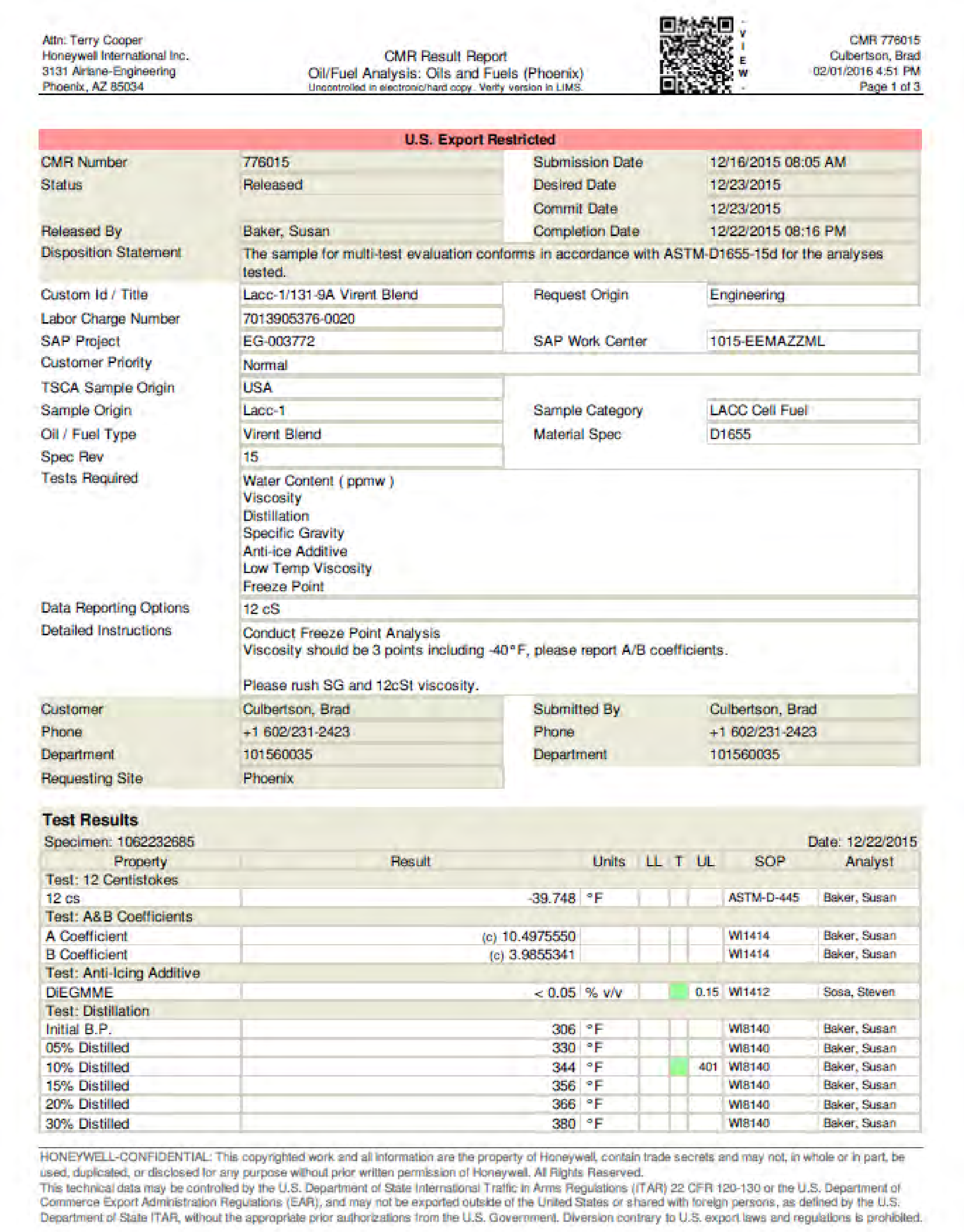

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CMR Number	776015	Submission Date	12/16/2015 08:05 AM
Status	Released	Desired Date	12/23/2015
		Commit Date	12/23/2015
Released By	Baker, Susan	Completion Date	12/22/2015 08:16 PM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the analyses tested.		
Custom Id / Title	Lacc-1/131-9A Virent Blend	Request Origin	Engineering
Labor Charge Number	7013905376-0020		
SAP Project	EG-003772	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	Lacc-1	Sample Category	LACC Cell Fuel
Oil / Fuel Type	Virent Blend	Material Spec	D1655
Spec Rev	15		
Tests Required	Water Content (ppmw) Viscosity Distillation Specific Gravity Anti-ice Additive Low Temp Viscosity Freeze Point		
Data Reporting Options	12 cS		
Detailed Instructions	Conduct Freeze Point Analysis Viscosity should be 3 points including -40°F, please report A/B coefficients. Please rush SG and 12cSt viscosity.		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062232685 Date: 12/22/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-39.748	°F				ASTM-D-445	Baker, Susan
Test: A&B Coefficients							
A Coefficient	(c) 10.4975550					WI1414	Baker, Susan
B Coefficient	(c) 3.9855341					WI1414	Baker, Susan
Test: Anti-Icing Additive							
DiEGMME	< 0.05	% v/v		🟩	0.15	WI1412	Sosa, Steven
Test: Distillation							
Initial B.P.	306	°F				WI8140	Baker, Susan
05% Distilled	330	°F				WI8140	Baker, Susan
10% Distilled	344	°F		🟩	401	WI8140	Baker, Susan
15% Distilled	356	°F				WI8140	Baker, Susan
20% Distilled	366	°F				WI8140	Baker, Susan
30% Distilled	380	°F				WI8140	Baker, Susan

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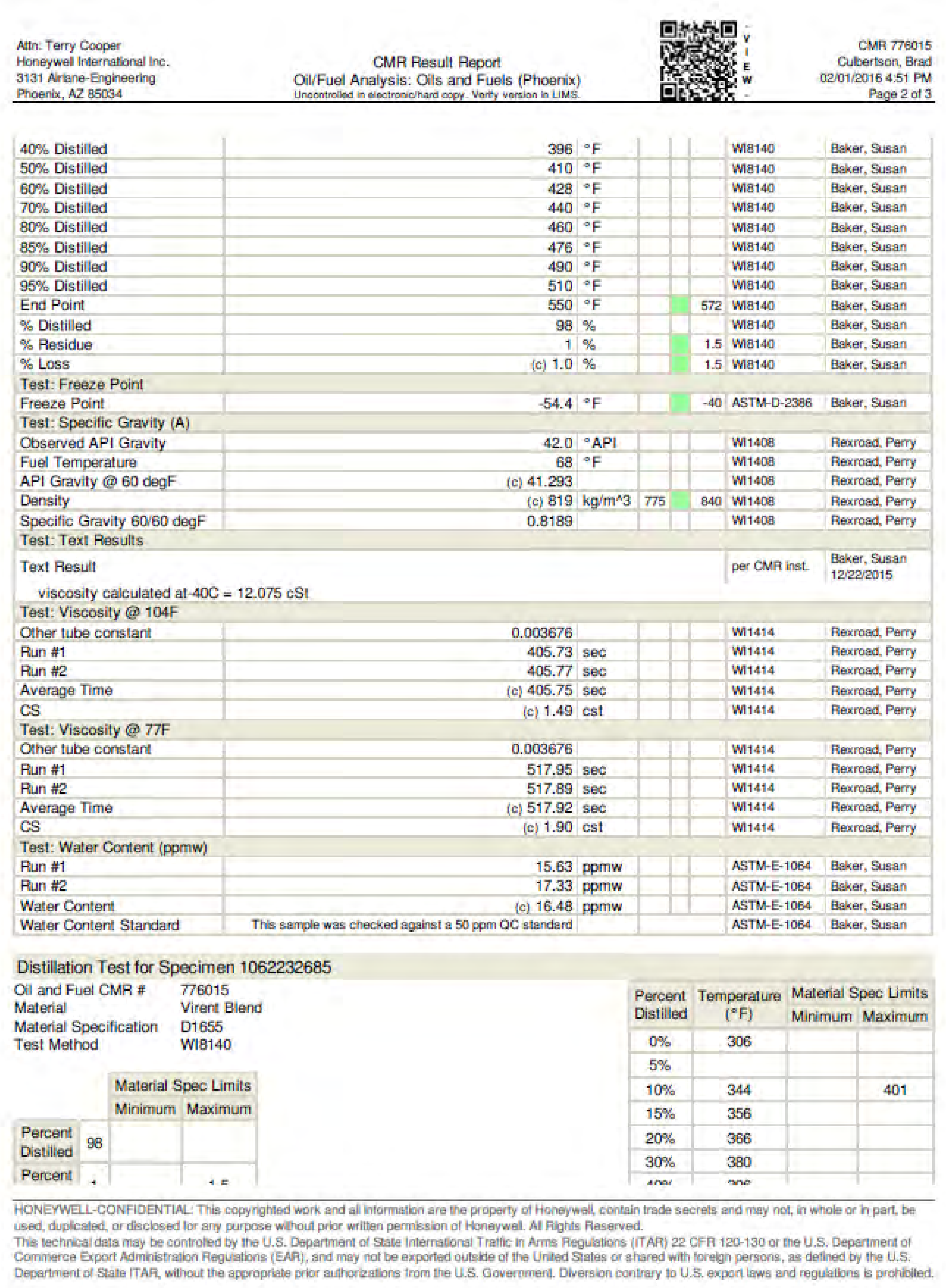

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40% Distilled		396	°F				WI8140	Baker, Susan
50% Distilled		410	°F				WI8140	Baker, Susan
60% Distilled		428	°F				WI8140	Baker, Susan
70% Distilled		440	°F				WI8140	Baker, Susan
80% Distilled		460	°F				WI8140	Baker, Susan
85% Distilled		476	°F				WI8140	Baker, Susan
90% Distilled		490	°F				WI8140	Baker, Susan
95% Distilled		510	°F				WI8140	Baker, Susan
End Point		550	°F		🟩	572	WI8140	Baker, Susan
% Distilled		98	%				WI8140	Baker, Susan
% Residue		1	%		🟩	1.5	WI8140	Baker, Susan
% Loss		(c) 1.0	%		🟩	1.5	WI8140	Baker, Susan
Test: Freeze Point								
Freeze Point		-54.4	°F		🟩	-40	ASTM-D-2386	Baker, Susan
Test: Specific Gravity (A)								
Observed API Gravity		42.0	°API				WI1408	Rexroad, Perry
Fuel Temperature		68	°F				WI1408	Rexroad, Perry
API Gravity @ 60 degF		(c) 41.293					WI1408	Rexroad, Perry
Density		(c) 819	kg/m^3	775	🟩	840	WI1408	Rexroad, Perry
Specific Gravity 60/60 degF		0.8189					WI1408	Rexroad, Perry
Test: Text Results								
Text Result viscosity calculated at-40C = 12.075 cSt							per CMR inst.	Baker, Susan 12/22/2015
Test: Viscosity @ 104F								
Other tube constant		0.003676					WI1414	Rexroad, Perry
Run #1		405.73	sec				WI1414	Rexroad, Perry
Run #2		405.77	sec				WI1414	Rexroad, Perry
Average Time		(c) 405.75	sec				WI1414	Rexroad, Perry
CS		(c) 1.49	cst				WI1414	Rexroad, Perry
Test: Viscosity @ 77F								
Other tube constant		0.003676					WI1414	Rexroad, Perry
Run #1		517.95	sec				WI1414	Rexroad, Perry
Run #2		517.89	sec				WI1414	Rexroad, Perry
Average Time		(c) 517.92	sec				WI1414	Rexroad, Perry
CS		(c) 1.90	cst				WI1414	Rexroad, Perry
Test: Water Content (ppmw)								
Run #1		15.63	ppmw				ASTM-E-1064	Baker, Susan
Run #2		17.33	ppmw				ASTM-E-1064	Baker, Susan
Water Content		(c) 16.48	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard						ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062232685

Oil and Fuel CMR #	776015
Material	Virent Blend
Material Specification	D1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	98		
Percent			

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	306		
5%			
10%	344		401
15%	356		
20%	366		
30%	380		

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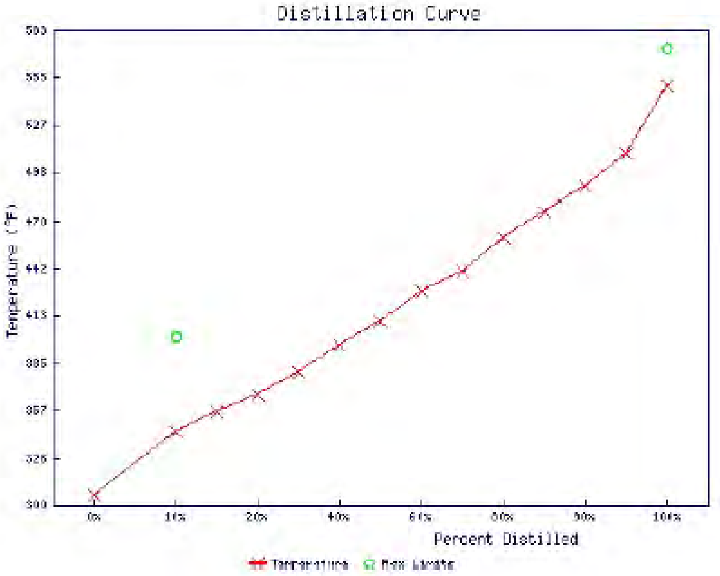
Residue	1		1.5
Percent Loss	1.0		1.5

40%	396		
50%	410		
60%	428		
70%	440		
80%	460		
85%	476		
90%	490		
95%	510		
100%	550		572



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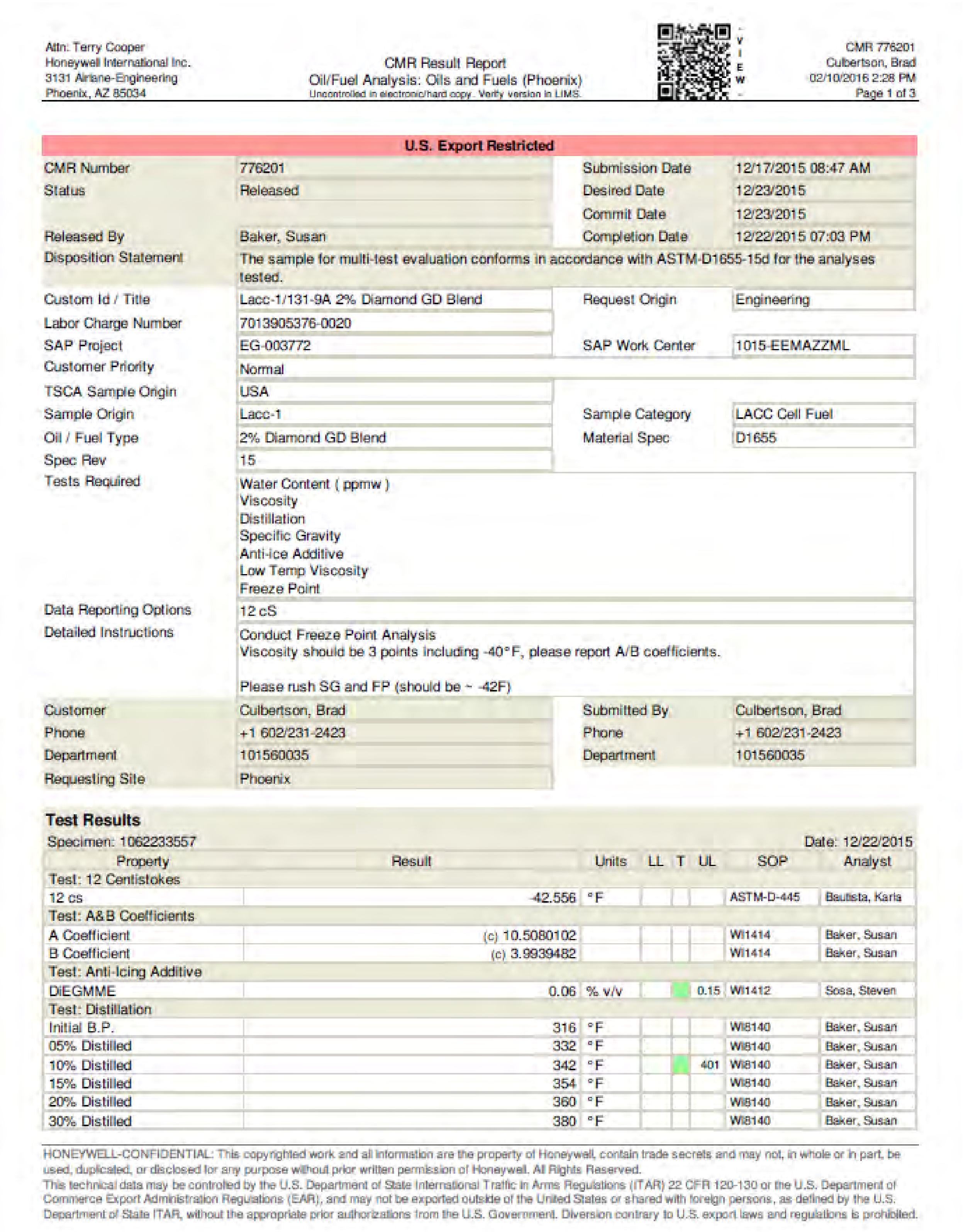

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Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 776201
Culbertson, Brad
02/10/2016 2:28 PM
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CMR Number	776201	Submission Date	12/17/2015 08:47 AM
Status	Released	Desired Date	12/23/2015
		Commit Date	12/23/2015
Released By	Baker, Susan	Completion Date	12/22/2015 07:03 PM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the analyses tested.		
Custom Id / Title	Lacc-1/131-9A 2% Diamond GD Blend	Request Origin	Engineering
Labor Charge Number	7013905376-0020		
SAP Project	EG-003772	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	Lacc-1	Sample Category	LACC Cell Fuel
Oil / Fuel Type	2% Diamond GD Blend	Material Spec	D1655
Spec Rev	15		
Tests Required	Water Content (ppmw) Viscosity Distillation Specific Gravity Anti-ice Additive Low Temp Viscosity Freeze Point		
Data Reporting Options	12 cS		
Detailed Instructions	Conduct Freeze Point Analysis Viscosity should be 3 points including -40°F, please report A/B coefficients. Please rush SG and FP (should be ~ -42F)		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062233557 Date: 12/22/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-42.556	°F				ASTM-D-445	Bautista, Karla
Test: A&B Coefficients							
A Coefficient	(c) 10.5080102					WI1414	Baker, Susan
B Coefficient	(c) 3.9939482					WI1414	Baker, Susan
Test: Anti-Icing Additive							
DiEGMME	0.06	% v/v		🟩	0.15	WI1412	Sosa, Steven
Test: Distillation							
Initial B.P.	316	°F				WI8140	Baker, Susan
05% Distilled	332	°F				WI8140	Baker, Susan
10% Distilled	342	°F		🟩	401	WI8140	Baker, Susan
15% Distilled	354	°F				WI8140	Baker, Susan
20% Distilled	360	°F				WI8140	Baker, Susan
30% Distilled	380	°F				WI8140	Baker, Susan

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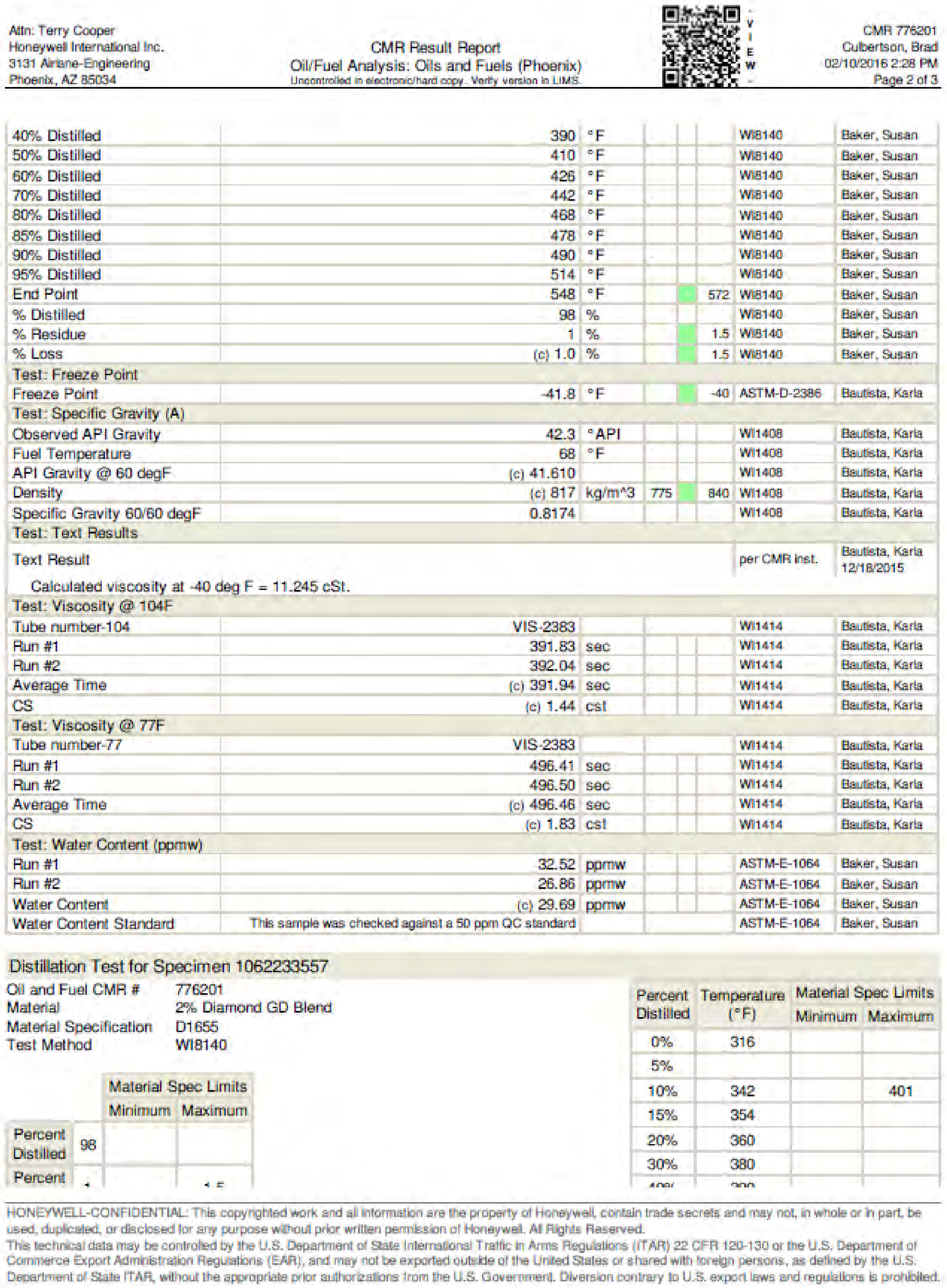

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Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 776201
Culbertson, Brad
02/10/2016 2:28 PM
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40% Distilled		390	°F				WI8140	Baker, Susan
50% Distilled		410	°F				WI8140	Baker, Susan
60% Distilled		426	°F				WI8140	Baker, Susan
70% Distilled		442	°F				WI8140	Baker, Susan
80% Distilled		468	°F				WI8140	Baker, Susan
85% Distilled		478	°F				WI8140	Baker, Susan
90% Distilled		490	°F				WI8140	Baker, Susan
95% Distilled		514	°F				WI8140	Baker, Susan
End Point		548	°F		🟩	572	WI8140	Baker, Susan
% Distilled		98	%				WI8140	Baker, Susan
% Residue		1	%		🟩	1.5	WI8140	Baker, Susan
% Loss		(c) 1.0	%		🟩	1.5	WI8140	Baker, Susan
Test: Freeze Point								
Freeze Point		-41.8	°F		🟩	-40	ASTM-D-2386	Bautista, Karla
Test: Specific Gravity (A)								
Observed API Gravity		42.3	°API				WI1408	Bautista, Karla
Fuel Temperature		68	°F				WI1408	Bautista, Karla
API Gravity @ 60 degF		(c) 41.610					WI1408	Bautista, Karla
Density		(c) 817	kg/m^3	775	🟩	840	WI1408	Bautista, Karla
Specific Gravity 60/60 degF		0.8174					WI1408	Bautista, Karla
Test: Text Results								
Text Result							per CMR inst.	Bautista, Karla 12/18/2015
Calculated viscosity at -40 deg F = 11.245 cSt.								
Test: Viscosity @ 104F								
Tube number-104		VIS-2383					WI1414	Bautista, Karla
Run #1		391.83	sec				WI1414	Bautista, Karla
Run #2		392.04	sec				WI1414	Bautista, Karla
Average Time		(c) 391.94	sec				WI1414	Bautista, Karla
CS		(c) 1.44	cst				WI1414	Bautista, Karla
Test: Viscosity @ 77F								
Tube number-77		VIS-2383					WI1414	Bautista, Karla
Run #1		496.41	sec				WI1414	Bautista, Karla
Run #2		496.50	sec				WI1414	Bautista, Karla
Average Time		(c) 496.46	sec				WI1414	Bautista, Karla
CS		(c) 1.83	cst				WI1414	Bautista, Karla
Test: Water Content (ppmw)								
Run #1		32.52	ppmw				ASTM-E-1064	Baker, Susan
Run #2		26.86	ppmw				ASTM-E-1064	Baker, Susan
Water Content		(c) 29.69	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard						ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062233557

Oil and Fuel CMR #	776201
Material	2% Diamond GD Blend
Material Specification	D1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	98		
Percent	1		1.5

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	316		
5%			
10%	342		401
15%	354		
20%	360		
30%	380		

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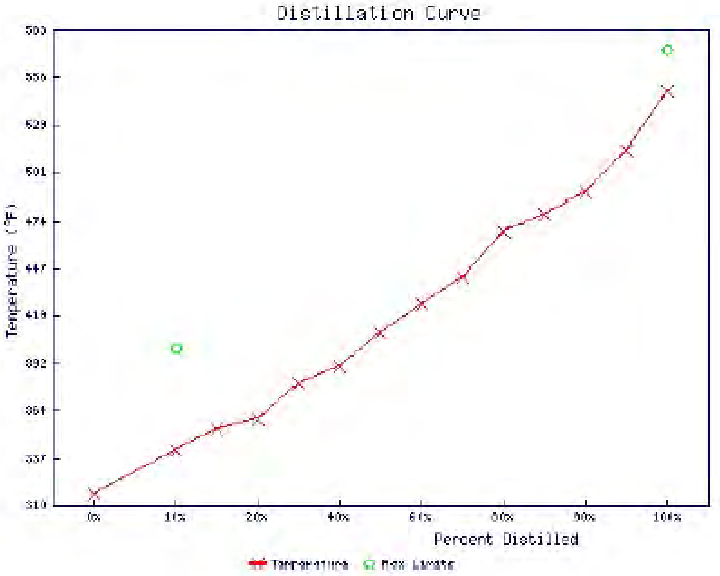
Residue	1		1.5
Percent Loss	1.0		1.5

40%	390		
50%	410		
60%	426		
70%	442		
80%	468		
85%	478		
90%	490		
95%	514		
100%	548		572



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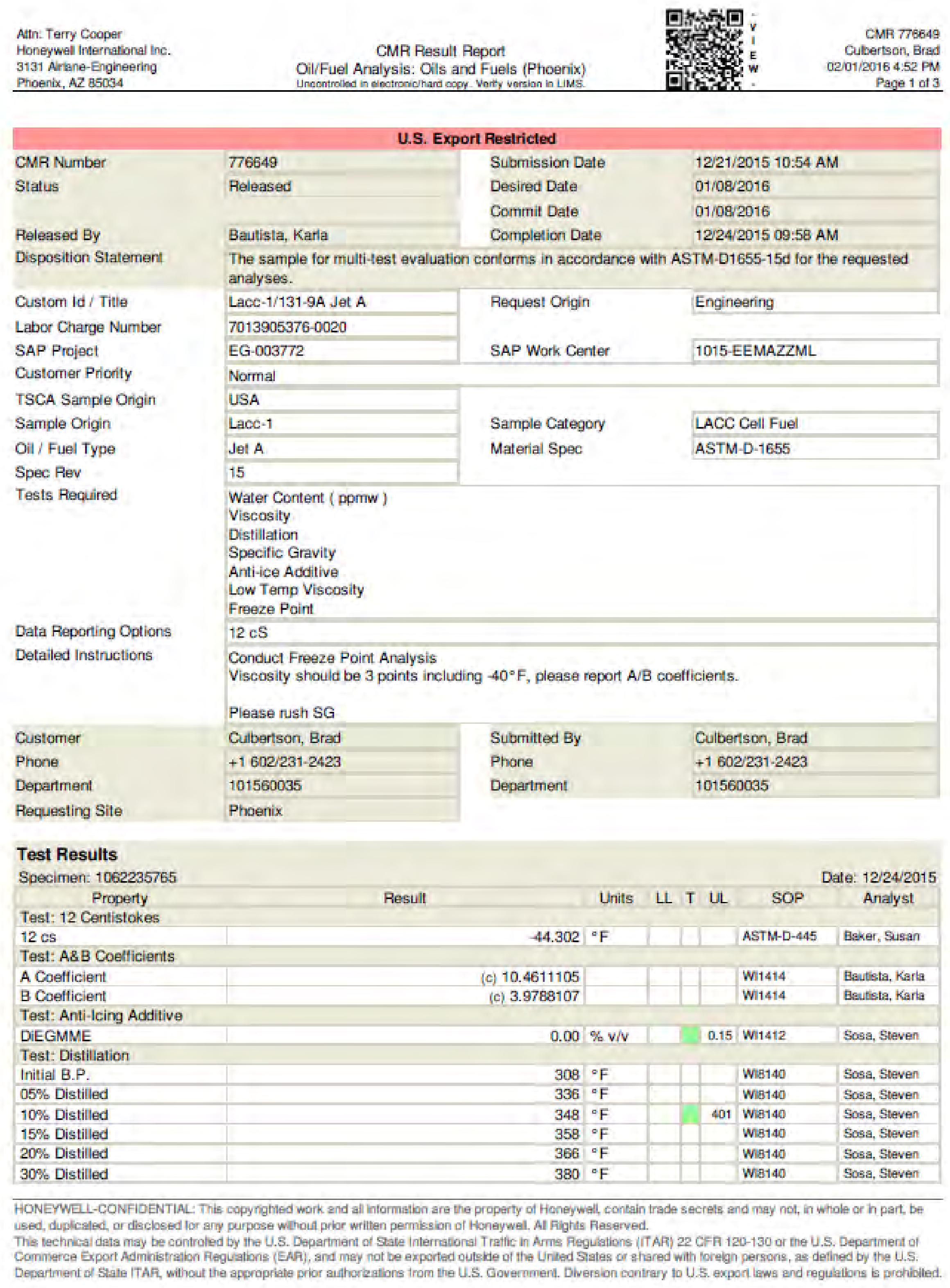

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Honeywell International Inc.
3131 Airlane-Engineering
Phoenix, AZ 85034

CMR Result Report
Oil/Fuel Analysis: Oils and Fuels (Phoenix)
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CMR 776649
Culbertson, Brad
02/01/2016 4:52 PM
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CMR Number	776649	Submission Date	12/21/2015 10:54 AM
Status	Released	Desired Date	01/08/2016
		Commit Date	01/08/2016
Released By	Bautista, Karla	Completion Date	12/24/2015 09:58 AM
Disposition Statement	The sample for multi-test evaluation conforms in accordance with ASTM-D1655-15d for the requested analyses.		
Custom Id / Title	Lacc-1/131-9A Jet A	Request Origin	Engineering
Labor Charge Number	7013905376-0020		
SAP Project	EG-003772	SAP Work Center	1015-EEMAZZML
Customer Priority	Normal		
TSCA Sample Origin	USA		
Sample Origin	Lacc-1	Sample Category	LACC Cell Fuel
Oil / Fuel Type	Jet A	Material Spec	ASTM-D-1655
Spec Rev	15		
Tests Required	Water Content (ppmw) Viscosity Distillation Specific Gravity Anti-ice Additive Low Temp Viscosity Freeze Point		
Data Reporting Options	12 cS		
Detailed Instructions	Conduct Freeze Point Analysis Viscosity should be 3 points including -40°F, please report A/B coefficients. Please rush SG		
Customer	Culbertson, Brad	Submitted By	Culbertson, Brad
Phone	+1 602/231-2423	Phone	+1 602/231-2423
Department	101560035	Department	101560035
Requesting Site	Phoenix		

Test Results

Specimen: 1062235765 Date: 12/24/2015

Property	Result	Units	LL	T	UL	SOP	Analyst
Test: 12 Centistokes							
12 cs	-44.302	°F				ASTM-D-445	Baker, Susan
Test: A&B Coefficients							
A Coefficient	(c) 10.4611105					WI1414	Bautista, Karla
B Coefficient	(c) 3.9788107					WI1414	Bautista, Karla
Test: Anti-Icing Additive							
DiEGMME	0.00	% v/v		🟩	0.15	WI1412	Sosa, Steven
Test: Distillation							
Initial B.P.	308	°F				WI8140	Sosa, Steven
05% Distilled	336	°F				WI8140	Sosa, Steven
10% Distilled	348	°F		🟩	401	WI8140	Sosa, Steven
15% Distilled	358	°F				WI8140	Sosa, Steven
20% Distilled	366	°F				WI8140	Sosa, Steven
30% Distilled	380	°F				WI8140	Sosa, Steven

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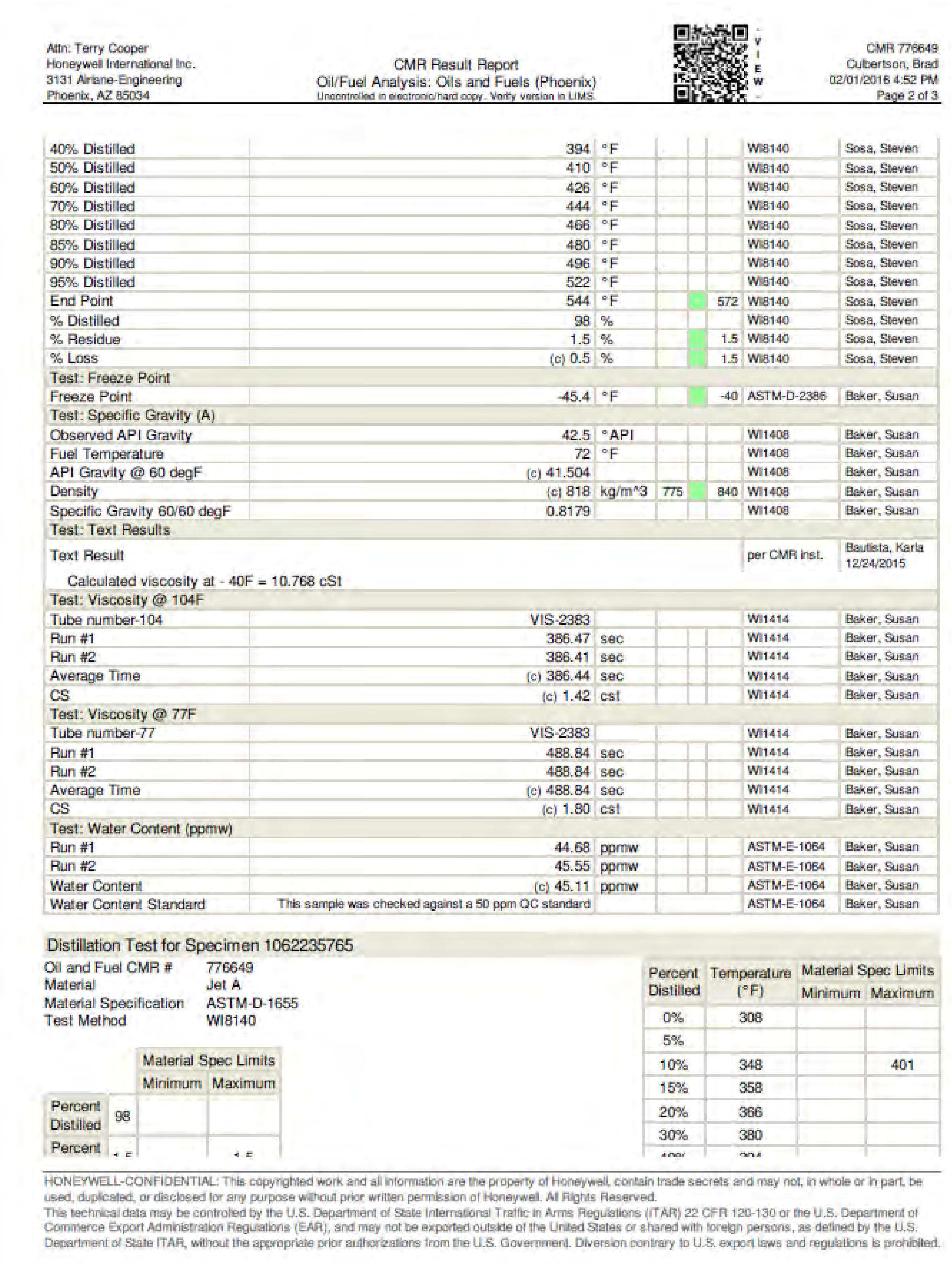

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CMR 776649
Culbertson, Brad
02/01/2016 4:52 PM
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40% Distilled		394	°F				WI8140	Sosa, Steven
50% Distilled		410	°F				WI8140	Sosa, Steven
60% Distilled		426	°F				WI8140	Sosa, Steven
70% Distilled		444	°F				WI8140	Sosa, Steven
80% Distilled		466	°F				WI8140	Sosa, Steven
85% Distilled		480	°F				WI8140	Sosa, Steven
90% Distilled		496	°F				WI8140	Sosa, Steven
95% Distilled		522	°F				WI8140	Sosa, Steven
End Point		544	°F		🟩	572	WI8140	Sosa, Steven
% Distilled		98	%				WI8140	Sosa, Steven
% Residue		1.5	%		🟩	1.5	WI8140	Sosa, Steven
% Loss		(c) 0.5	%		🟩	1.5	WI8140	Sosa, Steven
Test: Freeze Point								
Freeze Point		-45.4	°F		🟩	-40	ASTM-D-2386	Baker, Susan
Test: Specific Gravity (A)								
Observed API Gravity		42.5	°API				WI1408	Baker, Susan
Fuel Temperature		72	°F				WI1408	Baker, Susan
API Gravity @ 60 degF		(c) 41.504					WI1408	Baker, Susan
Density		(c) 818	kg/m^3	775	🟩	840	WI1408	Baker, Susan
Specific Gravity 60/60 degF		0.8179					WI1408	Baker, Susan
Test: Text Results								
Text Result							per CMR inst.	Bautista, Karla 12/24/2015
Calculated viscosity at - 40F = 10.768 cSt								
Test: Viscosity @ 104F								
Tube number-104		VIS-2383					WI1414	Baker, Susan
Run #1		386.47	sec				WI1414	Baker, Susan
Run #2		386.41	sec				WI1414	Baker, Susan
Average Time		(c) 386.44	sec				WI1414	Baker, Susan
CS		(c) 1.42	cst				WI1414	Baker, Susan
Test: Viscosity @ 77F								
Tube number-77		VIS-2383					WI1414	Baker, Susan
Run #1		488.84	sec				WI1414	Baker, Susan
Run #2		488.84	sec				WI1414	Baker, Susan
Average Time		(c) 488.84	sec				WI1414	Baker, Susan
CS		(c) 1.80	cst				WI1414	Baker, Susan
Test: Water Content (ppmw)								
Run #1		44.68	ppmw				ASTM-E-1064	Baker, Susan
Run #2		45.55	ppmw				ASTM-E-1064	Baker, Susan
Water Content		(c) 45.11	ppmw				ASTM-E-1064	Baker, Susan
Water Content Standard	This sample was checked against a 50 ppm QC standard						ASTM-E-1064	Baker, Susan

Distillation Test for Specimen 1062235765

Oil and Fuel CMR #	776649
Material	Jet A
Material Specification	ASTM-D-1655
Test Method	WI8140

		Material Spec Limits	
		Minimum	Maximum
Percent Distilled	98		
Percent			

Percent Distilled	Temperature (°F)	Material Spec Limits	
		Minimum	Maximum
0%	308		
5%			
10%	348		401
15%	358		
20%	366		
30%	380		

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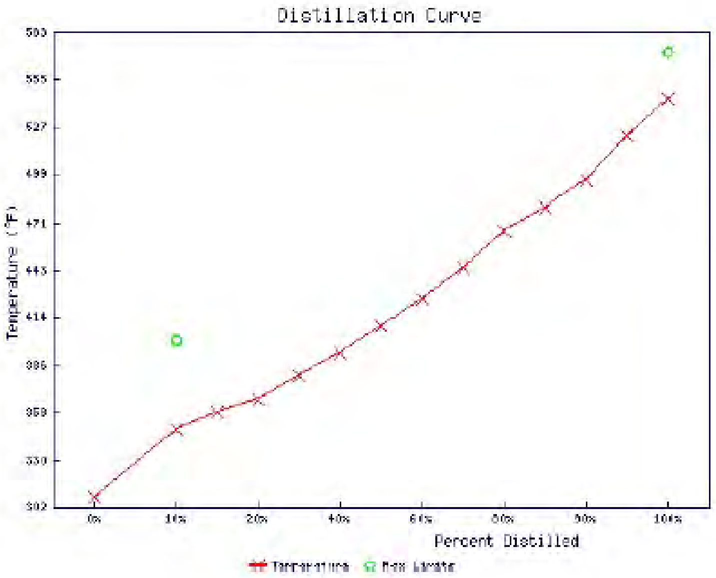
Residue	1.5		1.5
Percent Loss	0.5		1.5

40%	394		
50%	410		
60%	426		
70%	444		
80%	466		
85%	480		
90%	496		
95%	522		
100%	544		572



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