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Hybrid Thermally Efficient Core (HyTEC)
HyTEC Phase I—P&W SATF
Final Report

Jeannette Hill
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February 2026

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ACRONYMS

-A-

AC_D	Area X Coefficient Discharge
ADP	Aero Design Point
ALP	Air Loading Parameter
ARO 150	Aromatic 150
ASTM	American Society for Testing and Materials
ATJ-IPK	Alcohol-To-Jet Isoparaffinic Kerosene

-C-

CFD	Computational Fluid Dynamics
CO	Carbon Monoxide

-D-

DCN	Derived Cetane Number

-E-

EI	Emissions Index
ERA	Environmentally Responsible Aviation

-F-

FAR	Fuel-Air Ratio
FARR	Fuel-Air Ratio Ratio = Carbon Balance FAR divided by the Performance FAR
FFP	Fit For Purpose
FP_b	Combustor Flow Parameter

-G-

GCxGC	Comprehensive Two-dimensional Gas Chromatography

-H-

HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HyTEC	Hybrid Thermally Efficient Core

-I-

ID	Inner Diameter
IR	Infrared

-L-

LBO	Lean Blowout
LS	Lean Staged

-M-

MSR	Multisector Rig

-N-

NASA	National Aeronautics and Space Administration
NGSA	Next Generational Single Aisle
NHOC	Net Heat of Combustion
NOx	Nitrogen Oxides
nvPM	Non-Volatile Particulate Matter

-P-

P&W	Pratt & Whitney
P_3	Station 3.0 Compressor Exit Pressure (psia)
P’	Maximum Dynamic Pressure

-R-

RQL	Rich-Quench-Lean

-S-

SATF	Synthetic Aviation Turbine Fuel
SAK	Synthetic Aromatic Kerosene
SNR	Single Nozzle Rig

-T-

T/C	Thermocouple
TO	Take-off
TPM	Technical Performance Metrics
T_3	Station 3.0 Compressor Exit Temperature (R or °F as defined)

-U-

UDRI	University of Dayton Research Institute
UHC	Unburned Hydrocarbons

1. INTRODUCTION

This report details work conducted under the National Aeronautics and Space Administration (NASA) Hybrid Thermally Efficient Core (HyTEC) project intended to accelerate small turbofan engine turbine technologies. Pratt & Whitney (P&W) investigated continued development of two state-of-the-art combustor architectures: advanced Rich-Quench-Lean (RQL) and lean staged (LS) stoichiometry combustors. The primary objective of these investigations was to evaluate the impact of 100% blend synthetic aviation turbine fuel (SATF) on key engine and system performance metrics such as gaseous emissions, non-volatile particulate matter (nvPM) emissions, liner durability, combustor dynamics, and combustor operability, including combustion efficiency, lean blowout (LBO), and ignition characteristics.

To achieve these objectives, the team i) sourced four (4) high blend SAFs (100% Hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK), 50:50 HEFA-SPK: alcohol-to-jet isoparaffinic kerosene (ATJ-IPK), and two (2) other blended 100% “drop-in” SATF candidates), ii) tested the SATFs as well as Jet A in the advanced RQL and LS burners in both single and multisector configurations, with multiple builds for each configuration, and iii) developed a framework for predicting various properties of SATFs to better understand the spray characteristics of the sustainable fuels.

As a result of the multiple design/test/computational fluid dynamics (CFD) campaigns over a three (3)-year period, it was concluded that all the aspects of burner performance with the SATFs the team investigated are comparable to that of petroleum-based Jet A, sufficient to meet sustainability goals for the next generation single aisle (NGSA) aircraft.

This section will contain introductory information including key tasks, technical performance metrics (TPM) required by the HyTEC contract, criteria used for SATF selection and corresponding fuel property data, as well as a brief overview of the single and multisector scale test rigs.

The specific rig design, experimental results from both single nozzle rig (SNR) and multisector rig (MSR) scaled test rigs, are described in subsequent sections. Section 2 and Section 3 include the results of advanced RQL configuration testing with SNR and MSR scales, respectively. Section 4 and Section 5 show the results of the LS configuration with SNR and MSR scales, respectively. The tool developed for SATF property prediction and subsequent spray simulation is described in Section 6. Key takeaways over the entire campaign will be summarized in Section 7. An assessment of the test results with respect to the corresponding TPM is also included in the conclusion section.

1.1 GOALS AND OBJECTIVES

Over the current campaign, P&W continued to develop the advanced RQL and LS technology to a more product-ready configuration, including the following key tasks:

- SNR testing for both advanced RQL and LS evaluating emissions, nvPM, combustion efficiency, tones, and durability
- MSR testing for both advanced RQL and LS evaluating ignition and LBO at sea level conditions

- Developing a SATF property prediction tool to implement in spray simulation and single sector scale CFD analysis both for Jet A and SATF combustion simulations and validate and analyze the system benefits

The SNR was used to evaluate the component performances and explore the design space and fundamentals of the advanced RQL and LS combustor concepts with Jet A and SATFs. The SNR also employed design tools such as CFD of the various components and spray bench testing. Enabling technologies included improved CFD models, spray models, and modeling approaches of the combustor for both advanced RQL and LS configurations.

The MSR evaluated criteria needed for successful product introduction and evaluation of the high-blend SATF(s) on ignition and LBO. The rigs were designed and scaled to the HyTEC core size advanced RQL and LS combustors, based on the single-sector design.

The tool development efforts included incorporating high-blend SATF into the design tools and CFD models. Combustor performance such as atomization and emissions performance were investigated. Results of the models were compared to the test data collected in the single-sector rig. The validated models were used to evaluate the impact of these high-blend SATFs on engine and system performance parameters. Possible system benefits were explored using these modeling tools.

Table 1-1 and Table 1-2 provide the TPM required by the contract for the advanced RQL and LS configurations, respectively. The TPMs were used to track the progress throughout the program.

Key to the planned effort for advanced RQL in Table 1-1 was that the ignition and LBO are as good as the ignition and LBO in current engines. For this effort, “as good as” and “comparable” are taken to mean that ignition and LBO occur at a fuel-air ratio (FAR) no greater than about 15% higher than the current commercially proven products. For tones, it has been observed that magnitudes of under a psi value in the single-sector rig correlate to tones that are not audible in engine operation. Thus, achieving less than this psi amplitude value was a key program metric. For the HyTEC campaign, because the focus is on sustainability, cruise NOx and cruise nvPM were considered since they are the primary emissions of concern at altitude.

The TPMs are shown in Table 1-2 for the LS combustor. Ignition and LBO are expected to be comparable, with current HyTEC RQL testing. Again, the combustor tones shall be an absolute measure, with a psi value measured in the single-sector rig. The NOx and nvPM are absolute measures as well. It was not expected that SATF will impact nvPM emissions at these very low levels.

Table 1-1 Advanced RQL TPMs for HyTEC

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
1	Ignition	Comparable (within 15%) or lower FAR
2	LBO	Comparable (within 15%) or lower FAR
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	>5% Improvement
5	Cruise nvPM	>70% Improvement

Table 1-2 LS TPMs for HyTEC

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
1	Ignition	Comparable (within 15%) or lower FAR
2	LBO	Comparable (within 15%) or lower FAR
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	40-60% Improvement
5	Cruise nvPM	>90% Improvement

1.2 SUMMARY OF FUELS

1.2.1 Fuel Selection Criteria and Details

Petroleum-derived Jet A fuel is the current industry standard. SATF is starting to penetrate the market, with the intent that SATFs in the future will be available to replace petroleum-derived Jet A with low carbon fuel sources. While it is intended that SATFs will be “drop-in” to petroleum-derived Jet A, P&W and NASA are interested in exploring the performance of next generation combustors with the variations of SATF that are currently available and may be available in the market. Thus, this effort explores the performance and response of future combustors to “non-drop-in” SATFs to understand the robustness of these technologies with respect to possible variations of future fuel composition.

The criteria of high-blend SATFs for testing included: the availability of the fuel for testing in a timely manner; properties such as viscosity, surface tension, and cetane number that are known to influence combustion, as well as properties that might reduce particulate matter and/or increase energy content per mass; and the potential of the fuel feed stock and process to achieve a 70% reduction in life cycle carbon emissions when matured.

As a result, a conventional Jet A baseline and four (4), 100% SATF formulations were selected for testing; two (2) were reach selections described below in more detail. The Jet A baseline had stringent density, aromatics, and sulfur content criteria to ensure closeness to an average petroleum-derived jet fuel. The four (4), 100% SATFs represented various 100% sustainable aviation fuel candidates, both "drop-in" and "non-drop-in," and were selected for their distinct physical and chemical properties. The five (5) test fuels and their targeted features include:

- Jet A baseline – an average fossil derived Jet A with density between 0.800-0.810g/mL at 15°C, total aromatics content between 16-22 vol.%, and sulfur content between 100-500ppm by weight.
- 100% HEFA-SPK – a 100% synthetic paraffinic kerosene containing neither aromatics nor sulfur species. Currently categorized as a "non-drop-in" fuel, this test material exhibits relatively low density, high-energy content per unit mass, and ease of ignitability as indicated by a high Derived Cetane Number (DCN).
- 50:50 HEFA-SPK:ATJ-IPK – a "non-drop-in" 100% synthetic paraffinic kerosene containing neither aromatics nor sulfur species. This fuel contains 50% isobutanol-derived isoparaffins, which results in a lower DCN fuel (higher resistance to ignitability) than its 100% HEFA-SPK counterpart.
- Reach selection 90:10 HEFA-SPK: aromatic 150 (ARO 150) – a 100% "drop-in" SATF candidate which is a blend of synthetic paraffins and monoaromatic hydrocarbons. Since synthetic aromatic kerosene (SAK) was not obtainable, petroleum-derived ARO 150 was used as an acceptable proxy given its similar monoaromatic hydrocarbon composition.
- Reach selection 90:8:2 HEFA-SPK:ARO 150:Naphthalene – A 100% "drop-in" SATF candidate with total aromatics content equal to the 90:10 HEFA-SPK:ARO 150 blend, but with significant concentrations of soot-promoting naphthalenes.

Table 1-3 summarizes the hydrocarbon composition of each sample as measured by two-dimensional gas chromatography, and Appendix A: Property Tables References contains the detailed hydrocarbon characterizations. All four (4) SATF samples used the same batch of 100% HEFA-SPK. 100% HEFA-SPK was procured from World Energy, LLC; ATJ-IPK was procured from GEVO, Inc.; ARO 150 was sourced from RB Products, Inc.; and naphthalenes were sourced from Sigma-Aldrich®, a division of the Merck Group. Fuel shipping and blending was performed by a third-party distributor of tailored aviation fuels. All SATF samples were stored and shipped in fifty-five (55)-gallon drums.

Table 1-3 Comprehensive Two-dimensional Gas Chromatography (GCxGC) Hydrocarbon Composition Summary

Property	Jet A	100% HEFA-SPK	50:50 HEFA-SPK:ATJ-IPK	Reach 90:10 HEFA-SPK:ARO 150	Reach 90:8:2 HEFA-SPK:ARO 150: Naphthalene
Hydrocarbon Composition Data					
University of Dayton Research Institute (UDRI)					
Average Molecular Weight (g/mol)	163	161	169	158	157
Hydrogen content (mass %)	13.9	15.3	15.3	14.8	14.6
Total n-paraffin, mass %	19.5	16.0	9.0	13.9	13.9
Total iso-paraffin, mass %	25.0	76.2	84.3	69.2	66.2
Total cyclo-paraffin, mass %	35.3	7.4	5.8	6.7	7.8
Total aromatics, mass %	20.2	0.4	0.2	10.1	12.1
Mono-aromatics [alkylbenzenes]	11.9	0.3	0.2	8.5	8.5
Di-aromatics [Napthalenes, etc.]	1.0	0.0	0.0	0.6	2.5
Cyclo-aromatics	7.3	0.0	0.0	1.1	1.2

1.2.2 Fuel Property Measurements

The key physical and chemical properties of the five (5) fuels were measured and compiled to describe relative differences in atomization, vaporization, ignition, energy release, and emissions processes. The measurements were carried out at contracted laboratories or collected from manufacturer certificates of analysis. The results were served as inputs to complementary modeling tasks described in Section 6 System and Tool Validation. Table 1-4 contains the measured properties, which influence different phases of the combustion process for all five (5) test fuels. Table 1-4 also cites the measurement methods, American Society for Testing and Materials (ASTM), and relevant Jet A specification requirements or fit-for-purpose criteria to reference norms of conventional jet fuel.

Table 1-4 Measured Fuel Properties

Property	Method	Jet A Spec / Fit For Purpose (FFP) criteria	Jet A	100% HEFA-SPK	50:50 HEFA-SPK:ATJ-IPK	Reach 90:10 HEFA-SPK:ARO 150	Reach 90:8:2 HEFA-SPK:ARO 150: Naphthalene
Certificate of Analysis Date			6/29/2023	7/30/2023	11/13/2023	7/17/2023	7/17/2023
Atomization							
Density @ 15°C (kg/m^3)	ASTM D4052	775 - 840	806	751	757	765	771
Kinematic Viscosity @ -20°C (mm^2/s)	ASTM D445	8.0, maximum	4.6	Not measured	4.2	4.7	4.8
Surface Tension @ 22°C (mN/m)	ASTM D1331C	N/A	26.2	24.1	23.6	24.4	24.7
Vaporization							
Specific Heat Capacity @ 0°C (J/g/K)	E1269*	N/A	1.86	2.17	2.17	2.08	2.09
Thermal Conductivity 0°C (W/mK)	ASTM D7896	N/A	0.122	0.125	0.111	0.125	0.125
Enthalpy of Vaporization, est (kJ/mol)	Estimation method**	N/A	59.1	56.3	58.9	56.3	56.2
Enthalpy of Vaporization, est (MJ/kg)		N/A	0.36	0.35	0.35	0.36	0.36
Distillation Temperature, 10% recovery (°C)	ASTM D86	205, maximum	185	158	167	160	162
T50-T10 (°C)		15, minimum (FFP)	21	32	19	31	31
T90-T10 (°C)		40, minimum (FFP)	61	88	74	88	84
Ignition							
DCN	ASTM D6890	40.0, minimum (FFP)	47.4	58.4	43.3	54.8	53.6
Flash Point (°C)	ASTM D56	38, minimum	53	40	40	42	40
Energy Release and Emissions							
Net Heat of Combustion (MJ/kg)	ASTM D3338/D3338M	42.8 minimum	43.2	44.1	44.0	43.8	43.7
Hydrogen content (mass %)	GCxGC-MS @ UDRI	13.4, minimum (FFP)	13.9	15.3	15.3	14.8	14.6
Sulfur (ppm by mass)	ASTM D5453/D2622	3000, maximum	191	<1	<1	1.9	2.1
Smoke Point (mm)	ASTM D1322	25.0, minimum	24	Not measured	43	45	45
Aromatics (% volume)***	ASTM D1319/D2425	25.0, maximum	18.8	<0.1	1.7	9.9	9.8

* a correction factor of eleven percent (11%) increase from base measurement applied. Factor derived from reported deviation of the dodecane standard

** estimate derived from average molecular weight and aromatics mass fraction (R. Xu, H. Wang, M. Colket, T. Edwards) [1]

*** Defer to GC x GC "Total aromatics" for more accurate measurement

Common fuel property relationships in hydrocarbon-based kerosene were observed. As shown in Figure 1-1, increases in paraffinic content correlated with a decrease in density and increase in net heat of combustion (NHOC). Variation in viscosities between samples were negligible. As expected, the 50:50 HEFA-SPK:ATJ-IPK blend had the lowest DCN of all samples due to high concentration of heavily-branched isoparaffins.

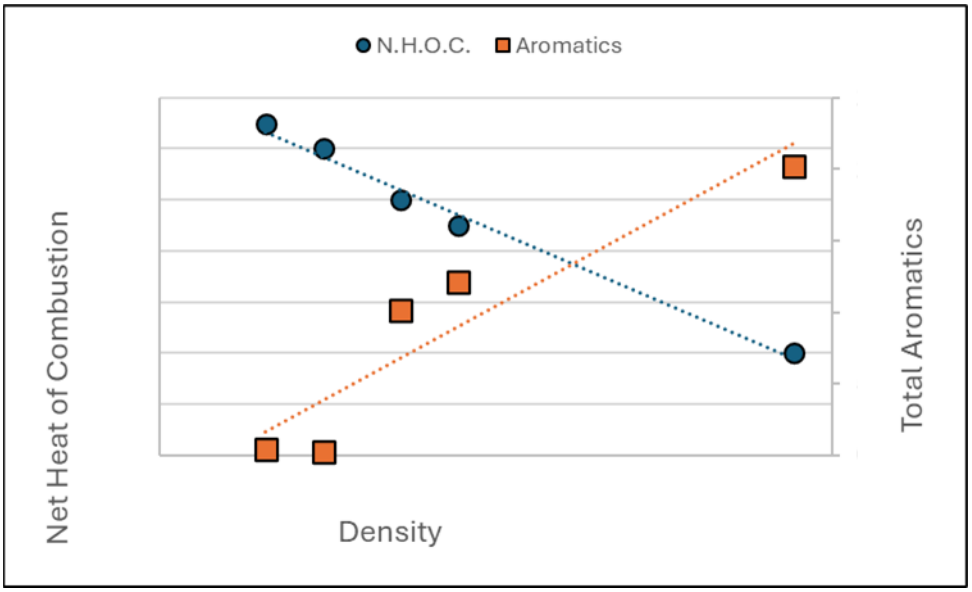


Figure 1-1 Bulk Fuel Property Relationships of Samples

1.3 COMBUSTOR RIG OVERVIEW

For combustion rig testing, there were two (2) types of rigs tested as part of this program. The first type was a SNR. The SNR was used for emission sampling, surveying combustor tones, and characterizing impacts to liner durability. For the SNR testing, two (2) builds were established. To quantify combustor durability, the SNR cell offers multiple measurement options, including infrared (IR) thermometry, thermocouples (T/C), and radiometry. SNR Build 1 also used T/C and radiometry measurements for combustor thermal characterization. For SNR Build 2, IR thermometry was not available with the updated rig design, so only T/C and radiometry measurements were carried out.

In addition to the quantitative measurements, the SNR facility has flame visualization capability. For HyTEC, two (2) different methods of flame visualization were utilized. For the initial builds of the SNR, both Advanced RQL and LS employed use of a fiberscope, which was installed in a borescope port on the rig side wall. The fiberscope focused on the view of the front end. The fiberscope shared the same sidewall port with the radiometer, so both could not be used at the same time. For the second build on SNR, a new design rig housing with a large quartz window on a side wall was used, thereby providing an expanded field of view inside the combustor. In addition, provisions were made on the other sidewall for two (2) radiometer ports. This allowed radiometer data and flame imaging to occur simultaneously. Figure 1-2 shows the flame visualization locations for SNR Build 1 and 2.

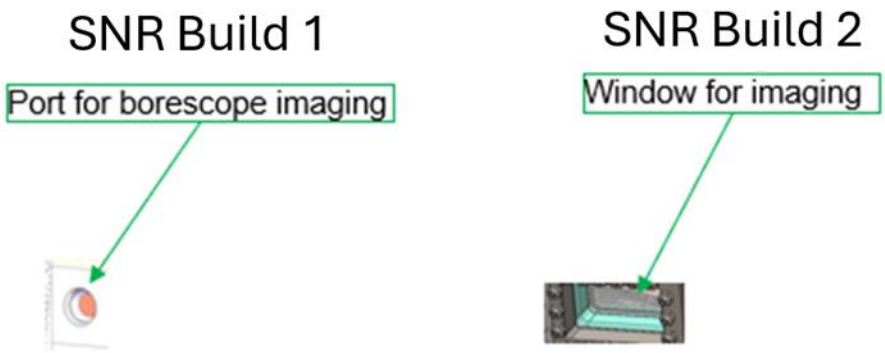


Figure 1-2 SNR Build 1 and Build 2 Flame Visualization

The second rig type for HyTEC was an MSR, which was constructed for the purpose of evaluating ignition and LBO capabilities of combustor configurations with the various fuel types.

For HyTEC, two (2) different types of MSR were built, the first for the advanced RQL combustor concept, and the second for an LS combustor concept. Both advanced RQL and LS MSR builds initiated from previously tested rigs. An RQL five (5) sector rig used for ultra-low emissions testing was rebuilt and baseline testing conducted. An LS three (3) sector rig was provided by NASA and modified for the testing.

For HyTEC SNR and MSR rig combustors, performance conditions were obtained from engines currently in service.

2. ADVANCED RQL SNR RESULTS

2.1 ADVANCED RQL SNR COMBUSTOR RIG OVERVIEW

Multiple test configurations were designed and tested in two (2) SNRs using the advanced RQL arrangement to achieve low emissions levels while meeting key combustor operational metrics.

The main test objectives for the HyTEC advanced RQL SNR test campaigns were:

1. Determine the impact of SATF on key engine and system performance metrics; and
2. Evaluate advanced RQL features relative to current product.

The second of the two (2) rigs required a new design and fabrication of the housing. The goals for the new rig were to:

- Decrease changeover time between tests through improved rig design; and
- Reduce the number of unique components required between advanced RQL and LS rig tests.

2.2 TESTING SUMMARY

2.2.1 Testing Summary of the Advanced RQL SNR Build 1

Advanced RQL SNR Build 1 testing was completed with the primary objective of characterizing the impact of using SATF in a combustor as compared to Jet A fuel. More specifically, the objective was to determine the impact of the SATFs on combustor efficiency, gas emissions, dynamics, nvPM, durability and panel temperatures. Table 2-1 provides the overall test matrix for Advanced RQL SNR Build 1 for completed points. The points include station 3.0 compressor exit temperature (R or °F as defined) (T_3), Station 3.0 compressor exit pressure (psia) (P_3), Combustor Flow Parameter (FP_b), aero design point (ADP). Note there were multiple combustor configurations with one (1) configuration being tested with four (4) different SATFs.

SNR results were used to compare key combustor performance metrics with Jet A and the four (4) different SATFs listed above in Section 1.2.1.

Table 2-1 Advanced RQL SNR Build 1 Test Matrix of Completed Points

		Config 1	Config 1	Config 1	Config 1	Config 1
	Fuel Type	Jet A	100% HEFA-SPK	50:50 HEFA-SPK: ATJ-IPK	90:10 HEFA	90:8:2 HEFA
SS GROUND IDLE						
301	FPb Sweep	■				
302	FPb Sweep	■				
303	FAR Sweep	■				
304	FAR Sweep	■				
305a	FAR Sweep	■	■	■		
305b	FAR Sweep	■	■	■		
306	FAR Sweep	■				
307	FAR Sweep	■	■	■		
308	T3 Sweep	■				
308	T3 Sweep	■				
309	P3 Sweep	■				
310	P3 Sweep	■				
Snap Accel						
403	FAR Sweep	■				
405	FAR Sweep	■				
407	FAR Sweep	■				
413	FAR Sweep	■				
415a	FAR Sweep	■	■	■		
415b	FAR Sweep	■	■	■		
417	FAR Sweep	■	■	■		
418	T3 Sweep	■				
423	FAR Sweep	■				
425	FAR Sweep	■				
427	FAR Sweep	■				
Approach						
501	FPb Sweep	■				
502	FPb Sweep	■				
503	FAR Sweep	■				
504	FAR Sweep	■				
505a	FAR Sweep	■	■	■		
506	FAR Sweep	■	■	■		
507	FAR Sweep	■	■	■		
508_1	T3 Sweep	■				
508_2	T3 Sweep	■				
509	P3 Sweep	■				
510	P3 Sweep	■				
Vision Cycle						
1	ADP	■	■	■		
2	Takeoff	■	■	■	■	■
3	Climb	■				
4	Approach	■				
6	Idle_1	■	■	■	■	■
7	Idle_2	■	■	■		

The first major test run characterized the impact of 100% HEFA-SPK and 50:50 HEFA-SPK:ATJ-IPK SATFs on emissions, by performing a FAR sweep at idle, approach, and high-power conditions using one configuration. Additionally, SATFs 3 and 4 are included with the results at high-power. The results are shown below in Figure 2-1, Figure 2-2, and Figure 2-3, where emissions index (EI) NOx, EI carbon monoxide (CO), EI unburned hydrocarbons (UHC),

combustion efficiency, nvPM mass, and nvPM number are each plotted for each combustor operating regime.

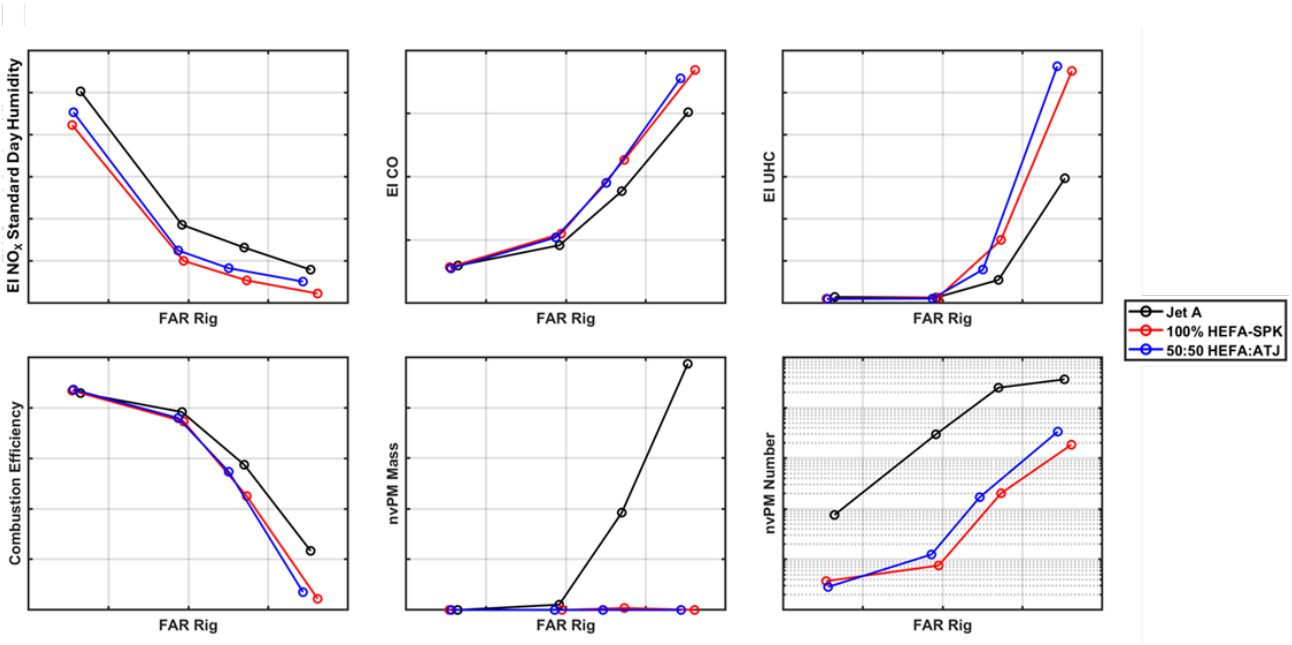


Figure 2-1 Advanced RQL SNR Build 1 FAR Sweep Ground Idle Condition SATF Emissions Results

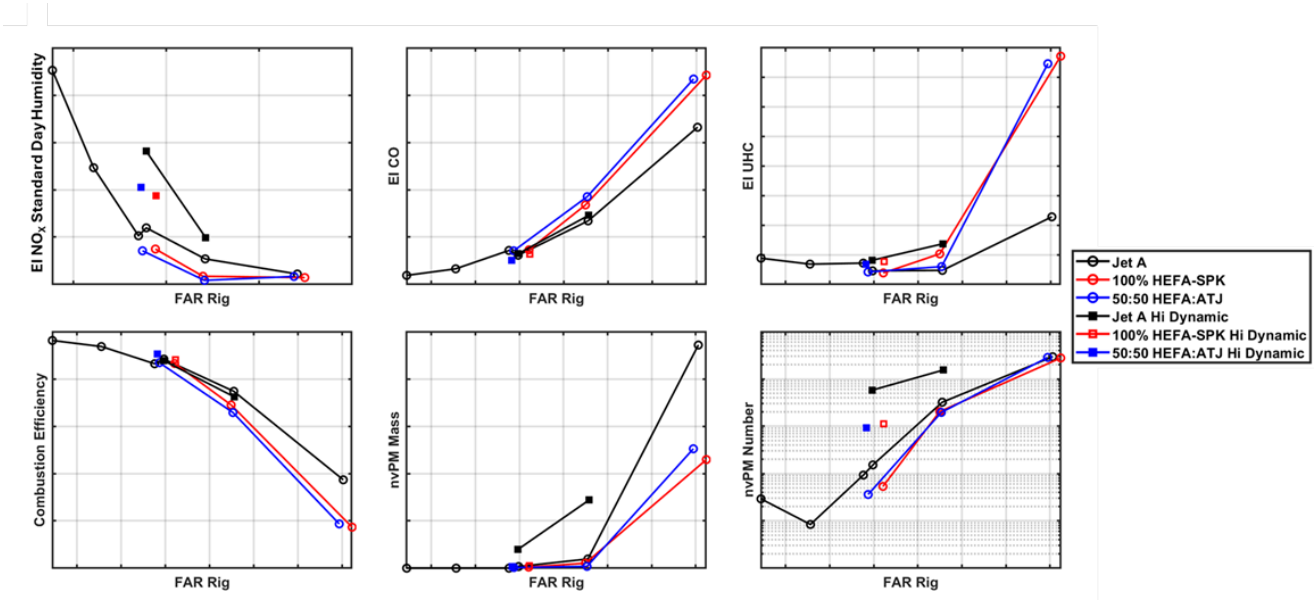


Figure 2-2 Advanced RQL SNR Build 1 FAR Sweep Approach Condition SATF Emissions Results

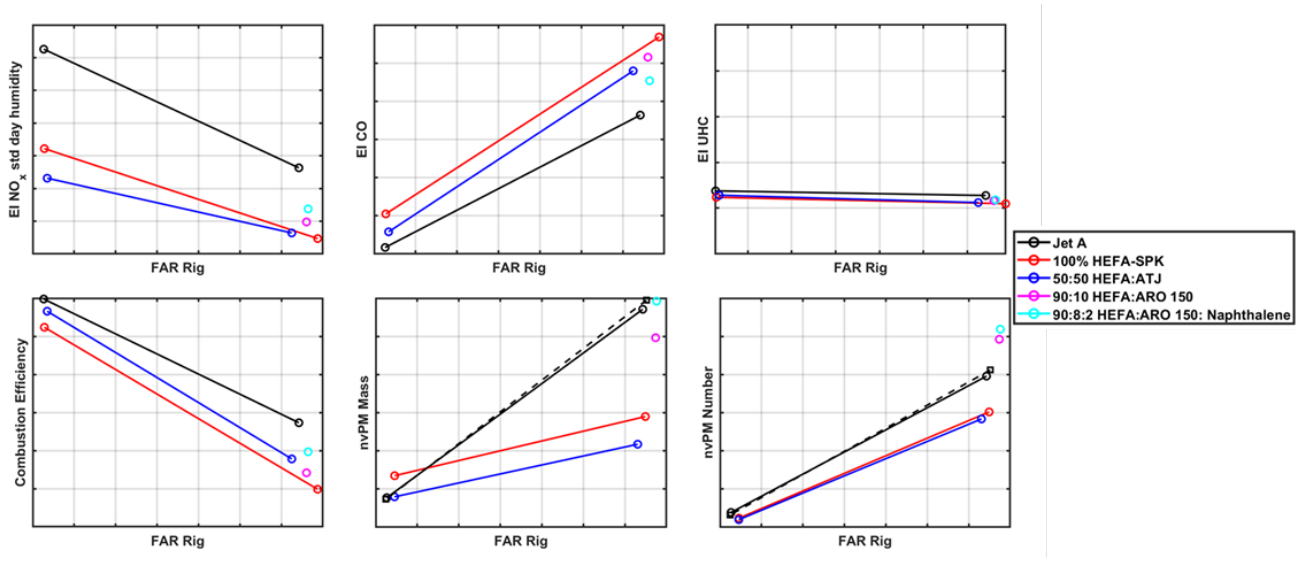


Figure 2-3 Advanced RQL SNR Build 1 FAR Sweep High-power Condition SATF Emissions Results

Overall, the results indicate that while SATFs demonstrate slightly lower combustion efficiency than Jet A (elevated CO and UHC at some conditions), SATFs were able to demonstrate a minor reduction in NOx emissions across the test conditions. More significantly

however, at low and high-power conditions, SATFs demonstrated significantly lower nvPM emissions. At idle conditions, nvPM number results are up to two (2) orders of magnitude lower than the Jet A data at comparable conditions. At approach conditions, the nvPM emissions were similar to Jet A, but the SATFs still demonstrated slightly lower values across the tested FAR range. At high-power conditions, the lower FAR point, which emulates a cruise condition, shows similar nvPM results between Jet A and SATF, but the high FAR point (simulating a TO condition) shows a substantial reduction with SATF. This reduction in nvPM using SATF is an expected result of this testing, as these fuels have very low aromatic content. Added evidence to support this is shown in the high-power results in Figure 2-3, where the 90:10 HEFA-SPK:ARO 150 and 90:8:2 HEFA-SPK:ARO 150:Naphthalene fuel blends with added aromatic content show a substantial increase in nvPM values compared to the other SATF blends. Another interesting observation in the data is that dynamics were found to have a significant impact on emissions at the approach condition shown in Figure 2-2. Some limited emissions data was taken at identical combustor operating conditions where a significant combustion tone was present in the combustor (indicated by the "High Dynamics" lines in the chart). These points often show substantially higher nvPM emissions, demonstrating how high dynamics can couple with the combustion process to produce unfavorable emissions results.

Following the emissions testing, the Advanced RQL SNR Build 1 was used to test the impact of SATFs on combustor dynamics. The impacts on dynamics of SATF versus Jet A were examined as a part of this testing, with results shown below Figure 2-4. The maximum dynamic pressure (P') versus FAR is shown for different points and frequencies.

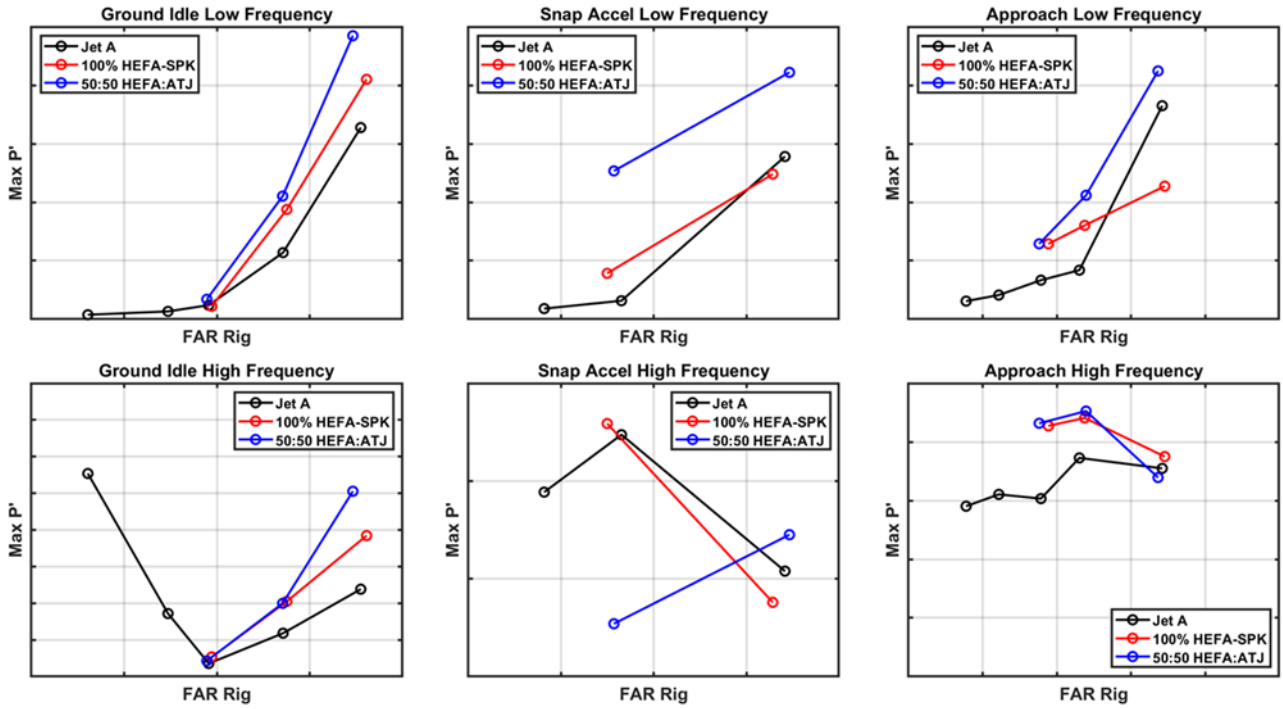


Figure 2-4 Advanced RQL SNR Build 1 FAR Sweep Condition SATF Dynamics Results

At ground idle, the SATFs were observed to generate slightly higher levels of dynamics than the baseline Jet A fuel, especially at high FAR conditions. It is a mixed story for snap accel and

approach. Although under limited conditions, some SATFs demonstrated similar or reduced dynamics, the SATFs often generated higher combustor tones, especially in the high frequency range at approach conditions. The alternative fuels clearly have an impact on how flame anchoring occurs within the combustor, causing a small but measurable change in tone generation by switching to SATF.

Another goal of the Advanced RQL SNR Build 1 test was to identify the impacts of SATFs on combustor thermal characteristics. These thermal characteristics were monitored during the test using IR thermometry and backside panel T/C.

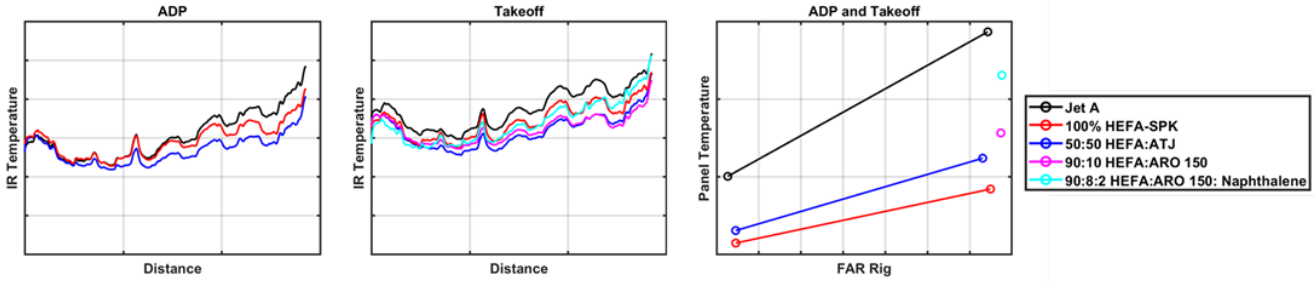


Figure 2-5 Advanced RQL SNR Build 1 Comparison of Thermal Characteristics between Jet A and SATFs

The thermal performance of the rig can be seen in the results in Figure 2-5. The two (2) left plots in Figure 2-5 are taken using the IR camera, and the right plot is data from the backside panel T/C. The thermal results from the test demonstrated minimal difference between Jet A and SATFs in thermal characteristics of the combustor, with similar panel temperatures, regardless of fuel. Despite the differences being small, Jet A does demonstrate the highest temperatures of all the tested fuels, especially in the downstream area of the combustor panel (higher distance values). This is likely due to the lower nvPM levels present in the SATFs, resulting in less radiative heat flux onto the combustor panels compared to baseline Jet A fuel.

Figure 2-6 and Figure 2-7 provide images of a high and low dynamics point taken at approach conditions for each fuel. These images were taken from the high-speed imaging system captured through the borescope port on the rig to visualize how the flame shape is affected by the different tested fuels. The luminosity of the SATF flames is significantly lower than that of Jet A, which is aligned with the nvPM measurements presented in Figure 2-1, Figure 2-2, and Figure 2-3. Soot production is highly sensitive to flame dynamics, which is demonstrated since the high dynamics points have substantially higher luminosity than the low dynamics points. This is well aligned with the data shown in Figure 2-3, where high dynamics points at identical combustor operating conditions resulted in higher nvPM measurements on both mass and number. High frequency dynamics at approach conditions are highly correlated to flame base anchoring, which is demonstrated in the high-speed videos collected at each of these conditions.

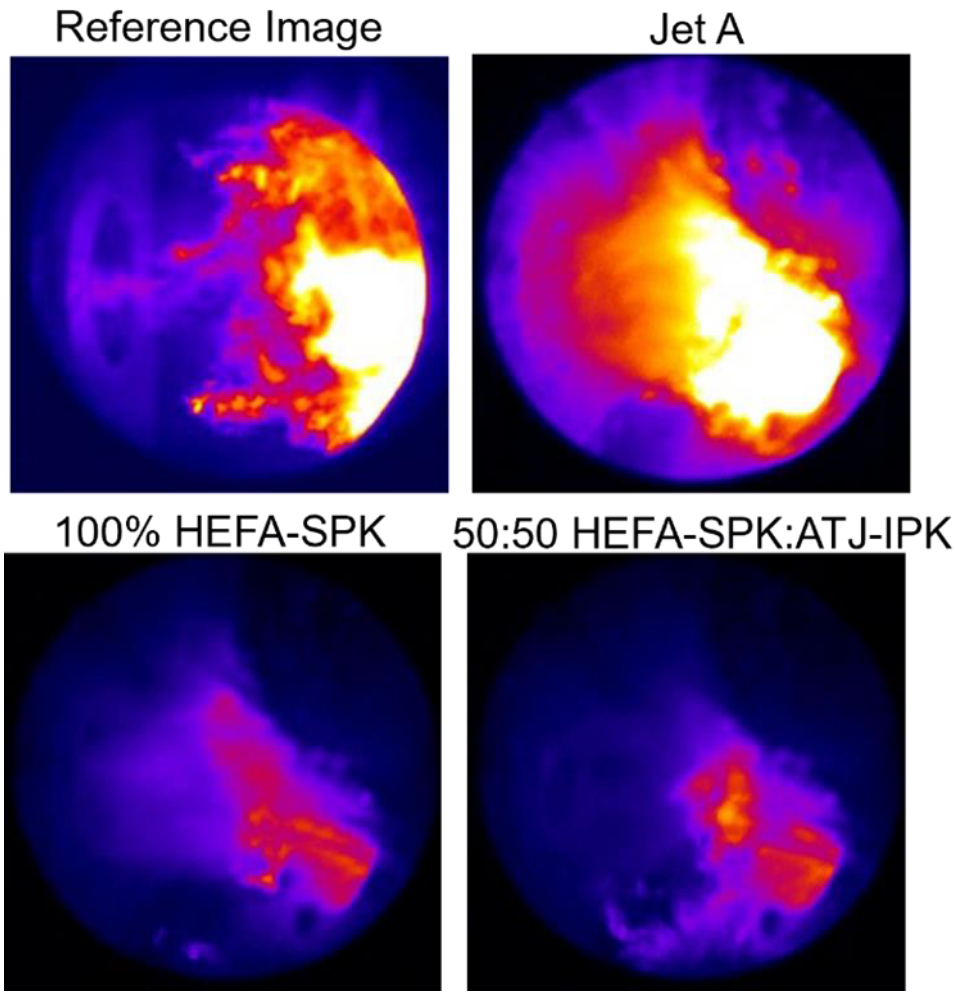


Figure 2-6 Advanced RQL SNR Build 1 Comparison of High Dynamics Point at Approach

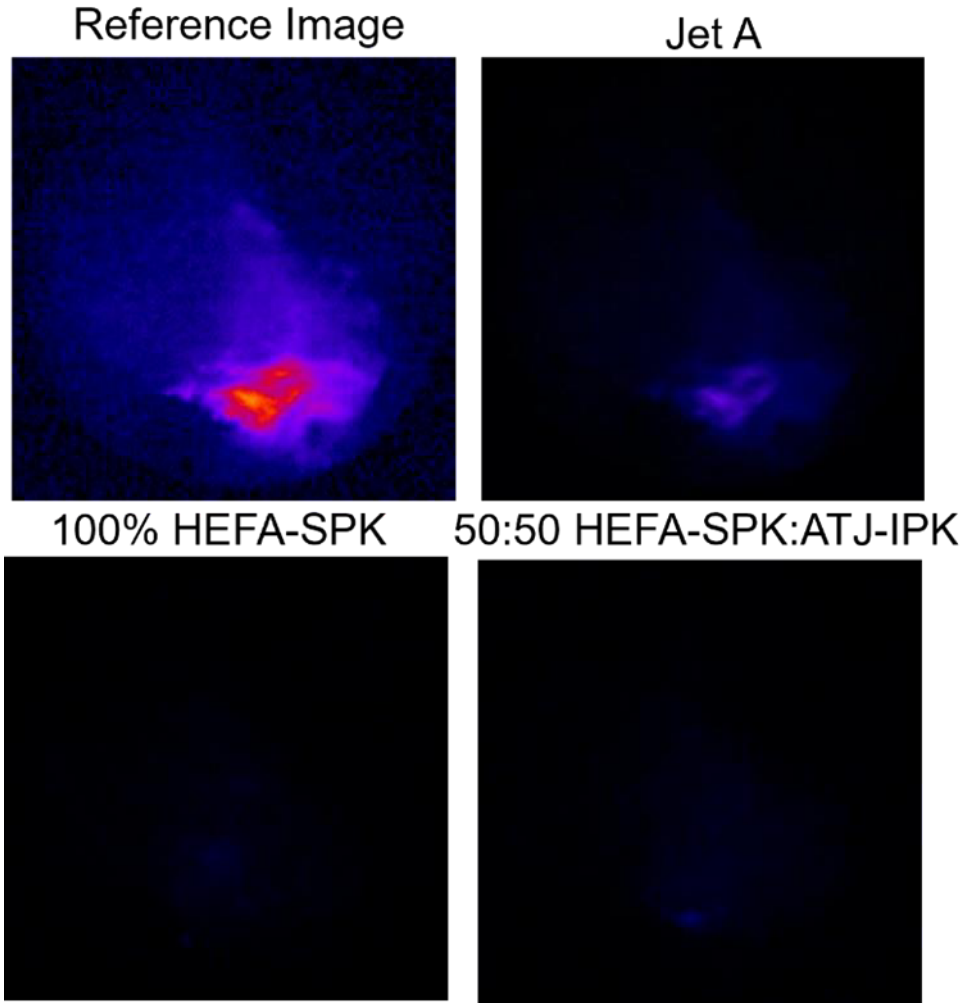


Figure 2-7 Advanced RQL SNR Build 1 Comparison of Low Dynamics Point at Approach

2.2.2 Testing Summary of the Advanced RQL SNR Build 2

Similar to Build 1 testing, the primary objective of the Advanced RQL SNR Build 2 testing was to characterize the impact of using SATFs in the combustor.

The test matrix for Advanced RQL SNR Build 2 testing is provided in Table 2-2 and Table 2-3. The green boxes were the points acquired in SNR Build 2 testing. The table indicates a series of test points for ground idle, approach, and high-power. The number of points for SATF testing were reduced to focus on the critical fuel-air sweeps to compare performance with Jet A. Note that the SATFs tested were the same 100% HEFA-SPK and 50:50 HEFA-SPK:ATJ-IPK tested in SNR Build 1 and only two (2) of the four (4) SATFs were tested in Build 2. Rig airflow was slightly increased for test 2 for rear step cooling not accounted for in test 1.

Table 2-2 Advanced RQL SNR Build 2 Test 1 Matrix of Completed Points, Jet A and 2 SATFs

	Fuel Type	Config 1 Jet A	Config 1 100% HEFA-SPK	Config 1 50:50 HEFA-SPK:ATJ-IPK
GROUND IDLE				
302	5% Ground Idle	■		
307	7% Ground Idle	■	■	■
308	FAR Sweep	■		
309	FAR Sweep	■	■	■
310	FAR Sweep	■		
311	FAR Sweep	■	■	■
APPROACH				
401	30% Approach	■	■	■
402	FAR Sweep	■		
403	FAR Sweep	■	■	■
404	FAR Sweep	■		
405	FAR Sweep	■	■	■
HIGH POWER				
500	100% Takeoff	■	■	■
501	85% Climb	■	■	■
502	FAR Sweep - High Power	■	■	■
503	FAR Sweep - High Power	■	■	■
504	FAR Sweep - High Power	■	■	■
505	FAR Sweep - High Power	■	■	■
507	FAR Sweep - Cruise	■	■	■
509	P3 Sweep -Cruise	■		
510	P3 Sweep -Cruise	■		

Table 2-3 Advanced RQL SNR Build 2 Test 2 Matrix of Completed Points, Jet A and 2 SATFs

	Fuel Type	Jet A	100% HEFA-SPK	50:50 HEFA-SPK:ATJ-IPK
GROUND IDLE				
307	7% Ground Idle	■	■	■
308	FAR Sweep	■	■	■
316	FAR Sweep	■	■	■
317	FAR Sweep	■	■	■
APPROACH				
401	30% Approach	■	■	■
402	FAR Sweep	■	■	■
403	FAR Sweep	■	■	■
HIGH POWER				
500	100% Takeoff	■	■	■
504	FAR Sweep - High Power	■	■	■
506	Cruise	■	■	■
513	FAR Sweep	■	■	■

The key results from the Advanced RQL SNR Build 2 combustor testing that are provided in this report are listed below:

1) Gas emissions and nvPM Jet A versus SATFs

2) Flame imaging Jet A versus SATFs
3) Combustor tones Jet A versus SATFs
4) Panel T/C and radiometer data Jet A versus SATFs

In presenting the emissions results, it is first important to show that FAR as obtained from the emissions sampling of total carbon gas concentration (not including smoke) aligns with the estimate based on the performance FAR. The carbon balance fuel-ratio divided by the performance FAR is called “Fuel Air Ratio Ratio” (FARR). An acceptable measurement accuracy range is typically considered to be within +/-15%.

Figure 2-8 provides FARR values achieved across three (3) different operating conditions: idle, approach, and take-off (TO). The plots indicate that the emissions sampling for Advanced RQL SNR Build 2 was mainly within requirements.

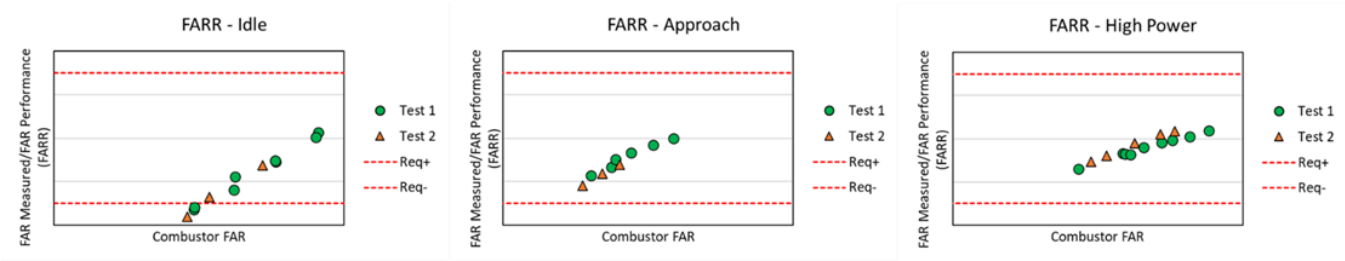


Figure 2-8 Advanced RQL SNR Build 2 FARR

The emissions comparison between Jet A and SATF at idle conditions is shown below in Figure 2-9. This data shows that idle combustion efficiency and NOx are not impacted by SATFs in either Test 1 or Test 2. nvPM mass appears slightly lower for SATF at high FARs, but all these values are below the detectability limit of the analyzer. The nvPM particle count is slightly lower for SATFs relative to Jet A.

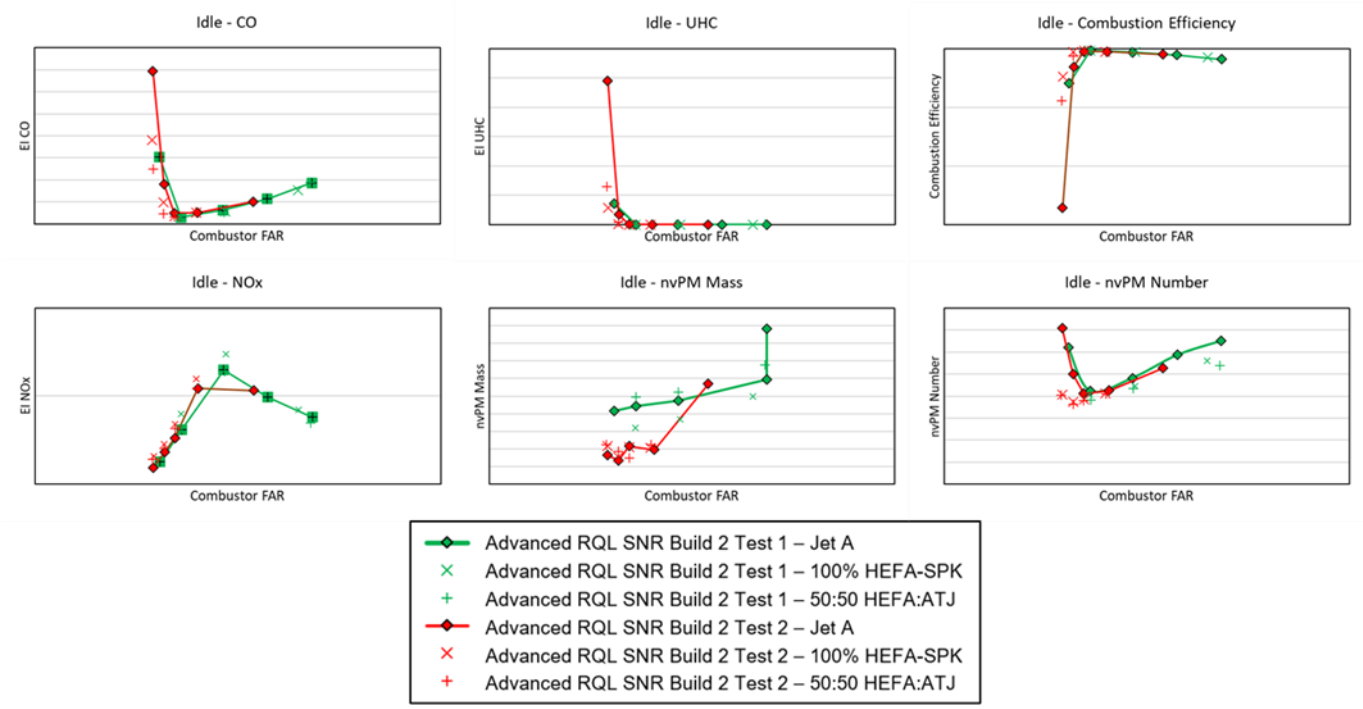


Figure 2-9 Advanced RQL SNR Build 2 Idle Jet A versus SATF

Emissions comparison between Jet A and SATF at approach is shown in Figure 2-10. Combustion efficiency is slightly lower for SATFs compared to Jet A. NOx is not significantly impacted by SATFs. nvPM mass is similar for SATF, and the particle count is lower for SATFs, relative to Jet A. TO results are provided in Figure 2-11. There is no significant difference between Jet A and SATF in the gas emissions measurements. SATFs show lower nvPM.

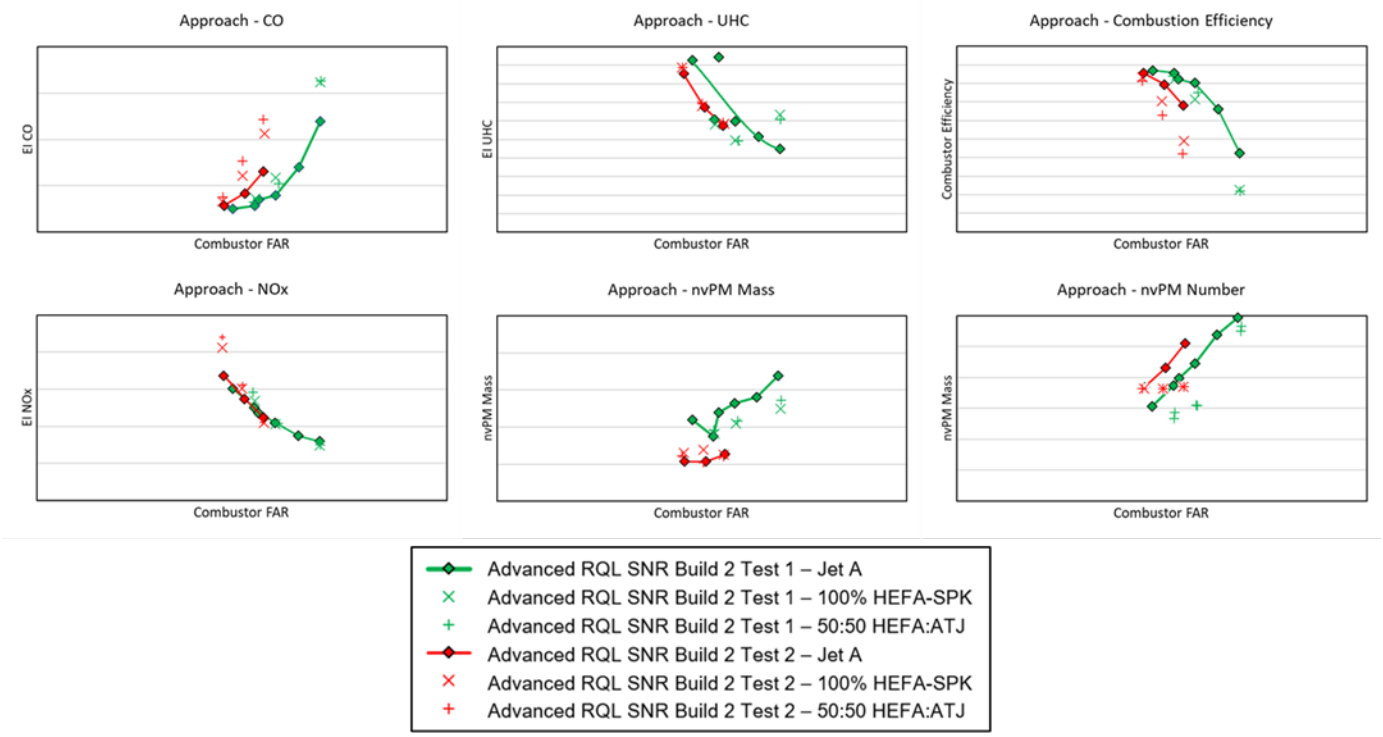


Figure 2-10 Advanced RQL SNR Build 2 Approach Jet A versus SATF

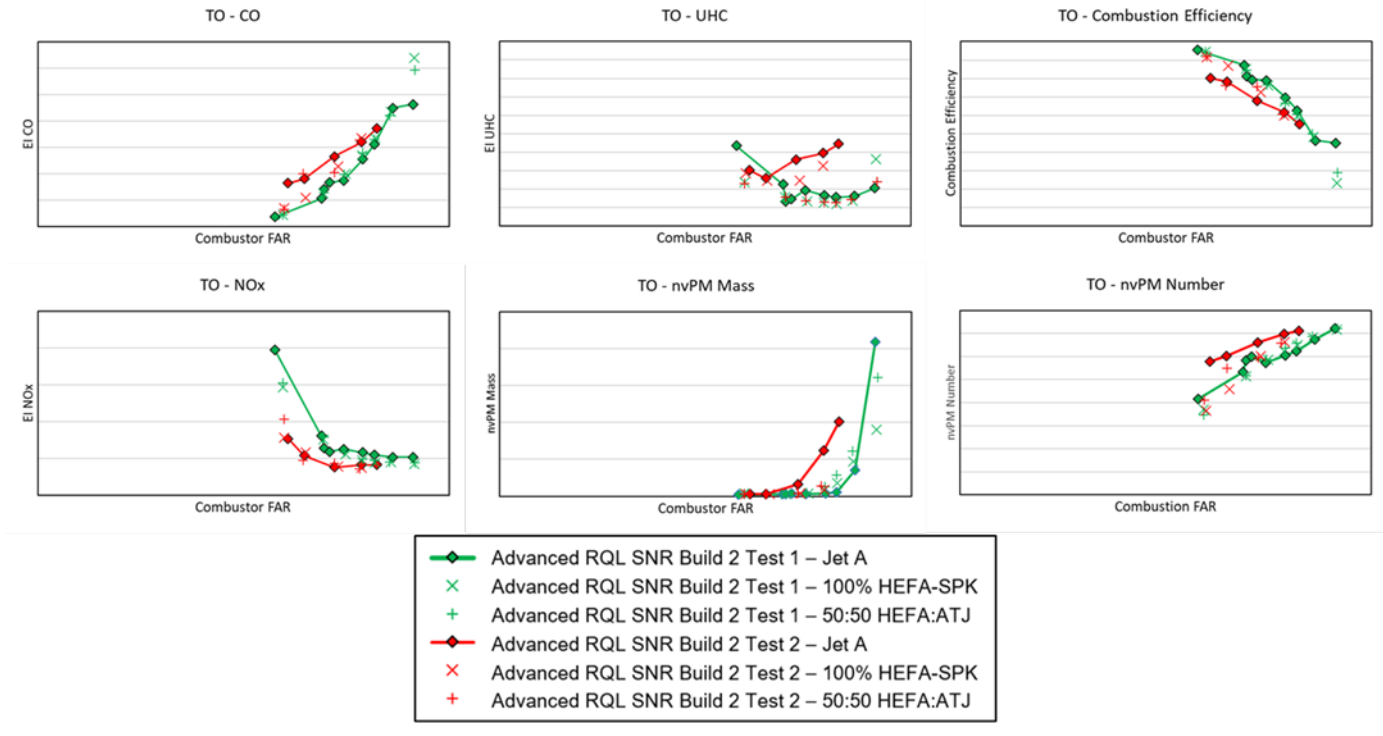


Figure 2-11 Advanced RQL SNR Build 2 TO Jet A versus SATF

For SNR Build 2, the quality of the high-speed flame imaging was improved. A comparison of the flame imaging between SNR Build 1 and Build 2 is shown in Figure 2-12. Relative to the

small borescope view port available in SNR Build 1, Build 2 has a large side window embedded in the sidewall that enables visualization and high-fidelity imaging over large regions of the combustor. The external camera was set up on a tripod, and angled toward the combustor front-end. The camera had an 85mm lens installed and was set to f/5.6. Imaging was performed at 8000fps for all conditions, including idle, approach, and high-power. This setup allowed flame imaging collection simultaneously with radiometer data collection from ports on the opposite sidewall.

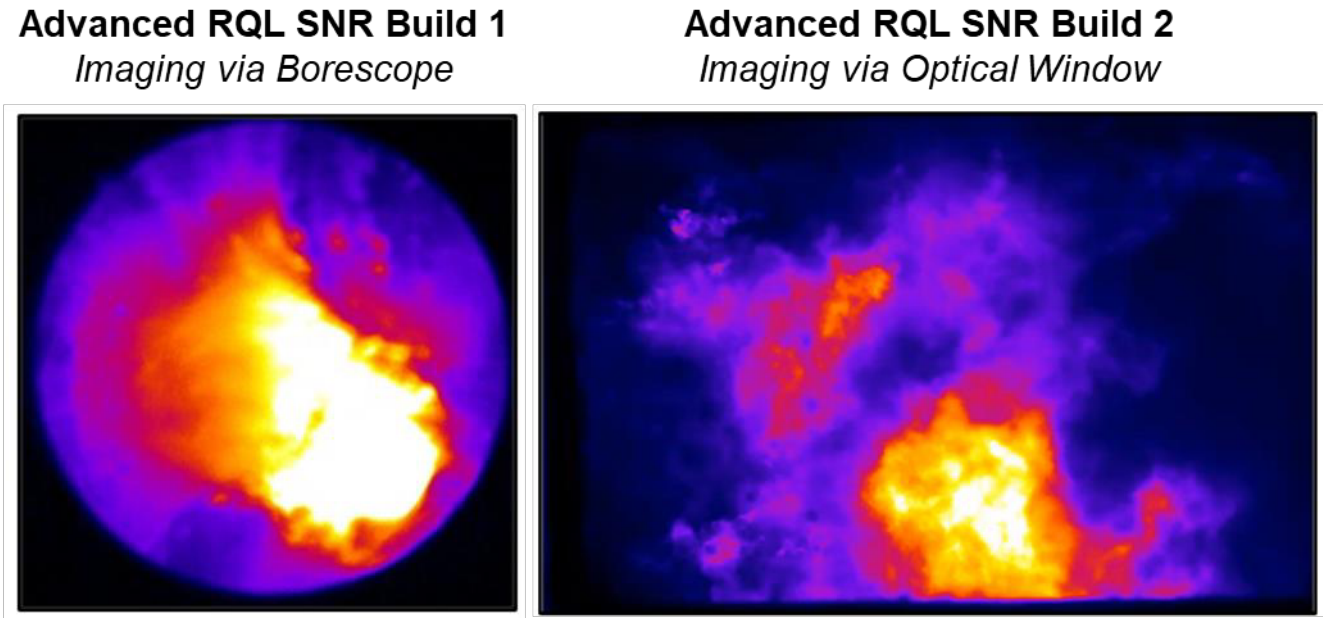


Figure 2-12 Advanced RQL SNR Build 1 versus Advanced RQL SNR Build 2 High-Speed Imaging Comparison

During both Test 1 and Test 2 of SNR Build 2, high-speed flame images were captured for various power settings with both Jet A and the two (2) SATFs tested. Figure 2-13 shows a comparison between high speed imaging frames at high FAR idle conditions, where the lower flame luminosity for SATFs is evident. By contrast, at lower FAR idle conditions, flame luminosity is more comparable between the three (3) fuels due to the lower overall soot levels within the flame. Figure 2-14 and Figure 2-15 show high speed flame images collected at approach conditions during Test 1 and Test 2, respectively. While both image sets demonstrate lower SATF luminosity compared to Jet A, the Test 2 images show a greater difference between Jet A and SATF, especially at the higher FAR condition. The adjusted combustor airflows present in this test result in higher soot levels (as shown in the nvPM data above), making the contrast more visible from switching to SATF. A similar trend is observed in the high-power high-speed imaging data, shown in Figure 2-16 and Figure 2-17 for Test 1 and Test 2, respectively. This is especially evident in the cruise condition data for Test 2, where SATF and Jet A have very different luminosity levels. Meanwhile, at the higher FAR TO condition, the difference between SATF and Jet A is less dramatic due to the overall higher soot levels generated within the system.

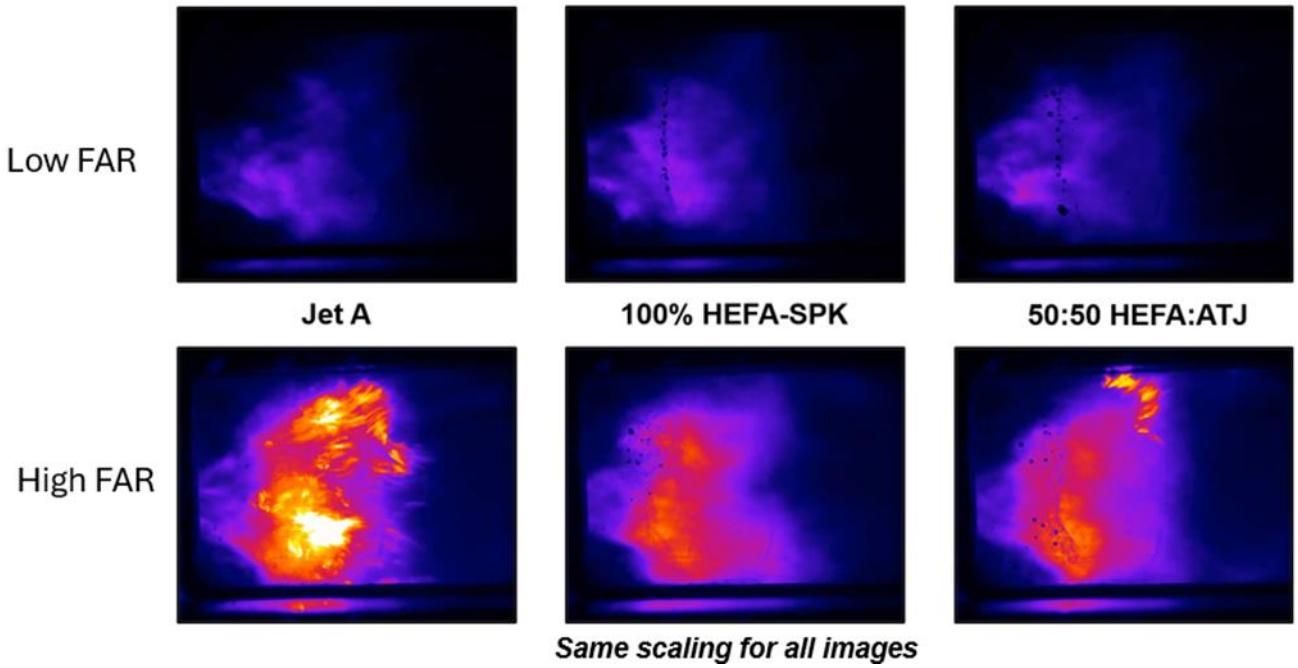


Figure 2-13 Advanced RQL SNR Build 2 Test 2 High-Speed Imaging at Idle for Jet A and SATFs

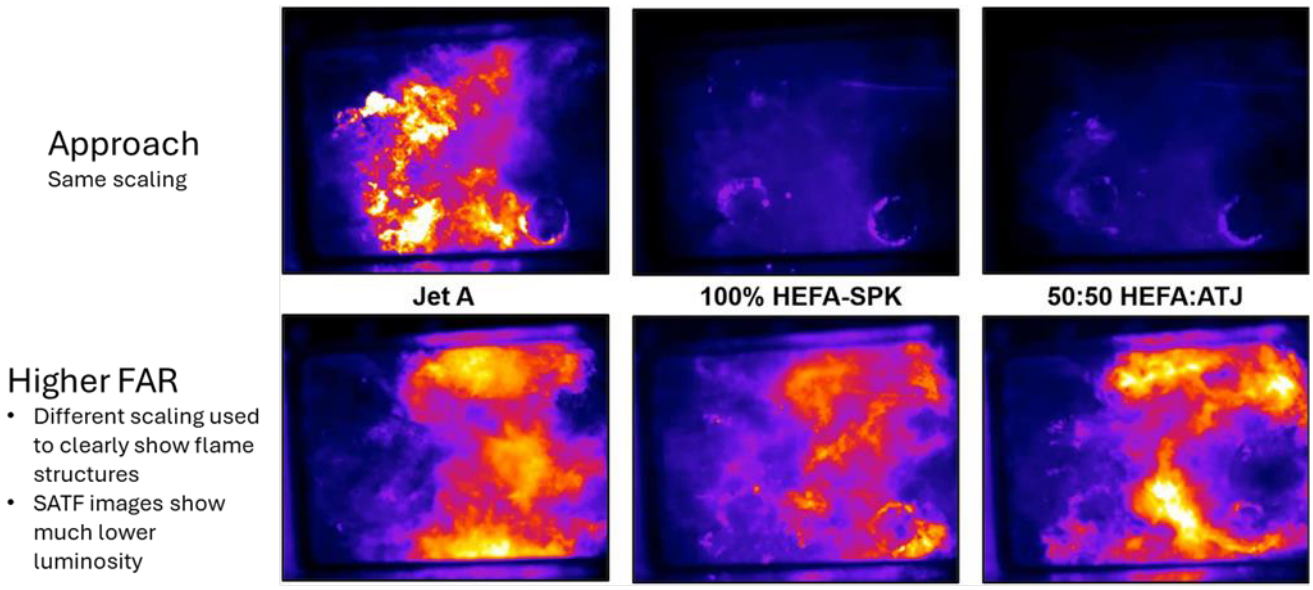


Figure 2-14 Advanced RQL SNR Build 2 Test 1 High-Speed Flame Imaging – Approach

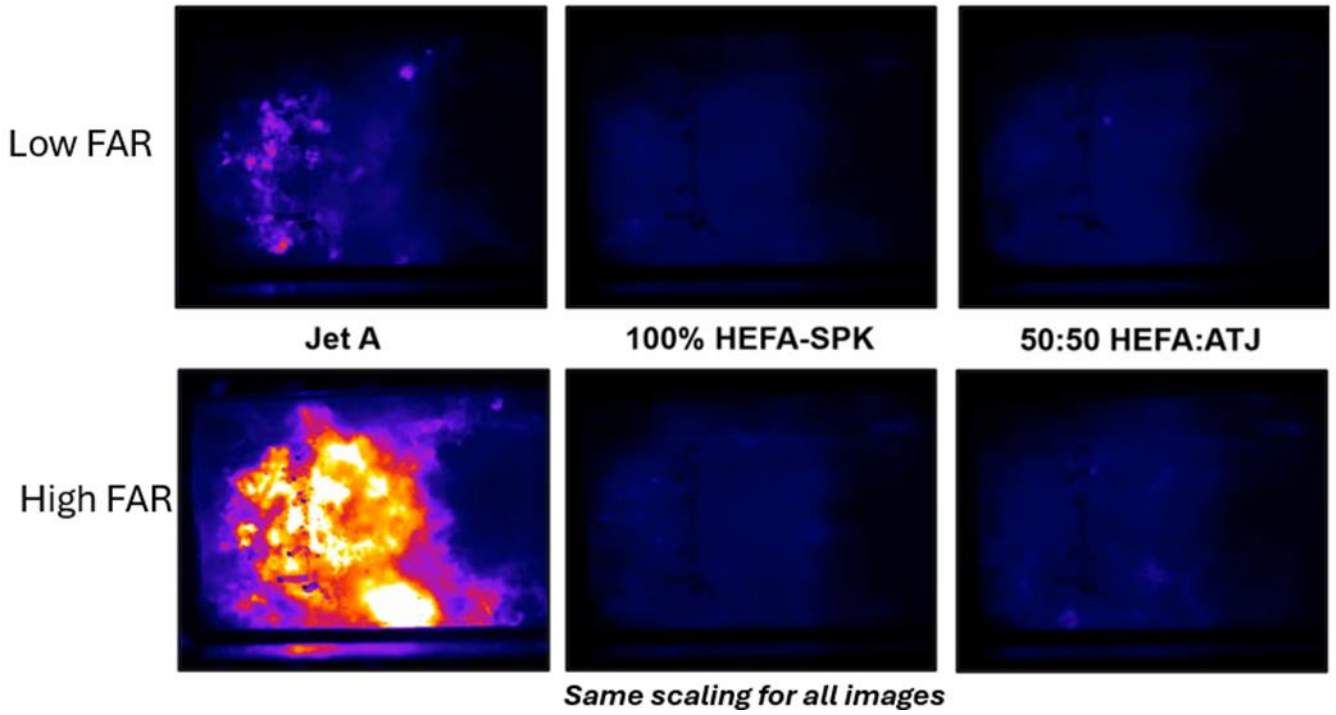


Figure 2-15 Advanced RQL SNR Build 2 Test 2 High-Speed Imaging at Approach for Jet A and SATFs

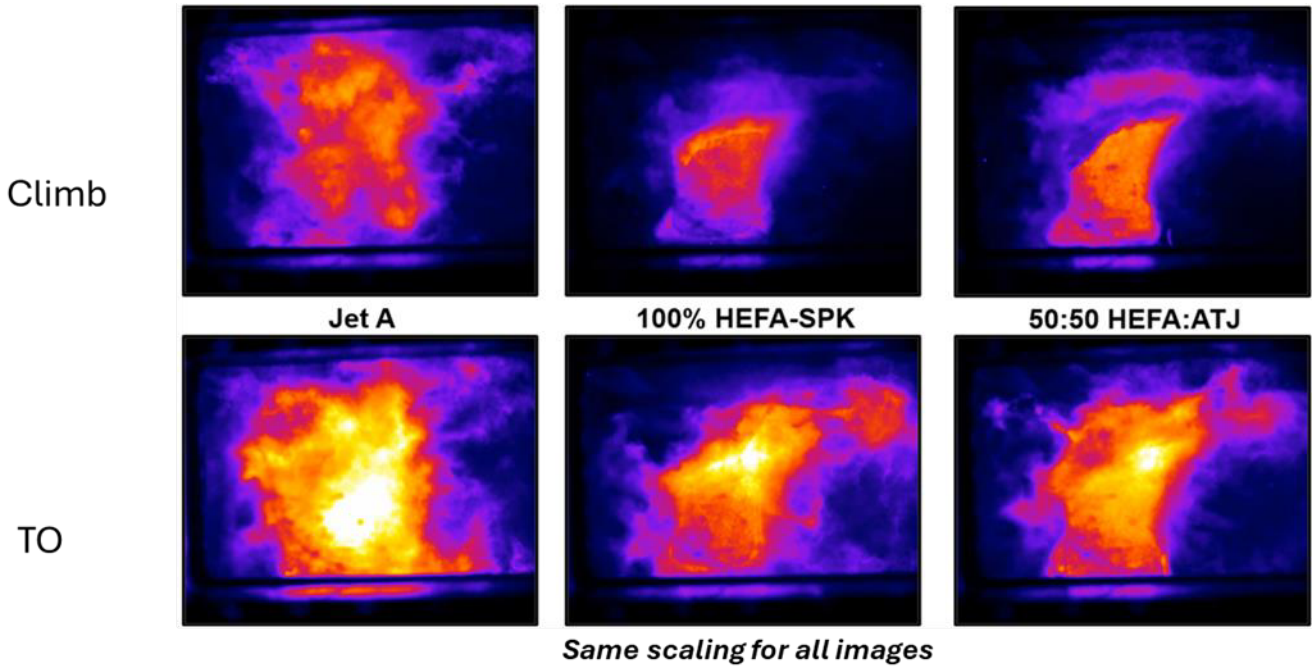


Figure 2-16 Advanced RQL SNR Build 2 Test 1 High-Speed Flame Imaging at Climb and TO

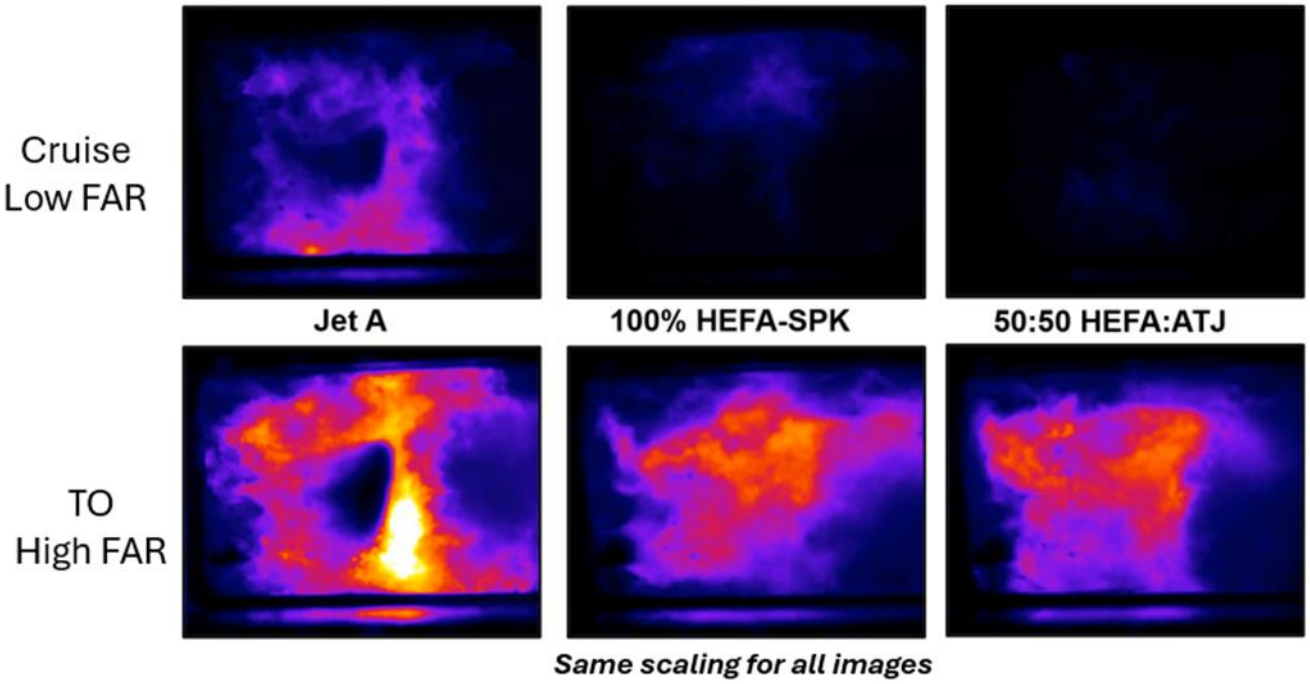


Figure 2-17 Advanced RQL SNR Build 2 Test 2 High-Speed Imaging at Cruise and TO for Jet A and SATFs

Combustion dynamics for the advanced RQL were measured and scanned at idle, approach, and high-power conditions. In addition, dynamics were measured with Jet A, 100% HEFA-SPK, and 50:50 HEFA-SPK:ATJ-IPK fuels. At idle, the advanced RQL had an observed combustor tone. Figure 2-18 provides flame imaging, and P' versus FAR plots at idle conditions. The plot shows the Test 2 data comparing Jet A and SATF. The two (2) red circles on the bottom right chart indicate the conditions which are shown in the high-speed video sweep plots, demonstrating the lower combustor tone experienced while testing both SATFs compared to the baseline Jet A.

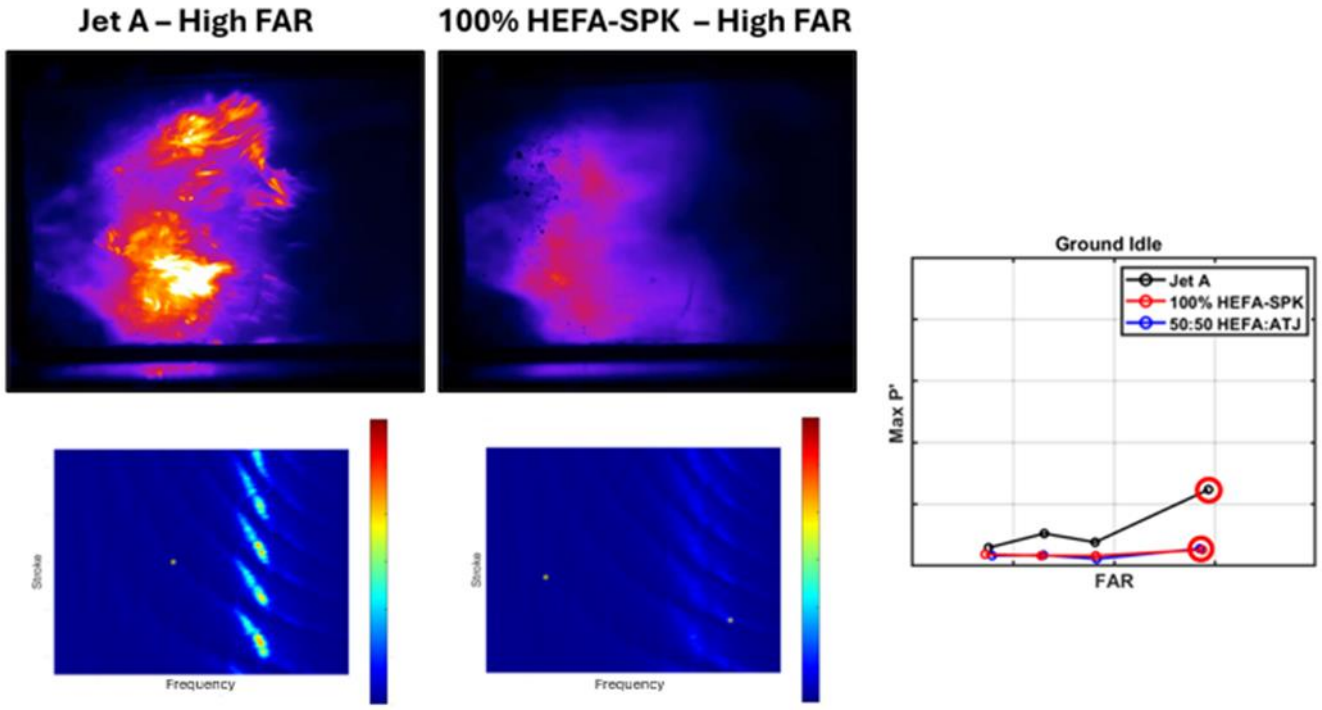


Figure 2-18 Advanced RQL SNR Build 2 Jet A Idle Tones with Flame Imaging

Figure 2-19 provides flame imaging, sweep results, and plots of the P' versus FAR comparing fuels at approach conditions.

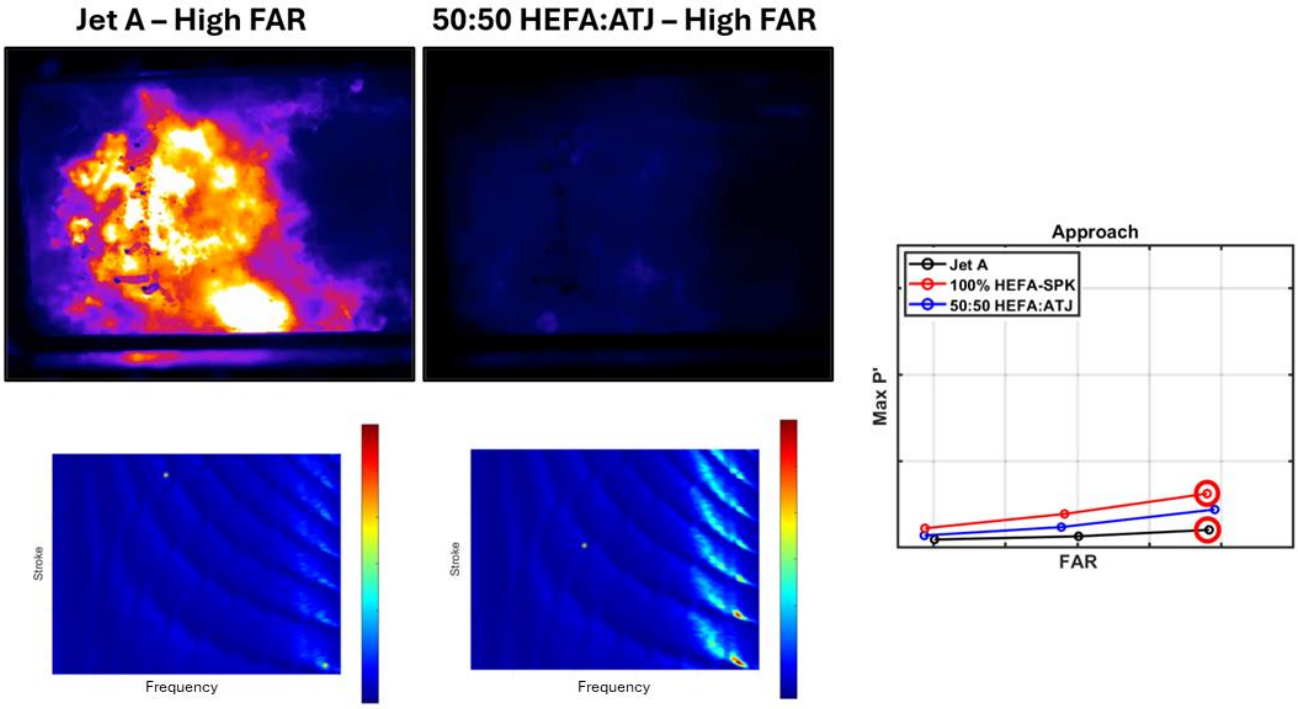


Figure 2-19 Advanced RQL SNR Build 2 Jet A Approach Tones with Flame Imaging

Similar combustion dynamics data for the Advanced RQL SNR Build 2 operating at high-power conditions is shown in Figure 2-20. This combustor demonstrated unusually high tone levels at high FAR, high-power conditions. Tone levels were consistent for all three (3) fuels tested in the combustor.

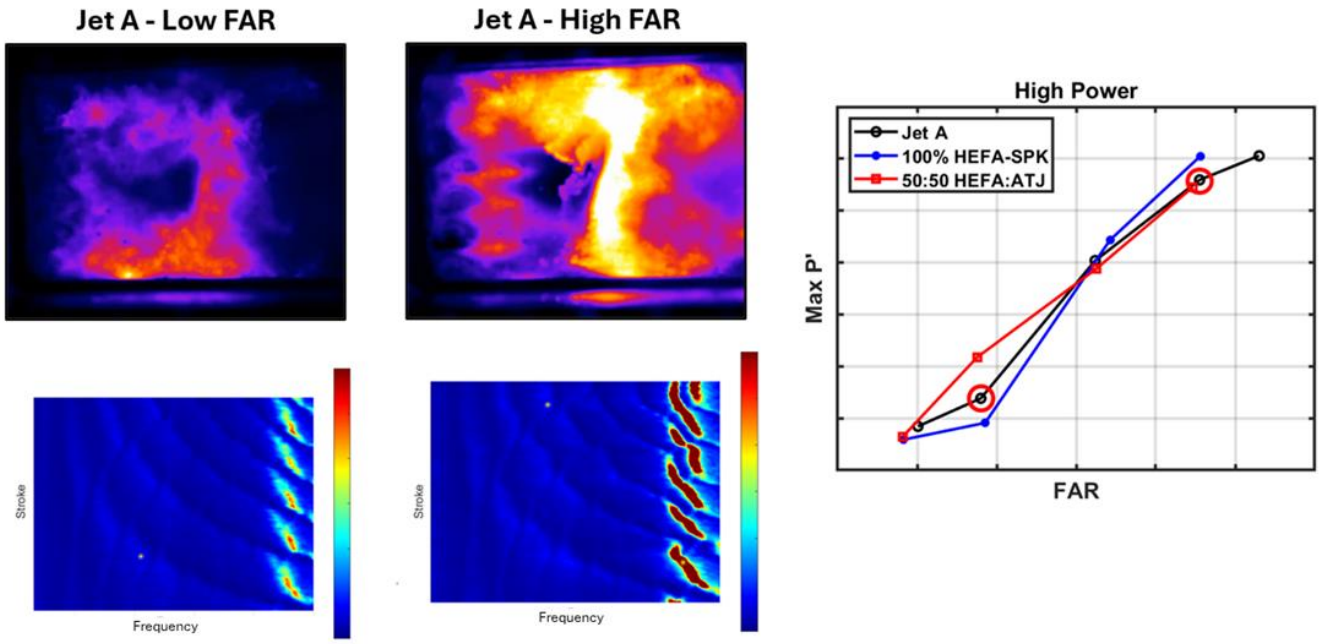


Figure 2-20 Advanced RQL SNR Build 2 Jet A High-power Tones with Flame Imaging

The Advanced RQL SNR Build 2 had twelve (12) T/C which were monitored throughout Jet A and SATF testing. Locations of the T/C on the bulkhead (TC1 and TC2), outer diameter (OD) (TC1 – TC8), and inner diameter (ID) (TC1-TC4) panels. Figure 2-21 shows results for these T/C at idle conditions, while Figure 2-22 and Figure 2-23 show T/C data at approach and high-power conditions, respectively. Note that ID panel T/C data is not shown at high-power, since T/Cs had failed before high-power testing was performed.

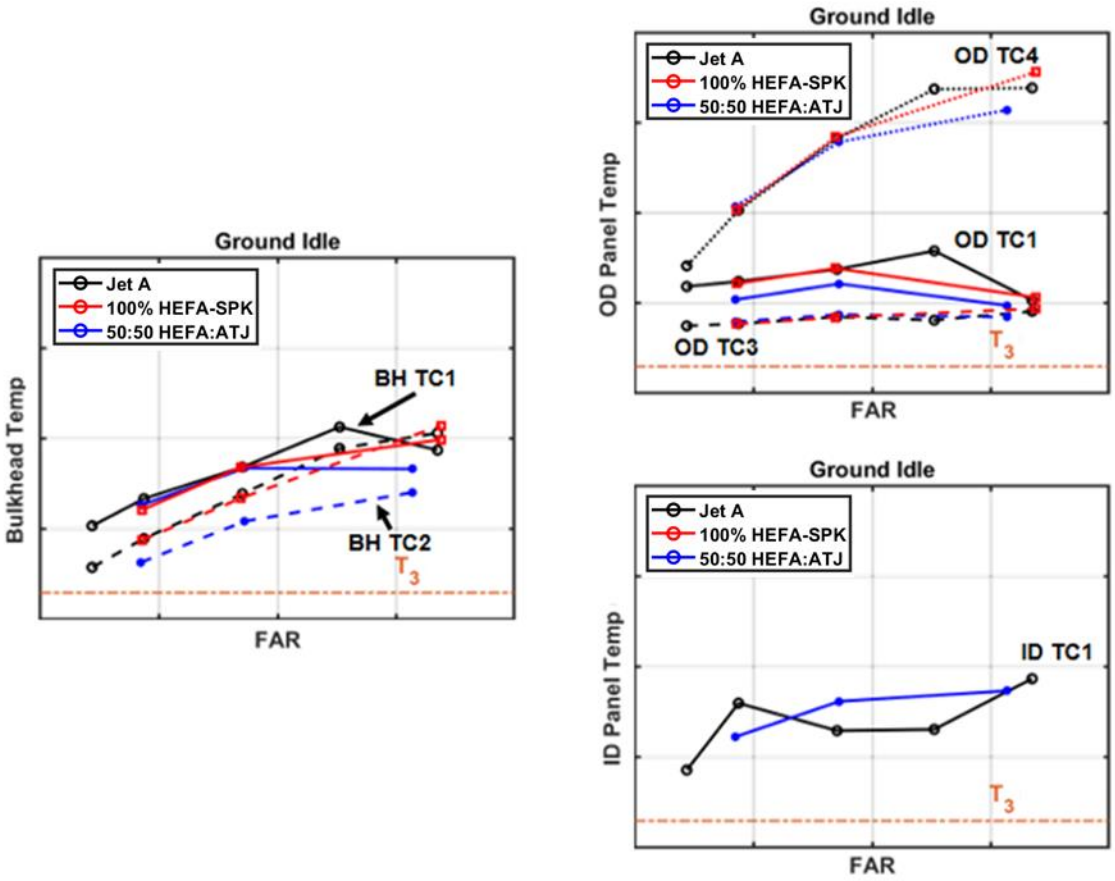


Figure 2-21 Advanced RQL SNR Build 2 T/C Results at Idle

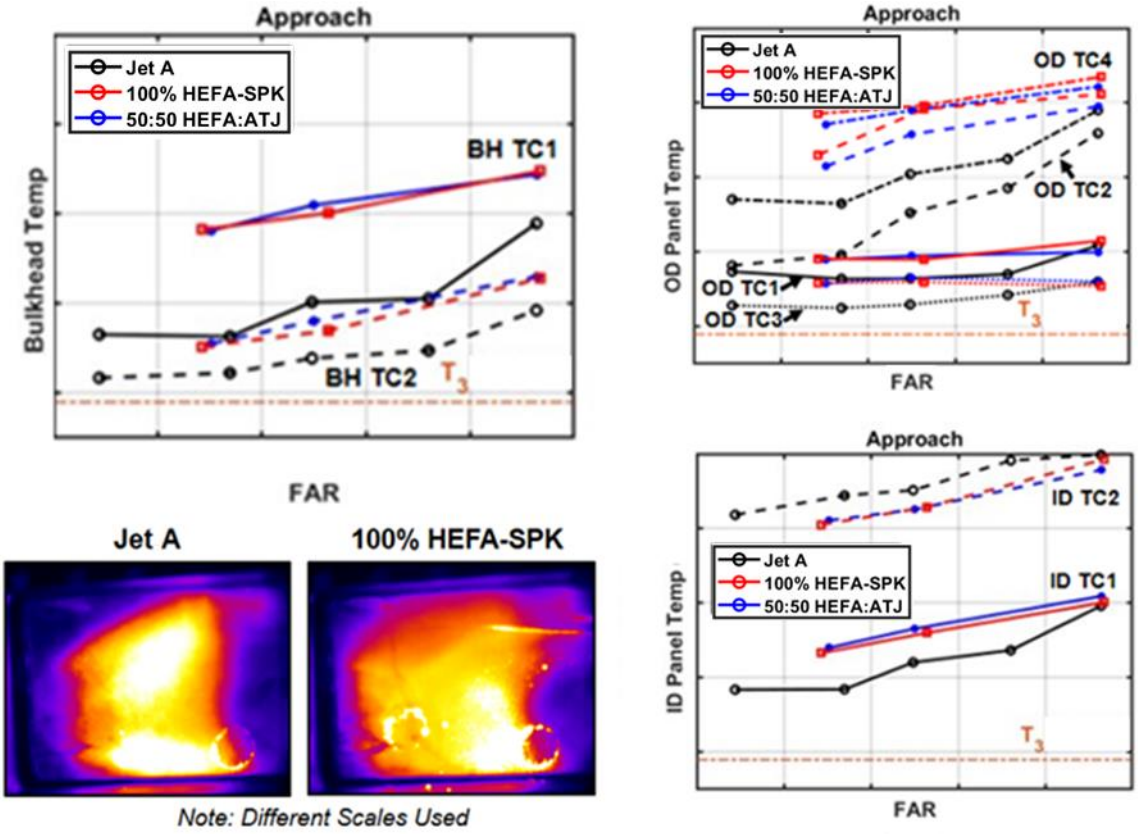


Figure 2-22 Advanced RQL SNR Build 2 T/C Results at Approach

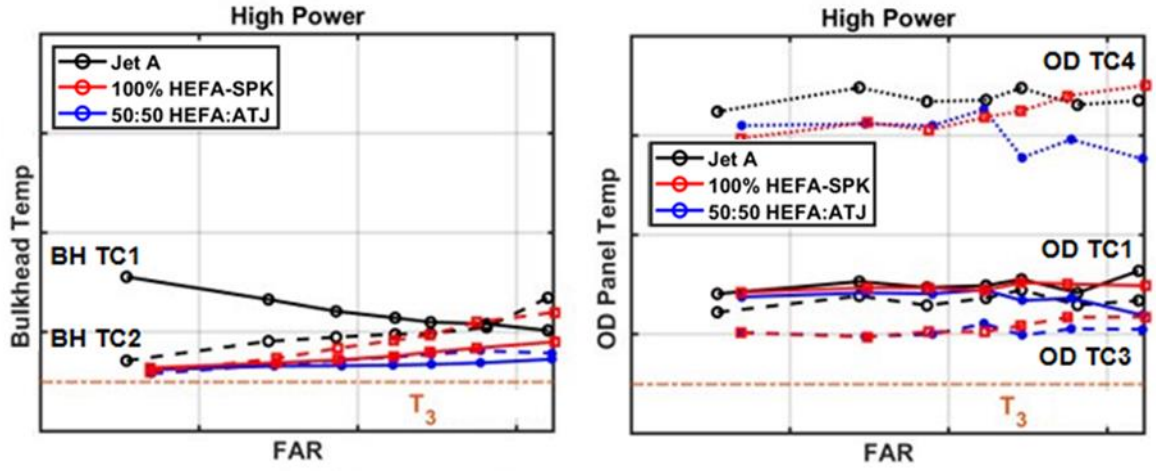


Figure 2-23 Advanced RQL SNR Build 2 T/C Results at High-power

Additional durability learning with the Advanced RQL and SATFs was obtained through collecting data from two (2) radiometers. The radiometers were installed to view different regions of the combustor. The radiometers were water-cooled with a nitrogen purge over the window to reduce soot blockage.

Radiometer results are presented with no post-test calibration performed on measurements. Additional testing with radiometers in an RQL configuration has shown significant reduction in heat flux readings can occur with view blockage due to soot accumulation on the windows. Accumulating different levels of soot on sensors is possible, and for this SNR testing, there was no ability to correct for variation. All high-power data was collected on the same test day with the test order being Jet A, 50:50 HEFA-SPK:ATJ-IPK, and 100% HEFA-SPK. Figure 2-24 shows radiometer results at high-power. All fuels show similar radiative flux values in the upstream radiometer. The downstream radiometer shows Jet A has higher radiation loading compared to both SATFs.

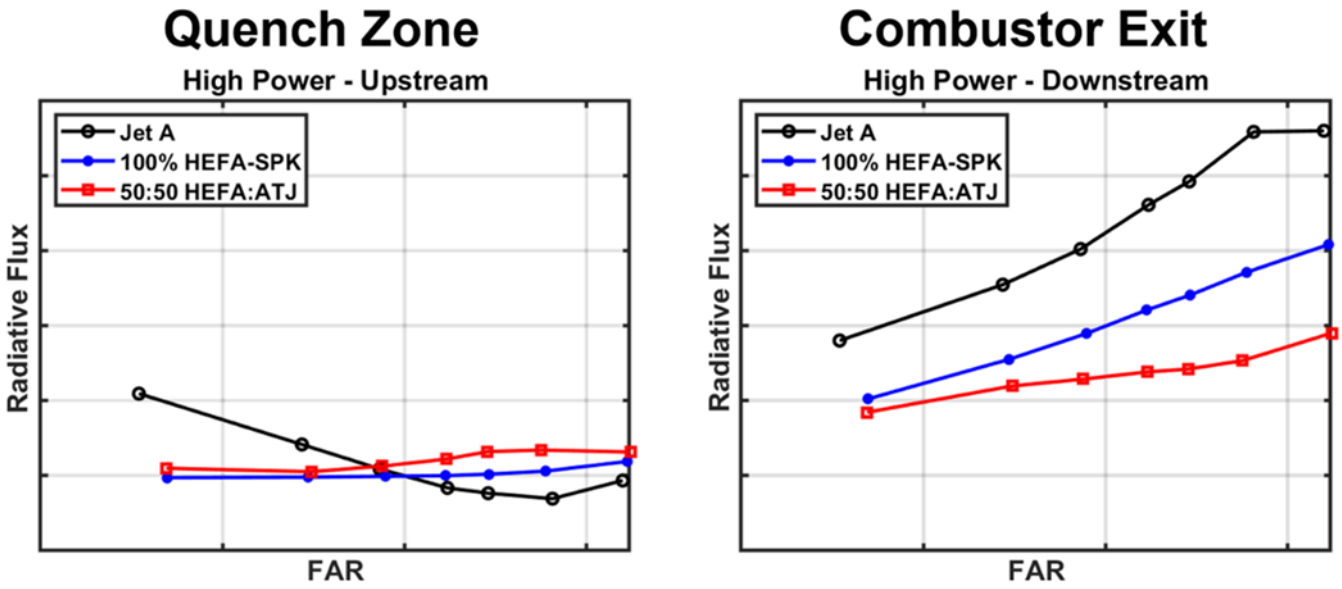


Figure 2-24 Advanced RQL SNR Build 2 Radiometer Data at High-power

3. ADVANCED RQL MSR RIG RESULTS

3.1 HYTEC COMBUSTOR RIG BUILD

The Advanced RQL MSR utilized a 5-sector combustor. An RQL rig previously used for ultra-low emissions testing was rebuilt and baseline testing was conducted. The main purpose and test objective for the Advanced RQL MSR test campaign was to assess the impact of SATFs on ignition and LBO.

3.2 ADVANCED RQL MSR TESTING SUMMARY

3.2.1 Testing Summary of the Advanced RQL MSR Rig

The primary goal of the Advanced RQL MSR testing was to examine ignition and LBO characteristic differences in Jet A versus SATF performance. Prior to the testing, the hardware Area X Coefficient Discharge (AC_D), fuel system, and instrumentation functionality were verified via a shakedown campaign.

At a given condition, ignition testing was performed by sparking a single ignitor while the rig maintained steady state at the targeted condition. Light-off was detected using both proof-of-light T/C and visual inspection via borescope. Ground start testing for Advanced RQL MSR consisted of a set of initial priority test points corresponding to typical engine start conditions, as well as a set of FAR sweeps. SATF testing was performed at these FAR sweeps to compare with Jet A performance.

Ignition results for the FAR sweep tests for Advanced RQL MSR Jet A versus SATFs are presented in Figure 3-1. Overall, the ignition performance is comparable for Jet A and SATFs tested and met expectations. While time-to-light was observed to go up at extremely low FARs, this was below the level at which engine testing occurred and is outside the normal operating range for the engine. At these low FARs, the SATFs were observed to be capable of lighting at lower FARs than Jet A. Minimum FAR sweep showed some differences between Jet A and SATFs for lower air loading parameter (ALP) condition. Top chart in Figure 3-1 has a lower ALP than the bottom chart. The minimum FAR sweep was a good way to differentiate SATFs at a more extreme operating condition.

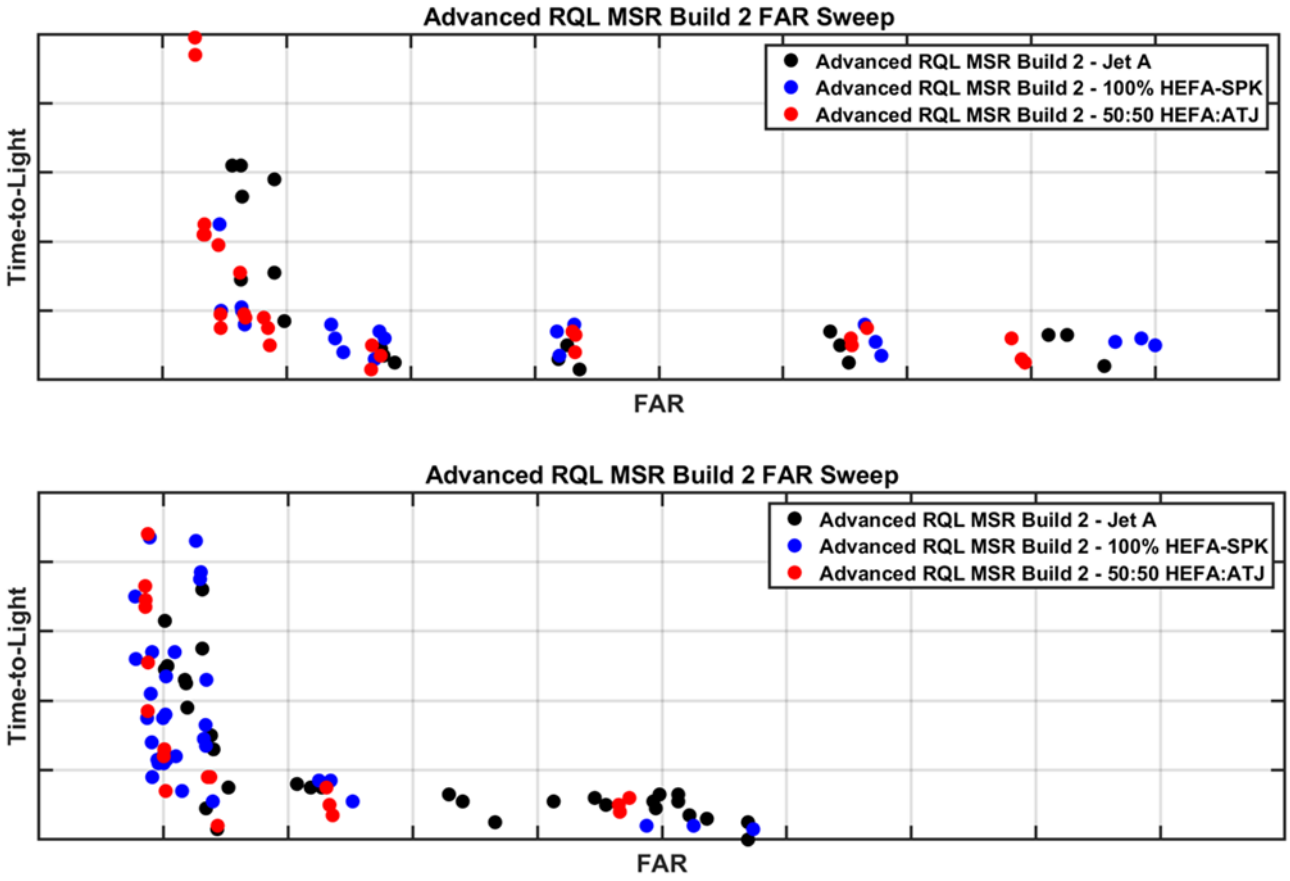


Figure 3-1 Advanced RQL MSR FAR Sweep

Instrumentation for the test was observed to operate effectively, with measurements via T/C and optical observation proving reliable. Some challenges were noted in maintaining consistent P_3 and T_3 at the low power conditions in use. This resulted in some difficulty in precisely matching ALP between test conditions, but is not believed to have heavily impacted the direct results. Proof-of-light type K T/Cs protruding from dilution holes worked well. The aft viewing port also provided reasonable imaging for ignition.

The second major focus of the Advanced RQL MSR test was to identify LBO characteristics in a scaled sector rig. Overall, Advanced RQL MSR LBO results exhibited good repeatability across the range of conditions tested. All tests demonstrated blowout significantly below the engine LBO audit limit for a similarly sized engine. Results can be found in Figure 3-2. LBO results are similar between Jet A and SATFs (100% HEFA-SPK, 50:50 HEFA-SPK:ATJ-IPK) for conditions 3 and 5. Advanced RQL MSR also demonstrated combustion down to extremely low FARs for conditions 3 and 5. At these conditions, the rig was able to maintain combustion down to fuel flow limits that were approaching the detectable limits of the flow system. Note that in Figure 3-2 the Jet A and 100% HEFA-SPK blue and black colored triangles are stacked behind the 50:50 HEFA-SPK:ATJ-IPK red triangles for conditions 3 and 5.

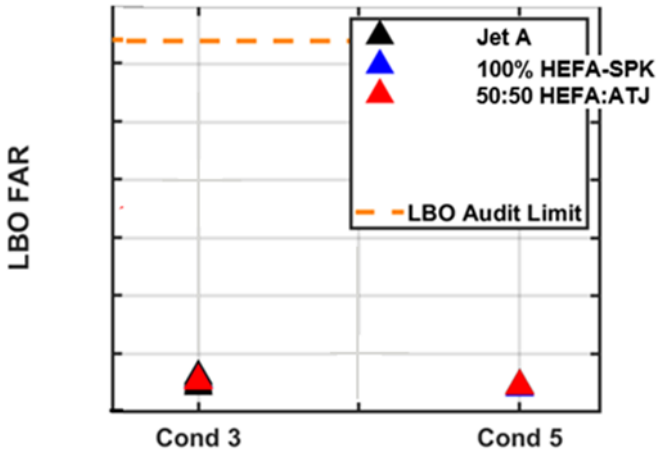


Figure 3-2 Advanced RQL MSR LBO Test Results

4. LS SNR RESULTS

4.1 HYTEC COMBUSTOR RIG BUILD

Two (2) combustors were built and tested as part of the LS SNR testing campaign.

For LS SNR Build 1 testing, the rig housing was re-used and resized from the Advanced RQL testing.

The LS SNR Build 2 testing had different components than LS SNR Build 1.

4.2 LS SNR TESTING SUMMARY

4.2.1 Testing Summary of the LS SNR Build 1

The configuration, as depicted in Table 4-1, was tested at ground idle, approach, and high-power flight conditions. Jet A fuel was tested to establish a baseline for emissions and performance. One (1) configuration was tested using three (3) different SATF blends: 100% HEFA-SPK, 50:50 HEFA-SPK:ATJ-IPK, and a 90:10 HEFA-SPK:ARO 150 blend.

Table 4-1 LS SNR Build 1 Configuration Test Matrix

				Config		Config		Config		Config
		Fuel Type		Jet A		100% HEFA-SPK		50:50 HEFA-SPK:ATJ-IPK		90:10 HEFA
	GROUND IDLE									
	200	Fuel Mapping								
	201	Fuel Mapping								
	202	Fuel Mapping								
	203	Fuel Mapping								
	204	Fuel Mapping								
	205	Fuel Mapping								
	206	Fuel Mapping								
	207	Fuel Mapping								
	208	Fuel Mapping								
	209	Fuel Mapping								
	210	Fuel Mapping								
	211	Fuel Mapping								
	212	Fuel Mapping								
	213	Fuel Mapping								
	214	FAR Sweep								
	215	FAR Sweep								
	216	FAR Sweep								
nvPM	217	5% Ground Idle								
nvPM	218	7% Ground Idle								
	219	FAR Sweep								
nvPM	220	FAR Sweep								
	221	FAR Sweep								
nvPM	222	FAR Sweep								
	223	P3 Sweep								
	224	P3 Sweep								
	225	T3 Sweep								
	226	T3 Sweep								

		Fuel Type		Config Jet A		Config 100% HEFA-SPK		Config 50:50 HEFA-SPK:ATJ-IPK		Config 90:10 HEFA
	APPROACH									
	450	30% Approach								
	451	30% Approach								
	452	30% Approach								
	453	30% Approach								
	454	30% Approach								
	455	30% Approach								
	456	30% Approach								
	457	30% Approach								
	458	30% Approach								
	459	30% Approach								
	460	Fuel Mapping								
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	473	Fuel Mapping								
	474	Fuel Mapping								
	475	Fuel Mapping								
	476	Fuel Mapping								
	477	Fuel Mapping								
nvPM	478	30% Approach								
nvPM	479	30% Approach								
nvPM	480	30% Approach								
	481	FAR Sweep								
nvPM	482	FAR Sweep								
	483	FAR Sweep								
nvPM	484	FAR Sweep								
	485	FAR Sweep								
nvPM	486	FAR Sweep								
	487	FPb Sweep								
	488	FPb Sweep								
	489	P3 Sweep								
	490	P3 Sweep								

		Fuel Type		Config Jet A		Config 100% HEFA-SPK		Config 50:50 HEFA-SPK:ATJ-IPK		Config 90:10 HEFA
	HIGH POWER									
	550	100% TO								
	551	100% TO								
	552	Fuel Mapping								
	553	Fuel Mapping								
	554	Fuel Mapping								
	555	Fuel Mapping								
	556	Fuel Mapping								
	557	Fuel Mapping								
	558	Fuel Mapping								
	559	Fuel Mapping								
	560	Fuel Mapping								
	561	Fuel Mapping								
	562	Fuel Mapping								
	563	Fuel Mapping								
	564	Fuel Mapping								
nvPM	565	100% TO								
nvPM	566	85% Climb								
nvPM	567	FAR Sweep								
nvPM	568	FAR Sweep								
	Cruise									
nvPM	650	Cruise								
nvPM	651	FAR Sweep								
nvPM	652	FAR Sweep								

A major focus of the SNR Build 1 testing was the characterization of SATFs in the LS combustor architecture. During testing, the effect of these SATFs on both emissions and dynamics was examined. Figure 4-1 and Figure 4-2 show comparisons of SATF at idle and approach conditions, respectively. For the most part, SATFs demonstrated similar or improved performance relative to Jet A. In particular, at idle and approach conditions, the SATFs demonstrated nvPM emissions in line with those of Jet A, and reduced NOx emissions relative to Jet A.

Unfortunately, the LS configuration experienced a hot shut down event after completing testing at idle and approach conditions. The hot shut down resulted in invalid results during high-power testing, so NOx and nvPM cruise emissions were compromised. Only this configuration was tested with SATFs and as a result, valid data was only obtained at low power.

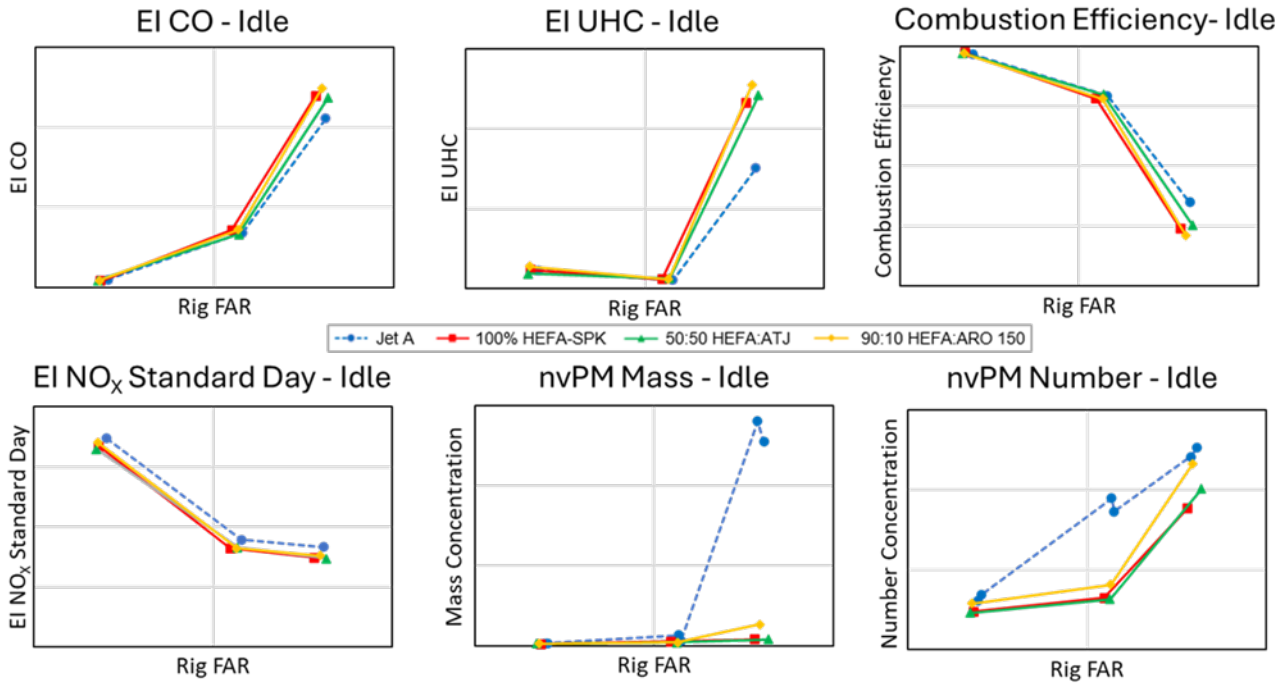


Figure 4-1 LS SNR Build 1 SATF Emissions Comparison – Idle

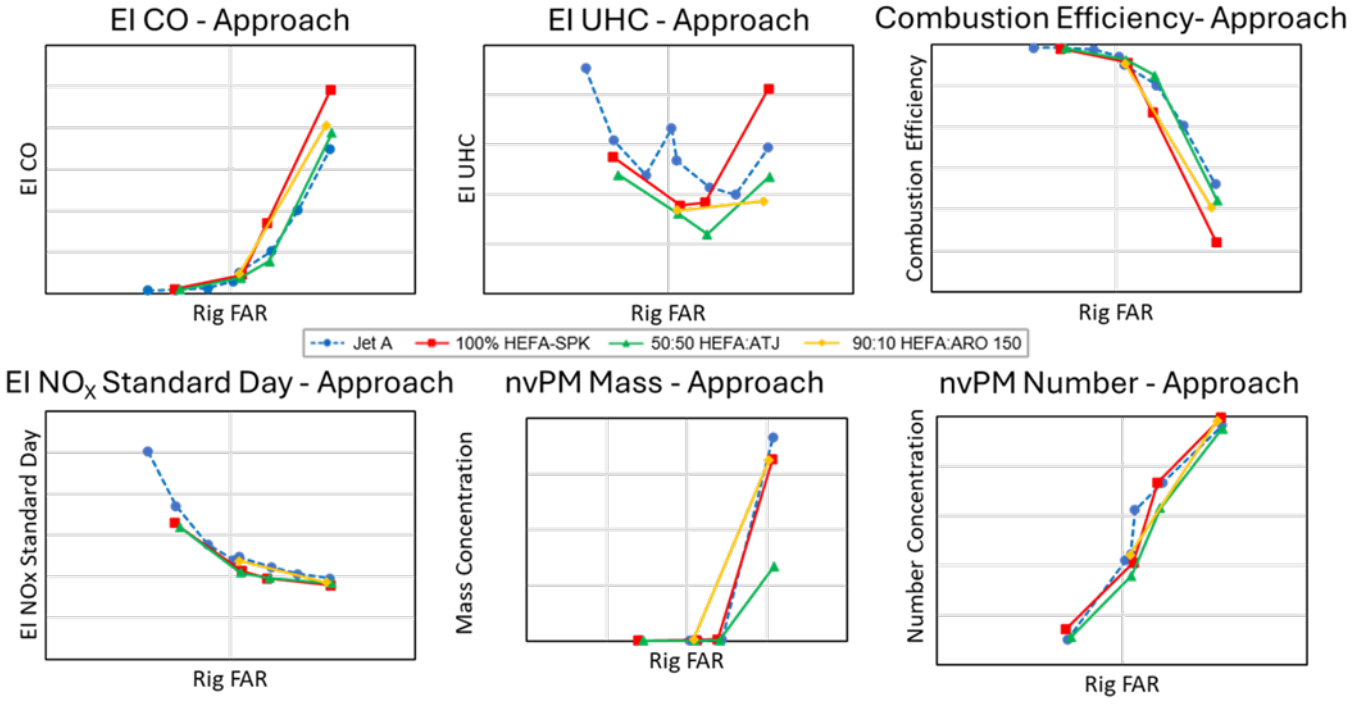


Figure 4-2 LS SNR Build 1 SATF Emissions Comparison – Approach

At higher power, as shown in Figure 4-3, the SATFs demonstrated broadly similar emissions to Jet A. This data was compromised after the hot shut down event.

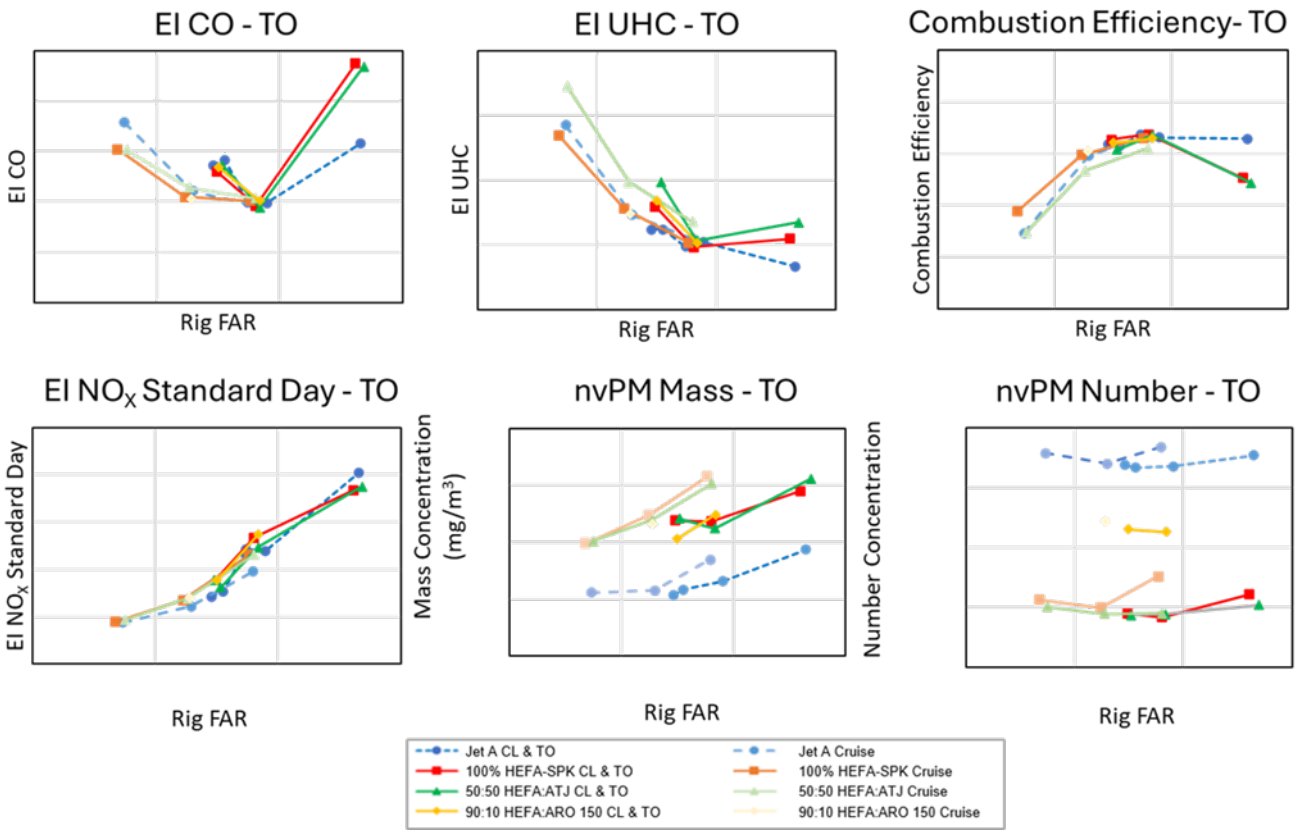


Figure 4-3 LS SNR Build 1 SATF Emissions Comparison – High-power

Dynamics results are shown in Figure 4-4. At ground idle, the SATF blends demonstrated slightly higher pressure fluctuations at high FAR. However, at approach and high-power conditions, SATF was equal to or better than Jet A with regards to dynamics.

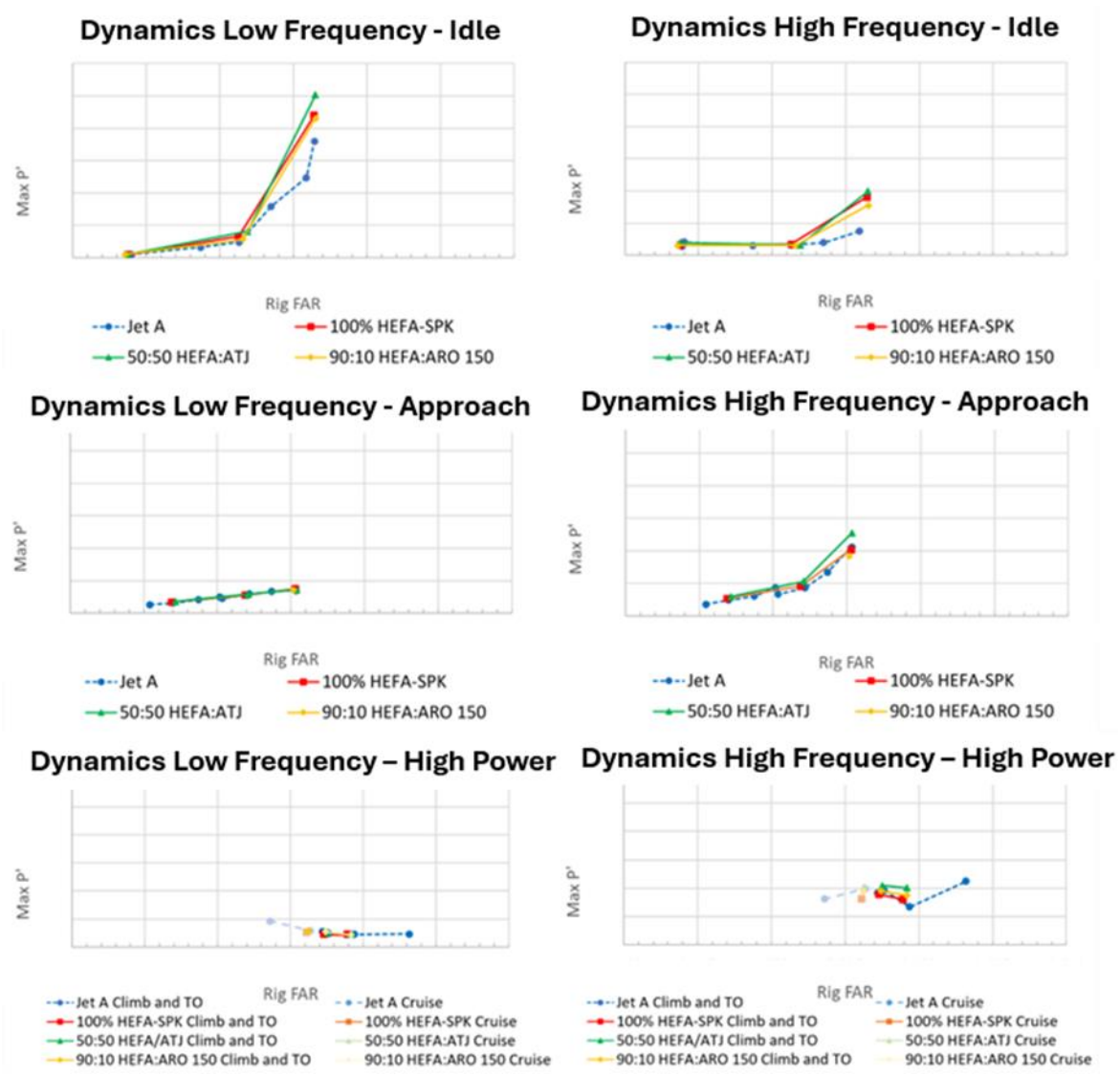


Figure 4-4 LS SNR Build 1 SATF Dynamics Comparison – All Power Settings

Throughout rig testing, metal temperatures on the cold side wall of both the bulkhead and ID panels within the combustor rig were measured using T/Cs. The T/C data was used to characterize the differences in wall temperature between Jet A and SATFs.

The T/C data for the bulkhead is plotted against combustor FAR at idle, approach and high-power and results are shown in Figure 4-5. Similar T/C plots for the ID panel are shown in Figure 4-6. Overall, Jet A and SATFs show similar panel metal temperatures at various power settings.

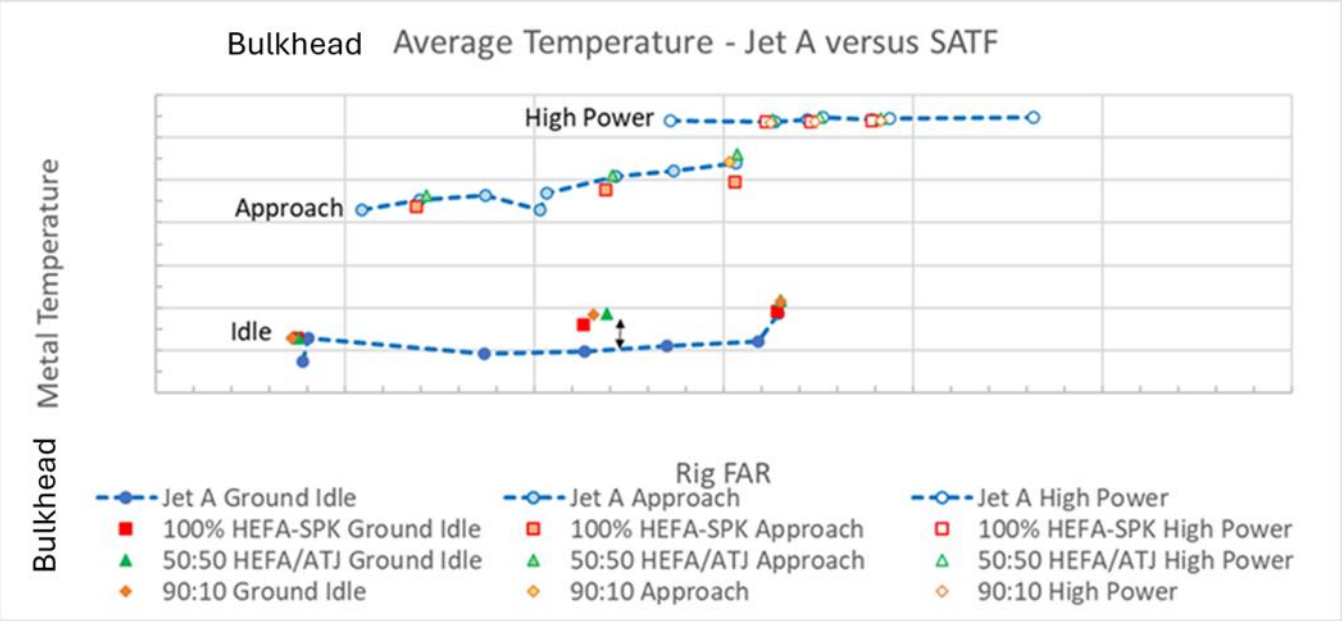


Figure 4-5 LS SNR Build 1 Bulkhead T/C Jet A versus SATF Results

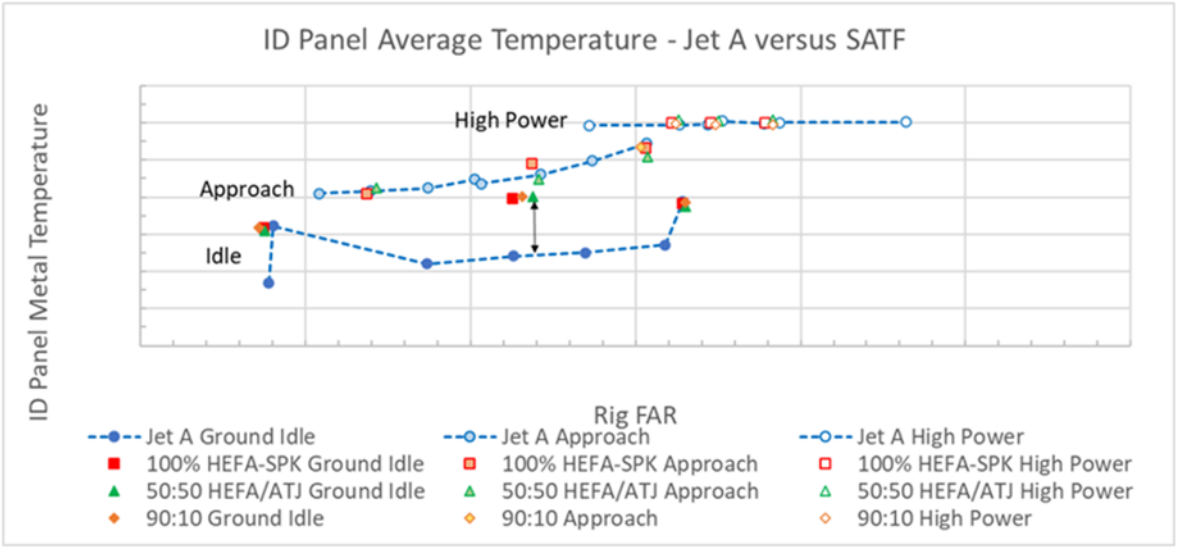


Figure 4-6 LS SNR Build 1 ID Panel T/C Jet A versus SATF Results

A challenge with the borescope measurement was carbon buildup on the measurement window. This was primarily caused by the proximity of the borescope entry point to the flame – during ignition a large amount of soot was created in the burner, which rapidly coated the borescope region. While the borescope window gradually regained visibility during testing as the soot burned off, the initial soot accumulation posed a challenge to overall measurement. This fouling also impacted radiometer measurements using the same borescope window. In order to characterize the magnitude of the impact on radiometry, the radiometer was tested with a calibrated blackbody cavity with both fouled and cleaned tips, to which a correction factor was calculated. In order to reduce the likelihood of similar challenges in the SNR Build 2, the

borescope was replaced with larger objective windows. In addition, the larger combustor planned for use in the SNR Build 2 was expected to result in the flame stabilizing further away from the windows, resulting in reduced soot accumulation relative to the SNR Build 1.

4.2.2 Testing Summary of the LS SNR Build 2

During the LS SNR Build 2 test, Jet A fuel was used to establish a baseline for emissions and performance. Following this, two (2) different SATF blends were tested: 100% HEFA-SPK and a 50:50 HEFA-SPK:ATJ-IPK blend.

The test matrix provided in Table 4-2 shows the test points completed during testing for LS SNR Build 2. The test points were separated into three (3) groups: ground idle, approach, and high-power. For the LS SNR Build 2, only one (1) configuration was tested.

Table 4-2 LS SNR Build 2 Test Matrix Completed Points

		Fuel Type	Config 1 Jet A	Config 1 100% HEFA-SPK	Config 1 50:50 HEFA-SPK: ATJ-IPK
	GROUND IDLE				
	304	Fuel Mapping	■		
	305	Fuel Mapping	■		
	306	Fuel Mapping	■		
	308	5% Ground Idle	■		
	309	7% Ground Idle	■	■	■
	310	FAR Sweep	■	■	■
	311	FAR Sweep	■	■	■
	312	FAR Sweep	■		
	313	FAR Sweep	■		
	APPROACH				
	405	Fuel Mapping	■		
	406	Fuel Mapping	■		
	407	Fuel Mapping	■		
	408	Fuel Mapping	■		
	409	30% Approach	■	■	■
	412	FAR Sweep	■	■	■
	413	FAR Sweep	■	■	■
	414	FAR Sweep	■		
	415	FAR Sweep	■		
	HIGH POWER				
	500	100% TO	■	■	■
	501	85% Climb	■	■	■
	502	FAR Sweep - High Power	■	■	■
	503	FAR Sweep - High Power	■	■	■
	504	FAR Sweep - High Power	■		
	505	FAR Sweep - High Power	■		
	506	Fuel Mapping	■		
	507	Fuel Mapping	■		
	508	Fuel Mapping	■		
	508	Fuel Mapping	■		
	509	Fuel Mapping	■		
	510	Fuel Mapping	■		
	511	Fuel Mapping	■		
	512	Fuel Mapping	■		
	600	Cruise	■	■	■
	601	FAR Sweep - Cruise	■	■	■
	602	FAR Sweep - Cruise	■	■	■
	603	Fuel Mapping	■		
	603	Fuel Mapping	■		

The final gas emission performed with this test campaign is a comparison between Jet A and two (2) SATF blends to evaluate the impact of SATF on combustor emissions using this combustor configuration. Figure 4-7 shows results at idle conditions, which show nearly identical performance between baseline Jet A and both tested SATFs. The nvPM number measurements

are a small amount lower than Jet A, especially at high FAR, as has been observed for most test campaigns in this program.

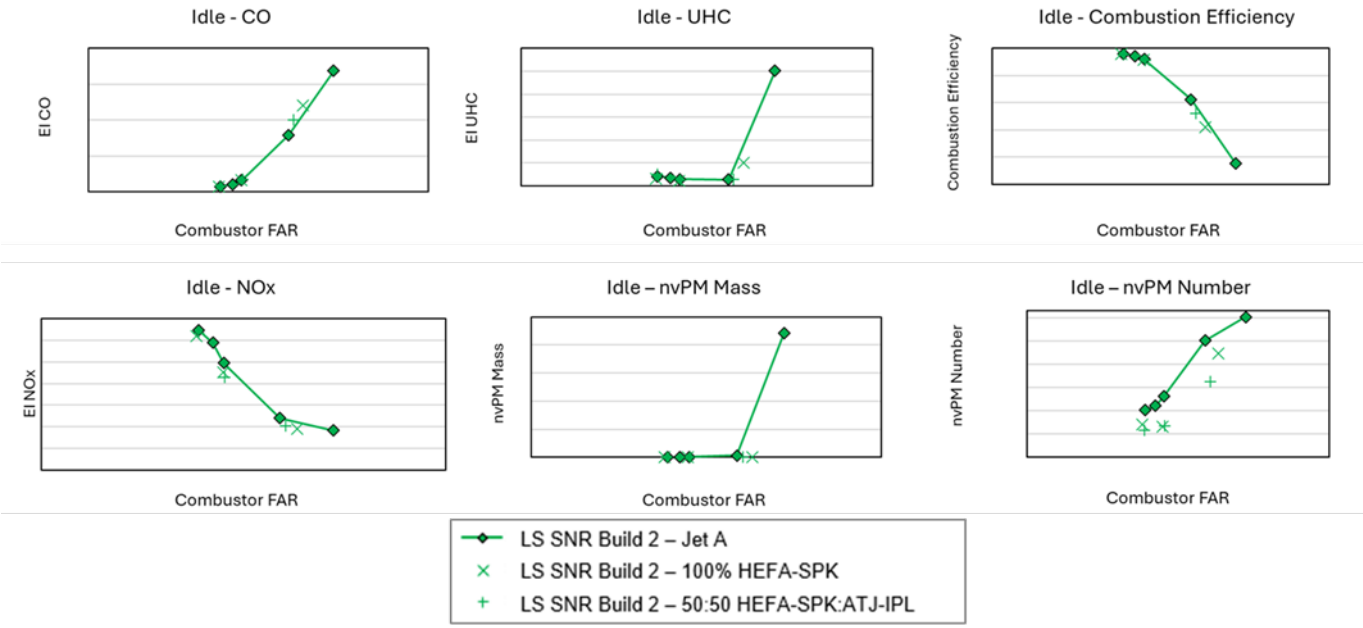


Figure 4-7 LS SNR Build 2 Emissions at Idle, Jet A versus SATFs

Results for approach conditions are shown in Figure 4-8. As with idle conditions, there are minimal differences between Jet A and SATF for gas emissions, including combustion efficiency and NOx. nvPM mass does trend substantially lower at the high FAR condition using SATF, which is generating extremely high soot levels with all fuels. However, the nvPM number levels are very similar to baseline, suggesting larger soot particles may be generated with Jet A compared to those generated with the SATF blends.

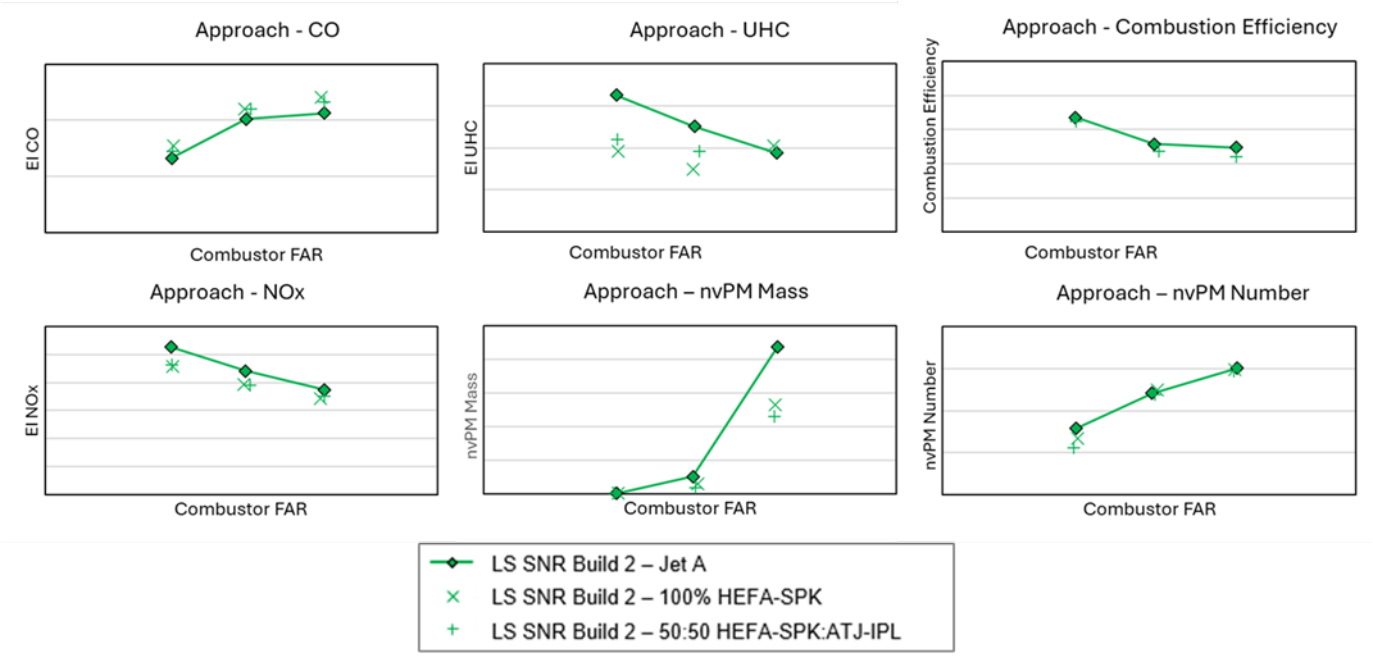


Figure 4-8 LS SNR Build 2 Emissions at Approach, Jet A versus SATFs

A final comparison between Jet A and SATFs at high-power conditions is shown in Figure 4-9. This data shows nearly identical NOx emissions between all three (3) fuels. For combustion efficiency, the 50:50 HEFA-SPK:ATJ-IPK fuel trended lower than Jet A, while the 100% HEFA-SPK trended higher than Jet A, especially at the low FAR range. All fuels tested showed low nvPM mass levels. For nvPM number, the SATF blends show slightly lower levels at low FAR conditions, but similar levels at high FAR conditions.

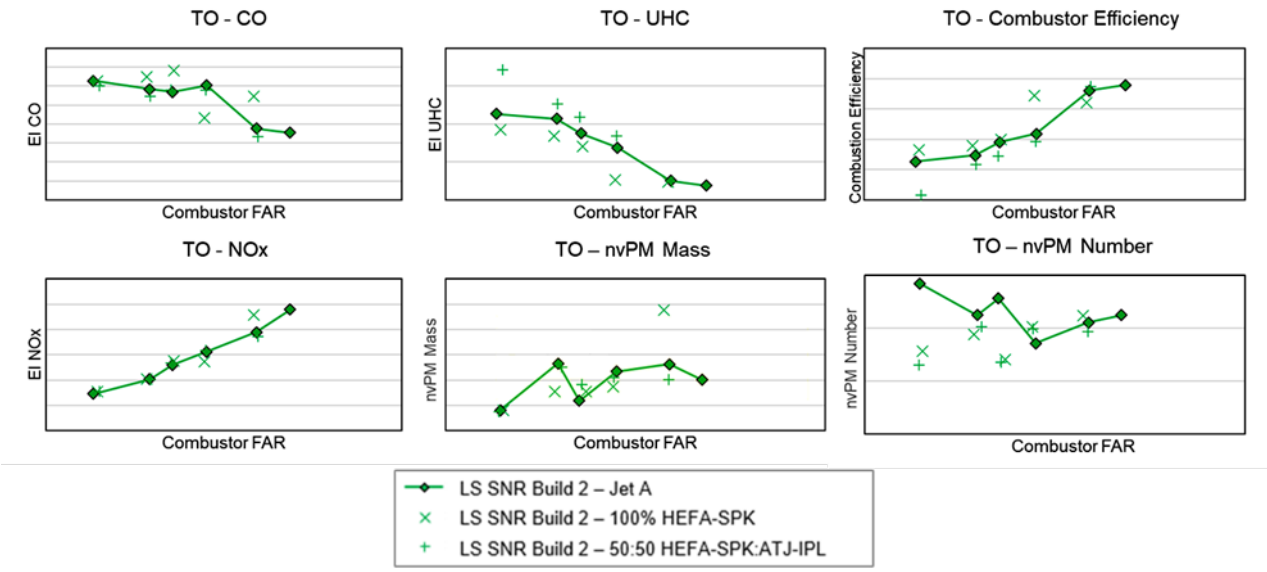


Figure 4-9 LS SNR Build 2 Emissions at High-power, Jet A versus SATFs

A large side window provided high-fidelity imaging over large regions of the combustor, as shown in Figure 4-10, which provides a side by side comparison of the borescope view used for SNR Build 1 (left image) with the large side window view used with the SNR Build 2 configuration (right image). An external high-speed camera was set up on a tripod, angled toward the front-end. Imaging was collected alongside radiometer data, unlike the LS SNR Build 1, where the radiometer had to be installed in-place of the borescope.

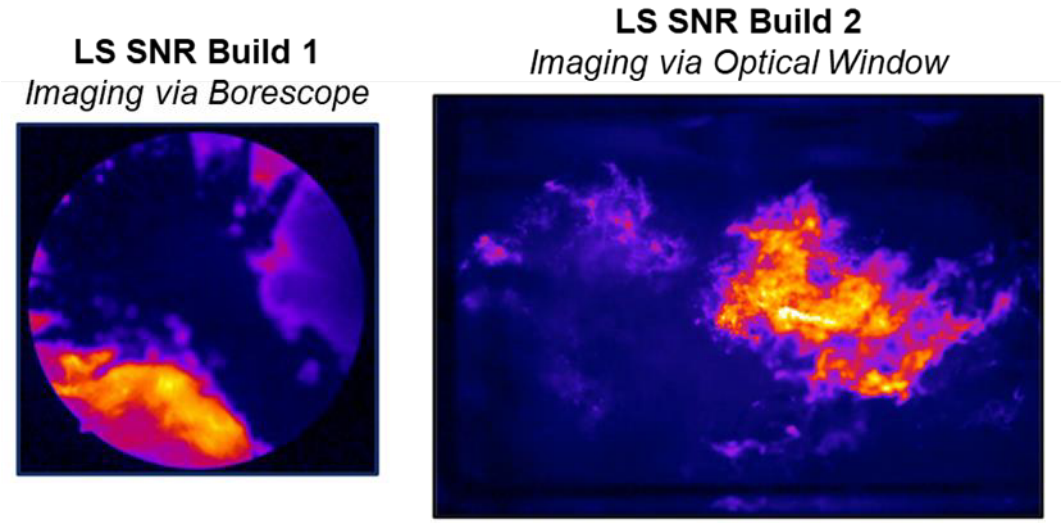


Figure 4-10 LS SNR Build 1 versus Build 2 Internal Combustor Imaging Comparison

A selection of high-speed video frames at idle conditions are shown in Figure 4-11. The images show a comparison between the three (3) tested fuels at the final idle operating conditions. The two (2) SATF blends show much lower flame luminosity compared to the baseline Jet A case, as has been the case in the videos shown throughout this report.

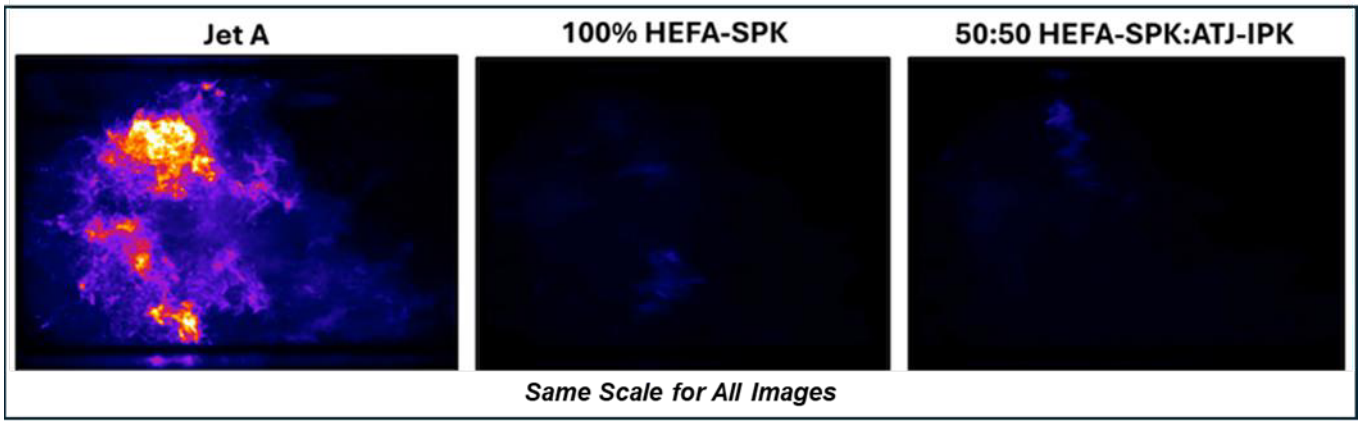


Figure 4-11 LS SNR Build 2 Flame Imaging at Idle

A selection of high-speed flame images at approach conditions are shown in Figure 4-12. The images compare the three (3) tested fuels at approach. As with the other sections, the flame luminosity is much lower for both SATF variants as compared to the Jet A baseline.

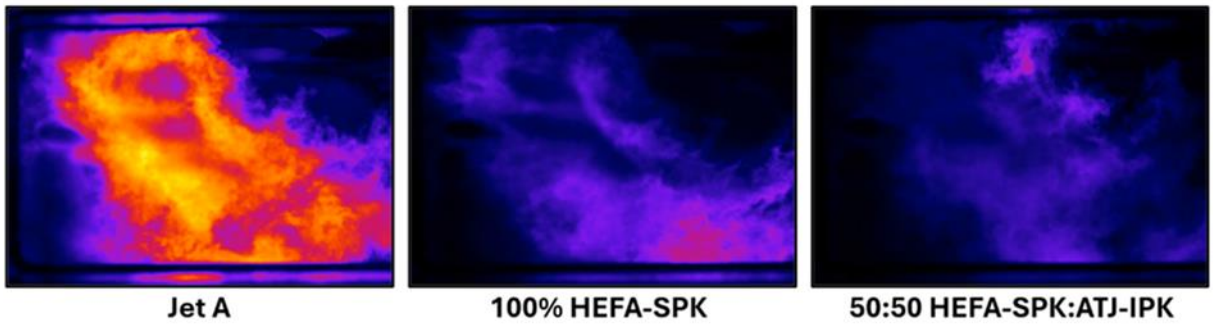


Figure 4-12 LS SNR Build 2 Flame Imaging at Approach

Figure 4-13 shows frames of high-speed flame imaging performed at high-power conditions comparing baseline Jet A fuel and both tested SATF blends. Two (2) conditions are shown, with the top row representing a standard cruise condition, and the bottom row representing a FAR higher than standard TO. Note that all six (6) images in this figure have had the same scaling applied to allow the luminosity to be compared across all the images. The SATF blends show lower luminosity than baseline Jet A in both cases.

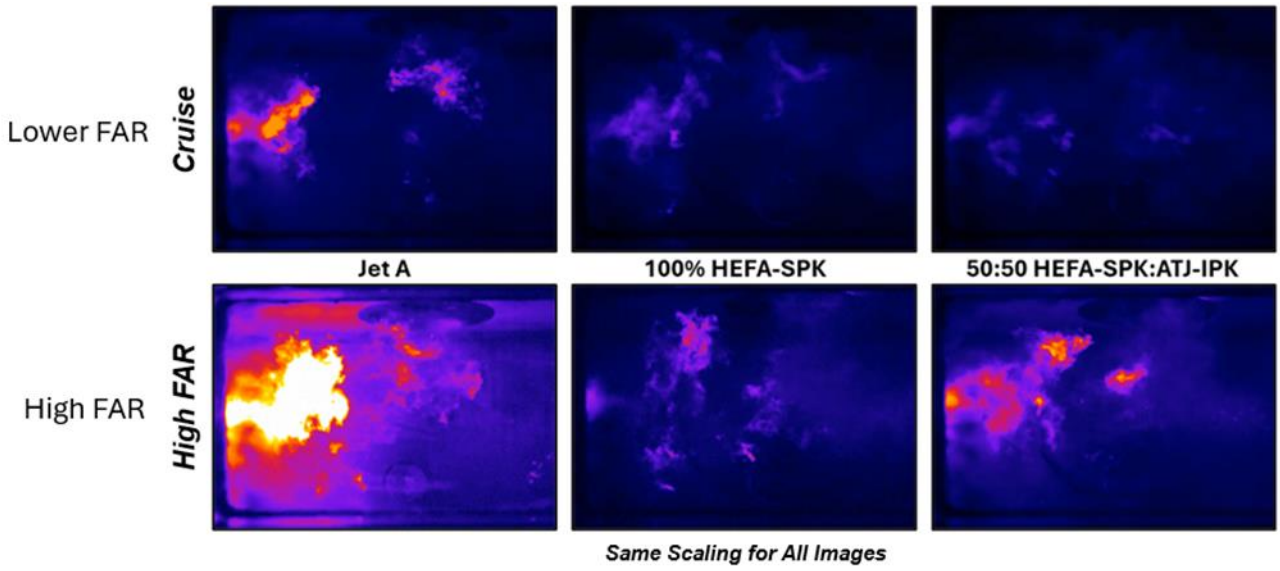


Figure 4-13 LS SNR Build 2 Flame Imaging at Cruise and High FAR

Combustor dynamics was a key metric of interest during this test campaign. Figure 4-14 shows the results from this testing at idle conditions, with the P' plotted against FAR. At the desired operational idle point, tone levels are very low for all three (3) tested fuels. However, at higher FAR conditions, some low frequency tones are excited within the system, which occurs on Jet A and both SATF blends. Figure 4-14 shows frames from high-speed video collected at low and high tone idle points, as indicated by the red circles in the plot. The video shows stable flame holding at the low-tone point, but substantial oscillation longitudinally in the combustor at the higher tone (higher FAR) point.

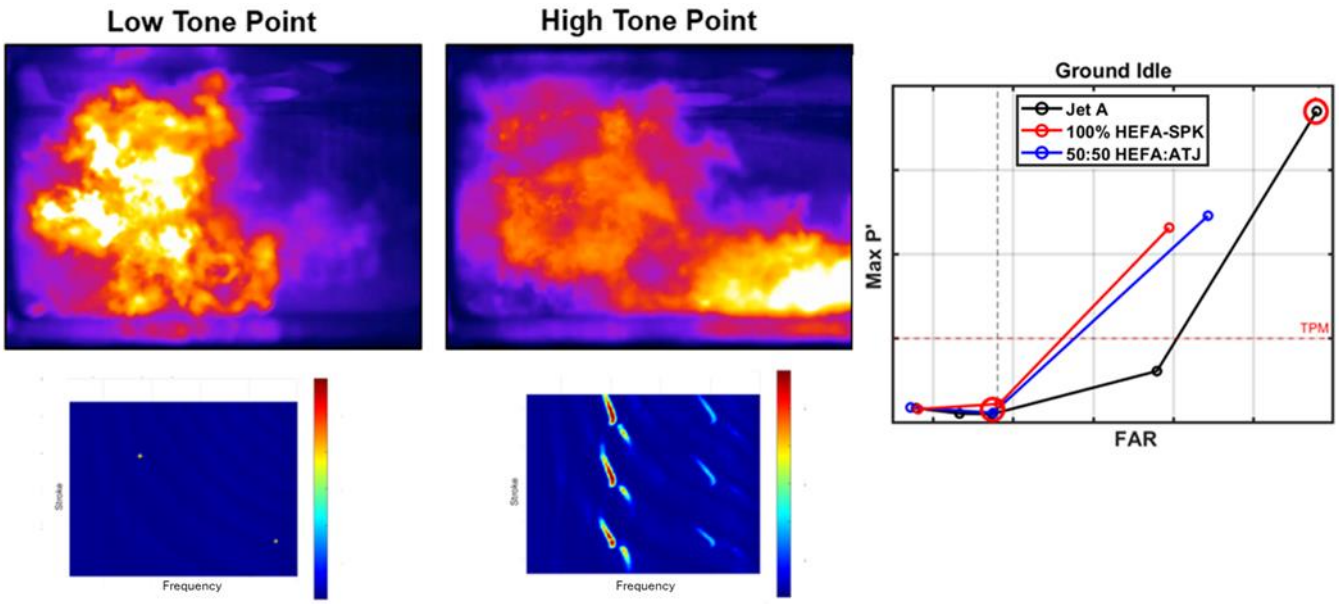


Figure 4-14 LS SNR Build 2 Combustors at Idle, Jet A versus

A similar figure is plotted for approach conditions in Figure 4-15. At these conditions, the Jet A baseline case showed negligible combustor tones, but higher levels were seen with both SATF blends. The 50:50 HEFA-SPK:ATJ-IPK blend showed substantially higher tone levels than the baseline Jet A, though the frequency of the tone is in the same range for all fuels.

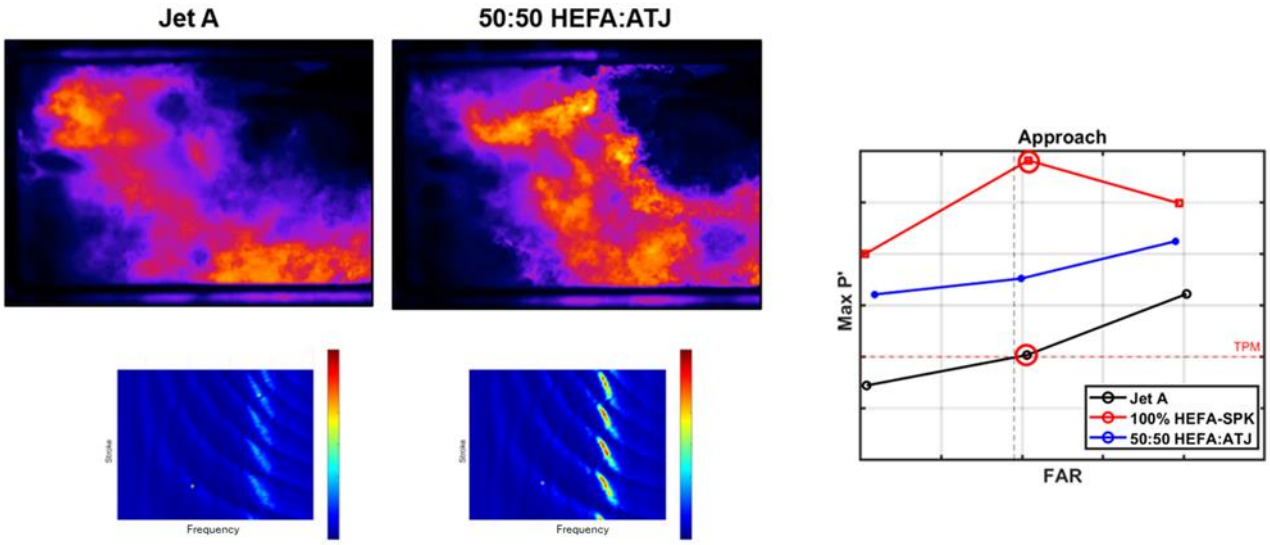


Figure 4-15 LS SNR Build 2 Combustor Tones at Approach, Jet A versus SATFs

Figure 4-16 shows the results from tone measurements at high-power conditions for this configuration. At high FAR conditions, incredibly high combustor tones were excited with this configuration across all three (3) tested fuels.

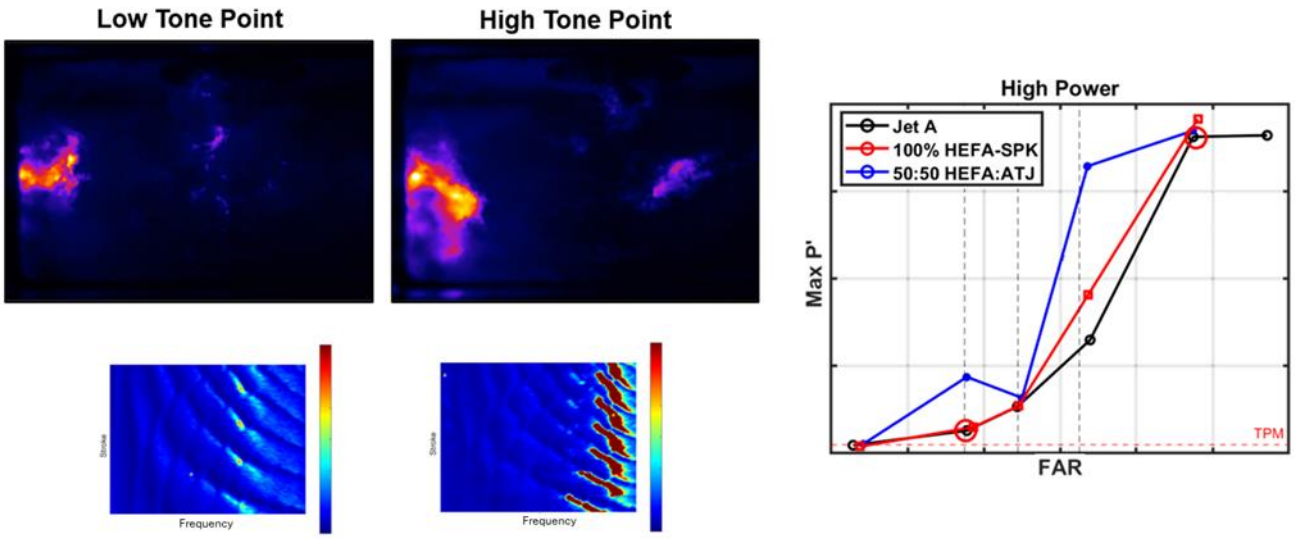


Figure 4-16 LS SNR Build 2 Combustor Tones at High-power, Jet A versus SATFs

For LS SNR Build 2, a selection of T/Cs were installed on the backside of the combustor panels to study combustor durability in a lean system. Two (2) T/Cs (TC1 and TC2) were on the bulkhead and four (4) T/Cs (TC1-TC4) on the ID panel.

Figure 4-17 shows T/C results at idle conditions, Figure 4-18 shows T/C data at approach conditions, and Figure 4-19 shows the data at high-power conditions. All of this data is shown comparing baseline Jet A fuel and the two (2) tested SATF blends. Across both combustor panels and all three (3) operating ranges, minimal differences were observed between the three (3) tested fuels. The one notable point of interest in the data was seen at high-power conditions on TC1, the most upstream T/C, which is shown in Figure 4-19 to be rapidly increasing. At lower FAR values, TC1 experiences one of the lowest ID panel temperatures, but it becomes the highest by a good margin at high FAR values. This indicates a sharp change in the flame shape within the combustor, moving the flame closer to the upstream part of the ID panel.

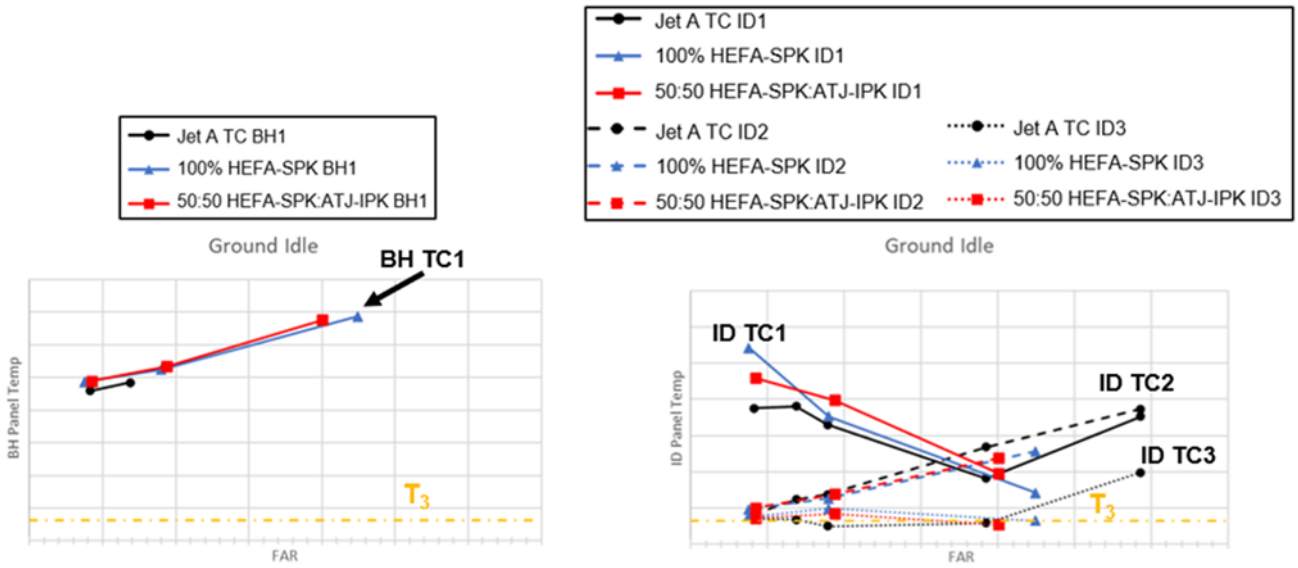


Figure 4-17 LS SNR Build 2 T/C Results at Idle

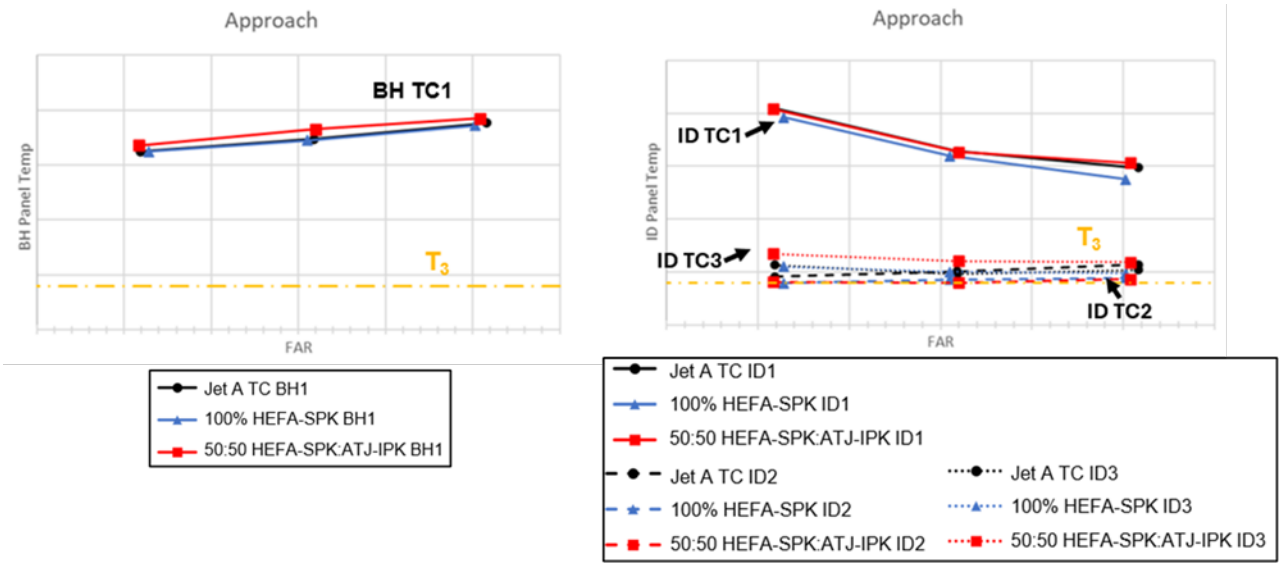


Figure 4-18 LS SNR Build 2 T/C Results at Approach

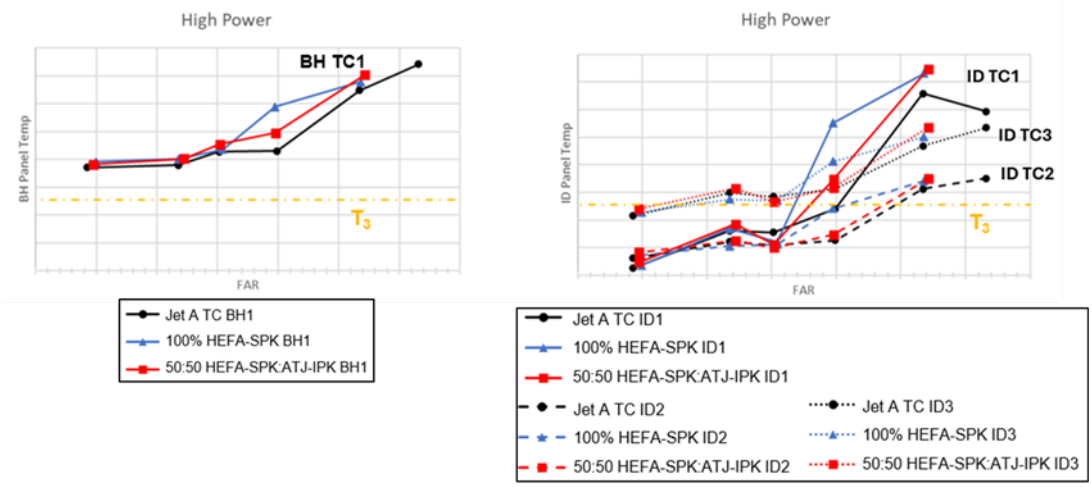


Figure 4-19 LS SNR Build 2 T/C Results at High-power

5. LS MSR RIG RESULTS

5.1 HYTEC COMBUSTOR RIG BUILD

The LS MSR Build included a newly designed combustor assembly comprised of new components, as well as used parts from a previously run NASA Environmentally Responsible Aviation (ERA) rig.

5.2 LS MSR TESTING SUMMARY

5.2.1 Testing Summary of the LS MSR Rig

The primary goals of the LS MSR testing were to examine ignition and LBO characteristics for both Jet A and SATFs.

Upon completion of the shakedown and cold flow testing, the next set of tests focused on ignition measurements. This tests were conducted like the advanced RQL MSR and consisted of holding ALPs steady while a single ignitor was commanded on, after which fuel was input at a fixed rate. Borescope and T/C measurements were used to confirm whether the burner had lit, at which point the ignitor was turned off. If the burner did not light in ten (10) seconds, the test was terminated.

In addition to the ground start priority point testing, FAR sweep ignition tests at two (2) ALP conditions were performed for the LS MSR. This was done to examine the effects with realistic FAR values to examine differences between Jet A and SATFs. FAR sweep comparison results for the LS MSR configuration tested are presented in Figure 5-1. There were no large differences between SATFs and Jet A.

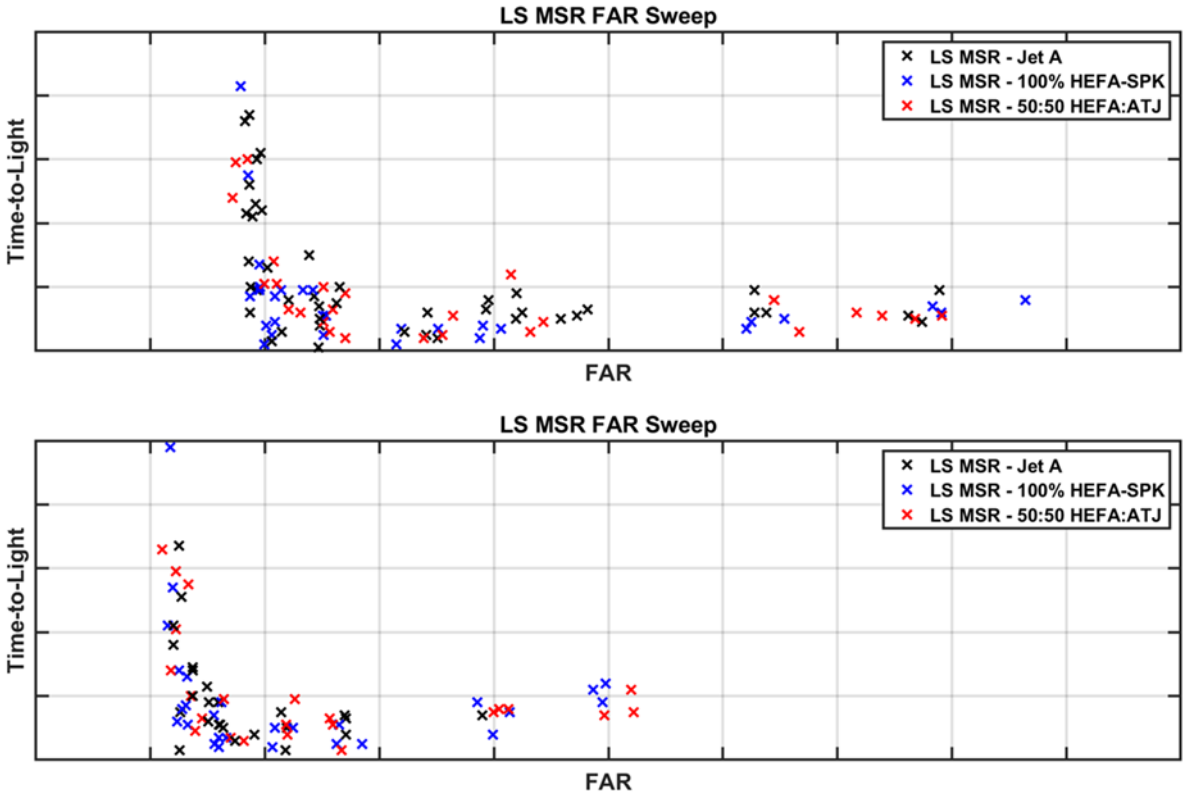


Figure 5-1 LS MSR Ignition Testing Results with Jet A and SATF

The second major focus of the LS MSR test was to identify LBO characteristics in a scaled sector rig. The LBO tests were completed using an identical procedure to that outlined for the Advanced RQL MSR.

Overall, LS MSR LBO results exhibited good repeatability across the range of conditions tested, and all test conditions demonstrated blowout significantly below the engine LBO audit limit, as shown in Figure 5-2. Similarly, only small differences were observed between Jet A and SATFs.

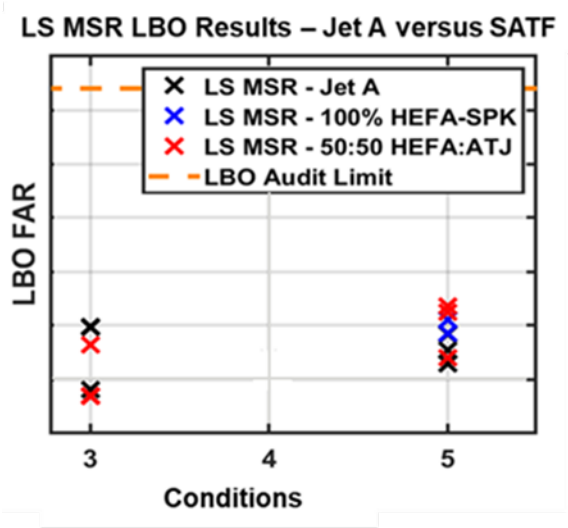


Figure 5-2 LS MSR LBO Comparison

6. SYSTEM AND TOOL VALIDATION

For Task 6, entitled Tool and Model Validation and System Benefits, properties characteristic of high-blend SATF were input into updated analytical tools for combustor design. The updated analytical tools enabled comparison of Jet A and SATF for combustor performance impacts, including atomization, combustion, heat release, flame stabilization, and heat transfer. Task 6 was broken into three (3) parts, the first, Task 6.1, involved the actual tool upgrades to incorporate the SATF modeling capability into two (2) existing design tools, a spray simulation tool and a CFD reacting flow tool. The second, Task 6.2, included a validation of the new capability of the tools. Finally, Task 6.3 used the new capability to evaluate combustor design for engine system level benefits.

The new spray simulation provided insight on impacts of SATFs at cold start conditions. The updated CFD tool provided trending impacts for SATFs on combustor pressure drop, combustor exit temperature quality, NOx, and soot emissions.

7. CONCLUSION

7.1 SUMMARY

7.1.1 Summary of Testing Results

The NASA HyTEC contract was intended to accelerate small turbofan engine turbine technologies and ensure the combustor technologies are ready for 100% blend (high-blend) SATFs to meet sustainability goals for the NextGen commercial aircraft. The contract took place over a three (3) year period, and included development work on two (2) combustor analytical tools to enable SATF modeling. As an overall summary of the HyTEC contract, high level accomplishments include successfully executing combustor rig testing, with all data acquired, documented, and analyzed. The results of this testing demonstrate that HyTEC designs met most of the TPMs assigned in the contract.

After reviewing all combustor rig test results under HyTEC, several important conclusions were extracted. From a SATF perspective, the tested high-blend fuels showed substantially lower nvPM, the same or slightly lower NOx, small changes to dynamics depending on combustor operating conditions, and minimal differences in ignition or LBO performance. Additionally, minimal differences were observed between the two (2) primary SATF blends tested during this program.

In addition to the SNR, where emissions, tones, and durability metrics were evaluated, a separate MSR rig was established to assess ignition and LBO capabilities. The ignition and LBO capabilities included testing with both Jet A and SATFs. For Advanced RQL, the sector rig ignition and LBO results were comparable to available engine results. No significant differences between Jet A and SATFs for ignition and LBO were measured.

Similarly, no significant differences between Jet A and SATFs were noted for ignition and LBO in the LS MSR rig.

7.1.1.1 Summary of Results for Advanced RQL SNRs

For SNR Build 1, the SATFs had significantly lower nvPM emissions, with NOx showing small reductions. The alternatively derived fuels measured similar combustion efficiency relative to conventional Jet A fuel.

Common conclusions from both SNR Build 1 and SNR Build 2 are that SATF shows substantially lower nvPM at high FAR conditions, with minimal other impacts.

7.1.1.2 Summary of Results for LS SNRs

LS SNR testing occurred over two (2) builds, SNR Build 1 and SNR Build 2. As with the Advanced RQL SNR testing, all configurations tested with SATF demonstrated a reduction in nvPM emissions, especially at high-FAR conditions, as compared to the baseline Jet A fuel.

7.1.1.3 Summary of Results for Advanced RQL MSR

All ground ignition times-to-light were sufficiently fast, and the LBO FARs were generally at or below the baseline. The ignition and LBO performance were similar when comparing Jet A and SATFs, particularly at required engine FARs and relevant conditions. In summary, all

observed ignition and LBO performances were well within target with sufficient margin to audit or performance limits.

7.1.1.4 Summary of Results for LS MSR

The LS MSR ground-start ignition results exhibited fast times-to-light at all relevant FARs. Similarly, the LS MSR LBO performance was well below engine audit limit. Finally, no significant ignition or LBO performance differences were observed with Jet A or SATFs tested.

7.1.1.5 Summary of Results for Tool Development

The tool development efforts included incorporating high-blend SATF into the design tools and CFD models. Combustor performance such as atomization and emissions performance were investigated. Results of the models were compared to the test data collected in the single-sector rig. The validated models were used to evaluate the impact of these high-blend SATFs on engine and system performance parameters. Possible system benefits were explored using these modeling tools.

The new spray simulation provided insight on impacts of SATFs at cold start conditions. The updated CFD tool provided trending impacts for SATFs on combustor pressure drop, combustor exit temperature quality, NOx, and soot emissions.

7.2 TPMS

7.2.1 Advanced RQL SNR Build 1 TPMs

Combustor tone results from SNR Build 1 with the baseline Advanced RQL combustor with one configuration tested across three (3) fuel types, Jet A, 100% HEFA-SPK, and 50:50 HEFA-SPK:ATJ-IPK are presented in Figure 7-1. The evaluation of SATFs was intended to compare tone levels against the Jet A baseline combustor levels at the prescribed product FAR value. The table indicates that SATFs meet the < psi amplitude level at ground idle for both the low and high tone frequency bands. For the Snap Accel condition, 100% HEFA-SPK meets the TPM requirement for both low and high frequency tones, but the 50:50 HEFA-SPK:ATJ-IPK only met the TPM requirement at high frequency – this fuel demonstrated an increase in low frequency tone amplitude. At Approach condition both SATFs only met the TPM at low frequency tone – both fuels showed an increased high frequency tone compared to the Jet A baseline.

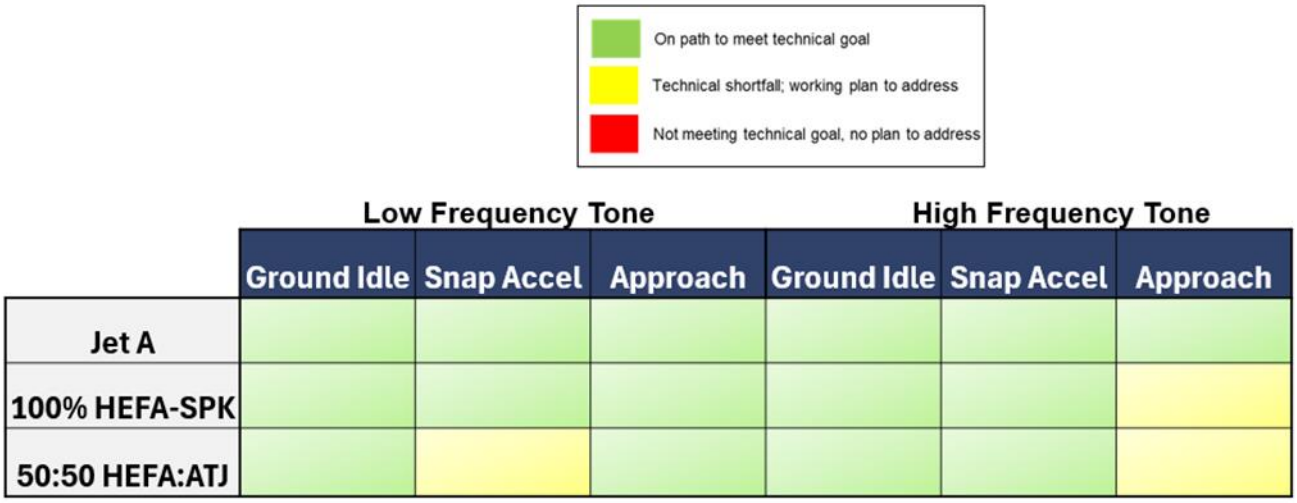
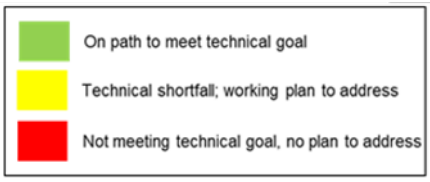


Figure 7-1 Advanced RQL SNR Build 1 Tone Results Compared Against TPM

A summary of the TPM results from the Advanced RQL SNR Build 1 testing are included in Table 7-1. The results indicate that there is a shortfall with SATFs for tones and nvPM emissions. NOx requirements for the SATFs were met. The quantitative values that support the results in Table 7-1 can be found in Figure 7-2, Figure 7-3, and Figure 7-4. 100% HEFA-SPK and 50:50 HEFA-SPK:ATJ-IPK met the required TPM >5% NOx reduction at cruise, as shown in Figure 7-2. The SATF results show the configurations are close, but do not meet TPM number requirements of >70% reduction for mass, as shown in Figure 7-3. For all fuels the nvPM mass levels were low and fell below the minimum detection range. As a result, the required reduction comparison was not confirmed with the measurement. Achieving the 70% reduction at these already low nvPM mass levels may not be meaningful. The cruise nvPM number reduction with SATFs met the 70% requirement, as shown in Figure 7-4.

Table 7-1 Advanced RQL SNR Build 1 TPM

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	>5% Improvement
5	Cruise nvPM	>70% Improvement



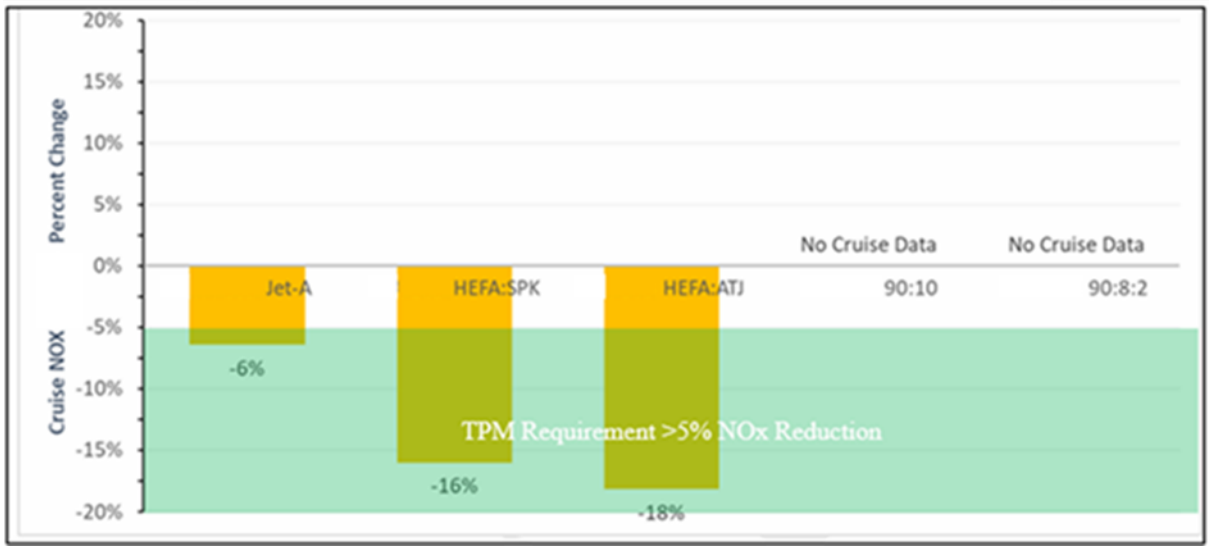


Figure 7-2 Advanced RQL SNR Build 1 Cruise NOx Jet A and SATFs Compared Against TPM

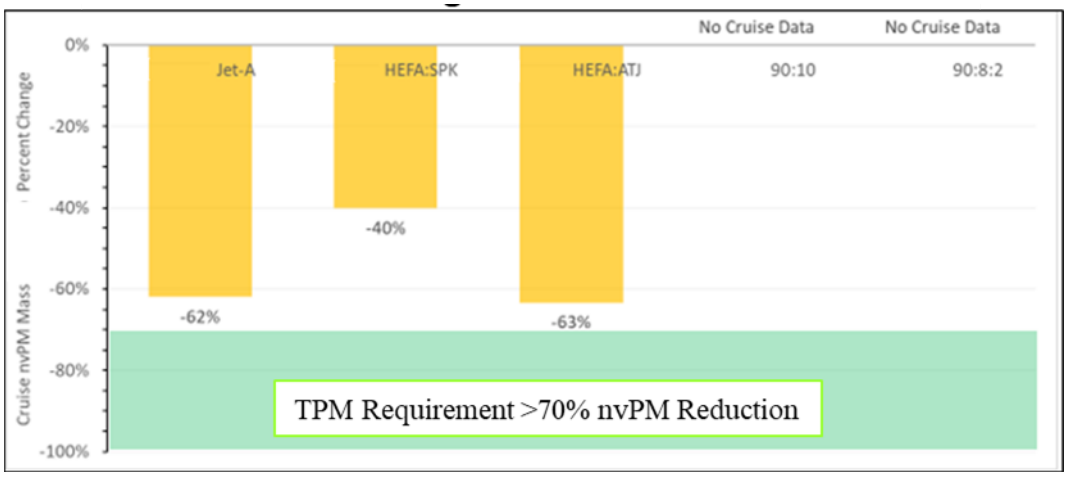


Figure 7-3 Advanced RQL SNR Build 1 Cruise nvPM Mass Jet A and SATFs with TPM

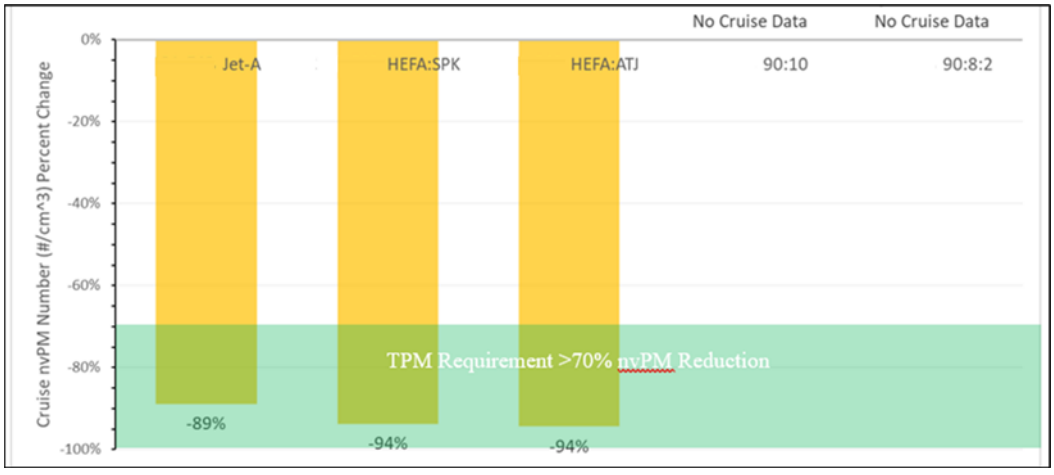


Figure 7-4 Advanced RQL SNR Build 1 Cruise nvPM Number Jet A and SATFs against TPM

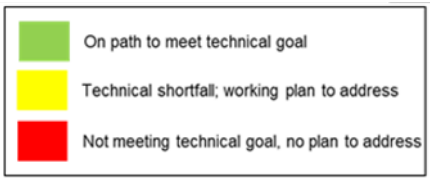
7.2.2 Advanced RQL SNR Build 2 TPMs

As a summary of the testing completed with the Advanced RQL combustor in SNR Build 2, the emissions and dynamics results were compared against the HyTEC TPMs. Table 7-2 provides the five (5) key performance measures for the combustor: ignition, LBO, tones, cruise NOx, and cruise nvPM. Data for tones, cruise NOx, and cruise nvPM were obtained during SNR testing. Note that the TPMs cover performance measures for SATFs.

Table 7-2 shows the Advanced RQL TPM status based on qualitative color coding, as described by the legend on the table. The table conclusions are supported quantitatively by bar charts presented in Figure 7-5, Figure 7-6, Figure 7-7, and Figure 7-8 . Results show that both Jet A and SATFs met the tone TPM requirement at idle, with 100% SATF blends being lower than Jet A. At approach, Jet A met tone requirements, with SATFs being just above the limit. Both Jet A and SATFs were above the tone requirement at high-power, as shown in Figure 7-5. In Figure 7-6, 50:50 HEFA-SPK:ATJ-IPK passed the TPM for NOx satisfying the >5% improvement. 100% HEFA-SPK barely missed the requirement for NOx at 4% reduction. In Figure 7-7, for all fuels, the nvPM mass levels were low and fell below the minimum detection range. As a result, the required reduction comparison was not confirmed with the measurement. Achieving the 70% reduction at these already low nvPM mass levels may not be meaningful. In Figure 7-8, nvPM number TPM requirements were met for both SATFs.

Table 7-2 Advanced RQL SNR Build 2 TPM Status

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	>5% Improvement
5	Cruise nvPM	>70% Improvement



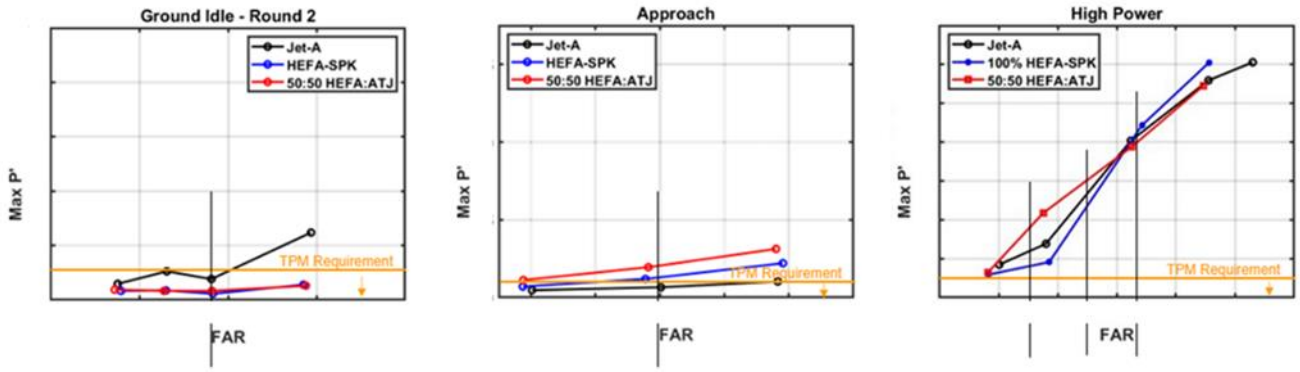


Figure 7-5 Advanced RQL SNR Build 2 TPM Combustor Tone Comparison

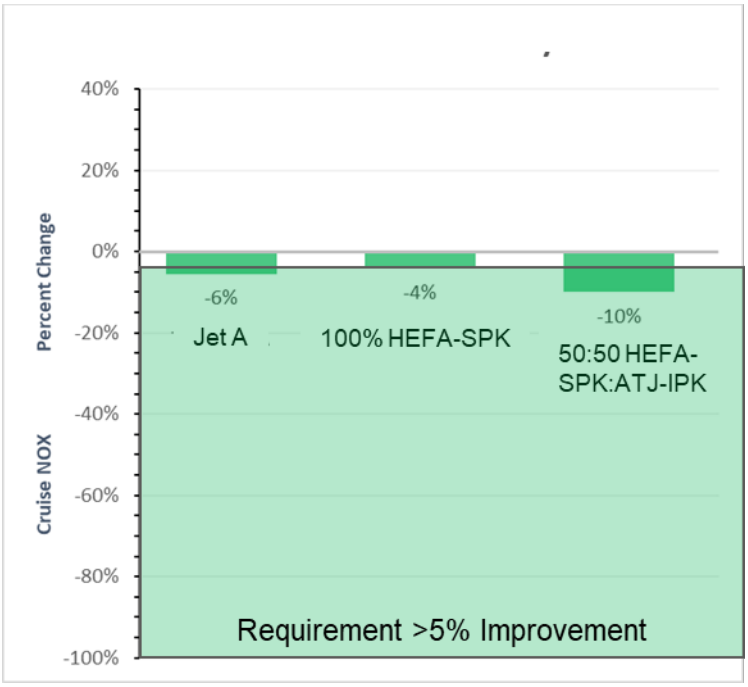


Figure 7-6 Advanced RQL SNR Build 2 TPM Cruise NOx Comparison



Figure 7-7 Advanced RQL SNR Build 2 SNR Cruise nvPM Mass Comparison

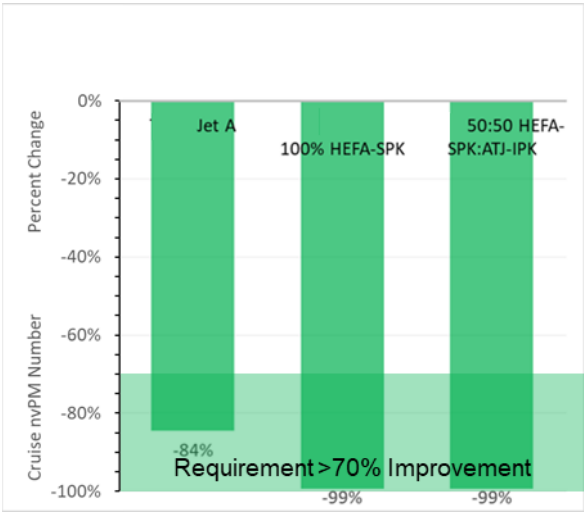


Figure 7-8 Advanced RQL SNR Build 2 Cruise nvPM Number Comparison

7.2.3 Advanced RQL MSR TPMs

Ignition TPM assessment results are shown in Table 7-3. The TPM assessment shows the Advanced RQL TPM passes criteria for both ignition and LBO. The quantitative results are shown in Figure 7-9. Advanced RQL shows ignition within requirements, with SATF showing comparable or lower FAR at ignition boundary. Advanced RQL successfully passed ignition TPMs for SATFs at the conditions tested.

Table 7-3 Advanced RQL MSR Ignition and LBO TPM

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
1	Ignition	Comparable (within 15%) or lower FAR
2	LBO	Comparable (within 15%) or lower FAR

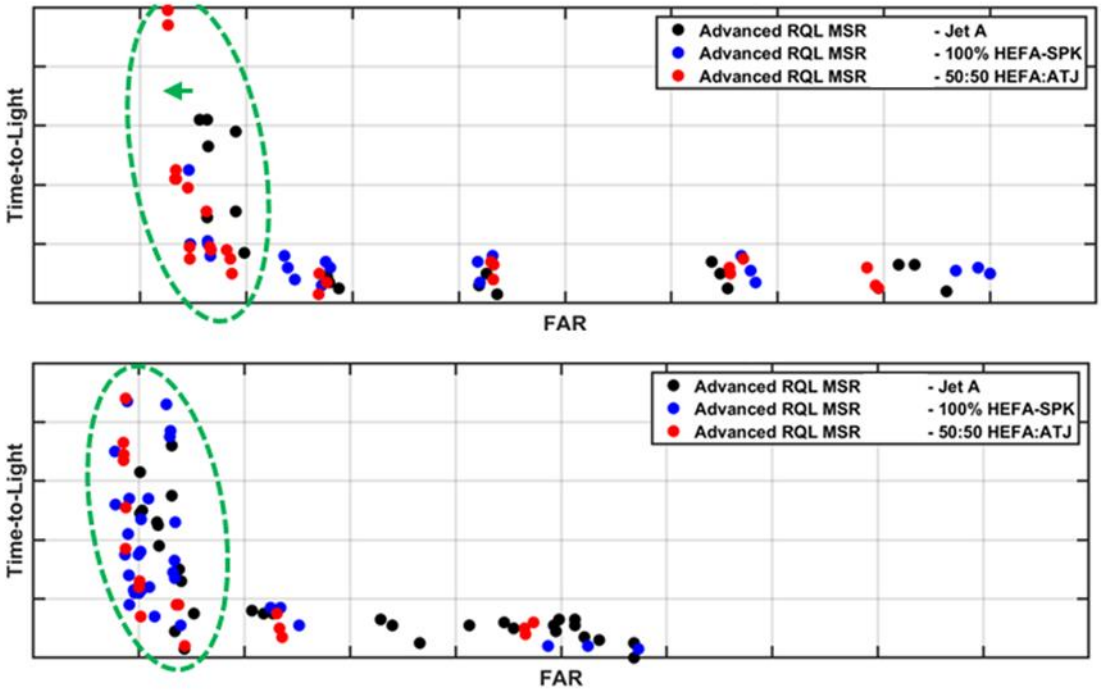


Figure 7-9 Advanced RQL MSR FAR versus Time to Light

The LBO TPM assessment results are shown in Table 7-3. The TPM assessment status is based on qualitative color coding, and the quantitative results are shown in Figure 3-2. Conditions 3 and 5 tested with both Jet A and SATFs, and the plot indicates no measurable difference in LBO FAR between Jet A, 100% HEFA-SPK, and 50:50 HEFA-SPK:ATJ-IPK. Advanced RQL MSR successfully passed LBO TPMs for SATFs at the conditions tested.

7.2.4 LS SNR Build 1 TPMs

Table 7-4 shows the overall qualitative TPM assessment for LS SNR Build 1. The quantitative results supporting conclusions are provided in Figure 7-10. Unfortunately, the LS configuration experienced a hot shut down event after completing testing at idle and approach conditions. The hot shut down resulted in invalid results during high-power testing, so cruise NOx, high-power tones, and nvPM cruise emissions were compromised. Only this configuration was tested with SATFs and as a result, valid data was only obtained at low power. The low power results for the SATFs passed the TPM target.

Table 7-4 LS SNR Build 1 TPM

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	40-60% Improvement
5	Cruise nvPM	>90% Improvement

On path to meet technical goal
Technical shortfall; working plan to address
Not meeting technical goal, no plan to address
No proper assessment relative to target

*SAF data compromised for High Power Tone, Cruise NOx or Cruise nvPM due to fuel nozzle coking during high power testing.

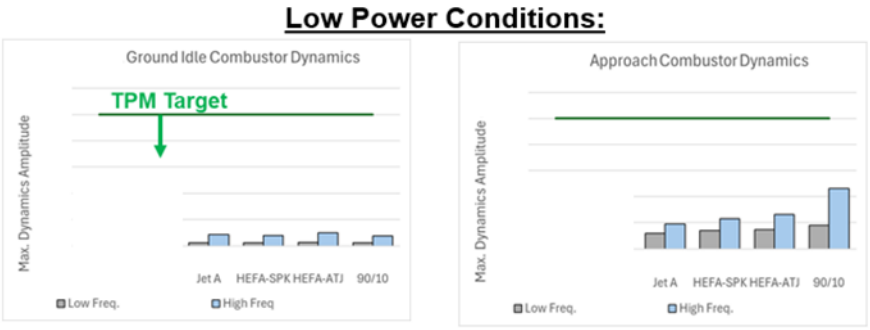


Figure 7-10 LS SNR Build 1 Combustor Tones

7.2.5 LS SNR Build 2 TPMs

In Table 7-5 a summary of the qualitative results for the TPM assessment for LS SNR Build 2 is provided. The quantitative values for the TPMs can be found in Figure 7-12, Figure 7-13, and Figure 7-14. The LS configuration did not meet tone TPMs as shown by the plots provided in Figure 7-11. Figure 7-12 displays the LS cruise NOx emissions results against the TPMs. The SATFs resulted in further NOx reduction when compared to Jet A and met the >40-60% TPM requirement. Figure 7-13 and Figure 7-14 show the results for the LS configuration with cruise nvPM emissions. The requirements were met for the nvPM number measurements for all fuels. The nvPM mass was measured to be very low for all the fuels and fell below the minimum

detection range. As a result, the required reduction comparison was not confirmed with the measurement. Achieving the 90% reduction at these already low nvPM mass levels may not be meaningful.

Table 7-5 LS SNR Build 2 TPM Summary

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
3	Combustor Tones	< psi in SNR
4	Cruise NOx Emissions	40-60% Improvement
5	Cruise nvPM	>90% Improvement

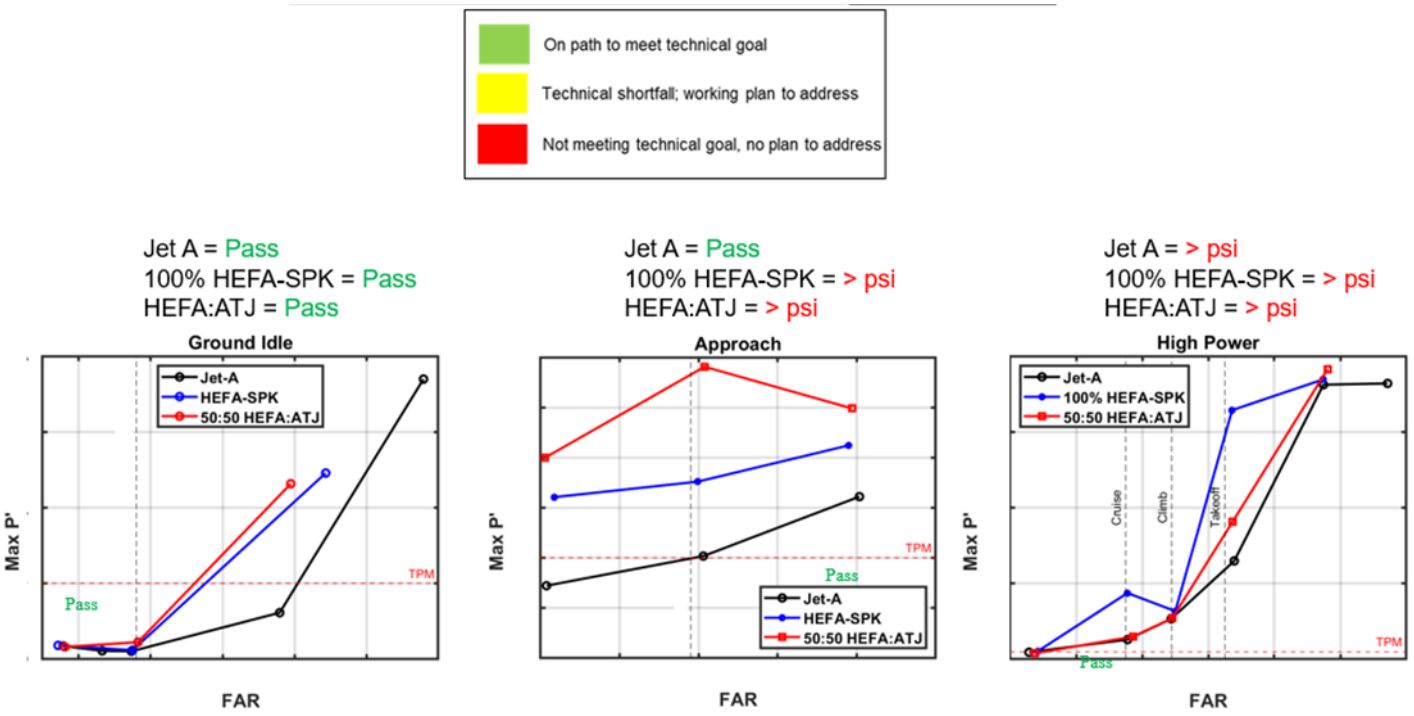
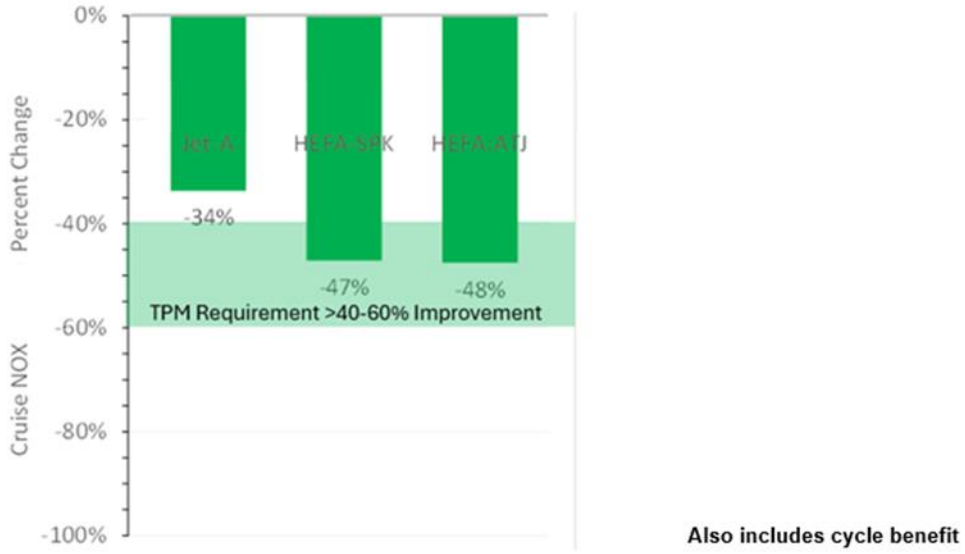


Figure 7-11 LS SNR Build 2 TPM Dynamics Comparison



Cruise nvPM reduction calculated relative to an engine certification test

Figure 7-12 LS SNR Build 2 TPM Cruise NOx Comparison

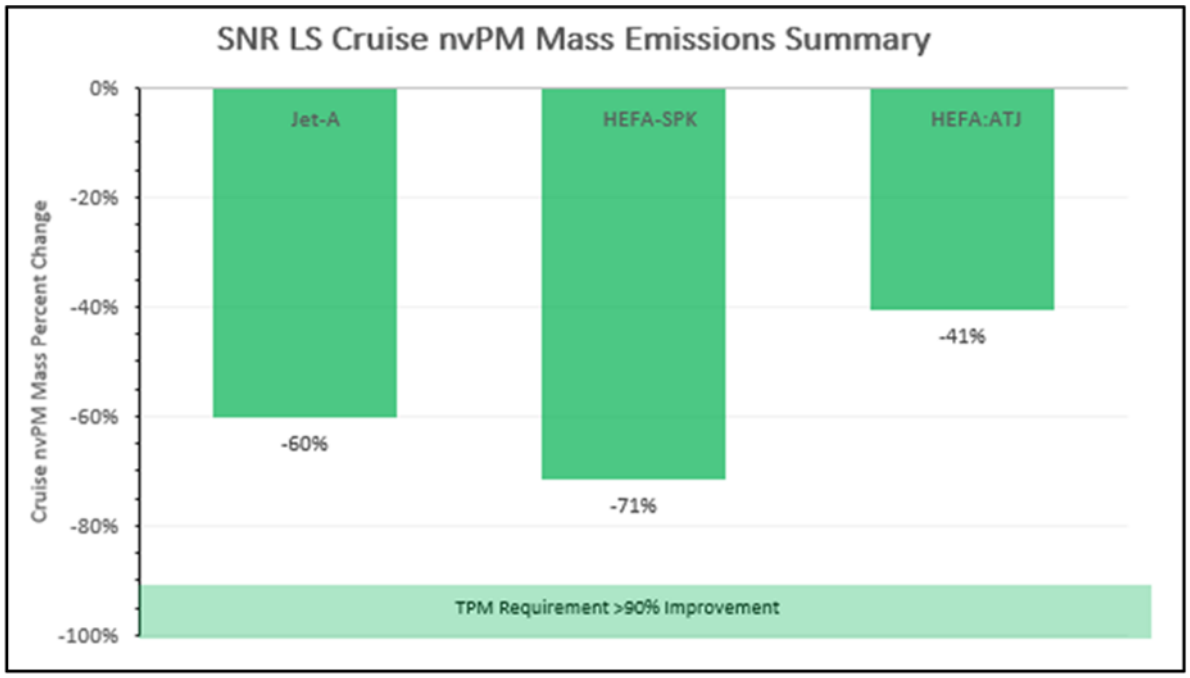


Figure 7-13 LS SNR Build 2 TPM Cruise nvPM Mass Comparison

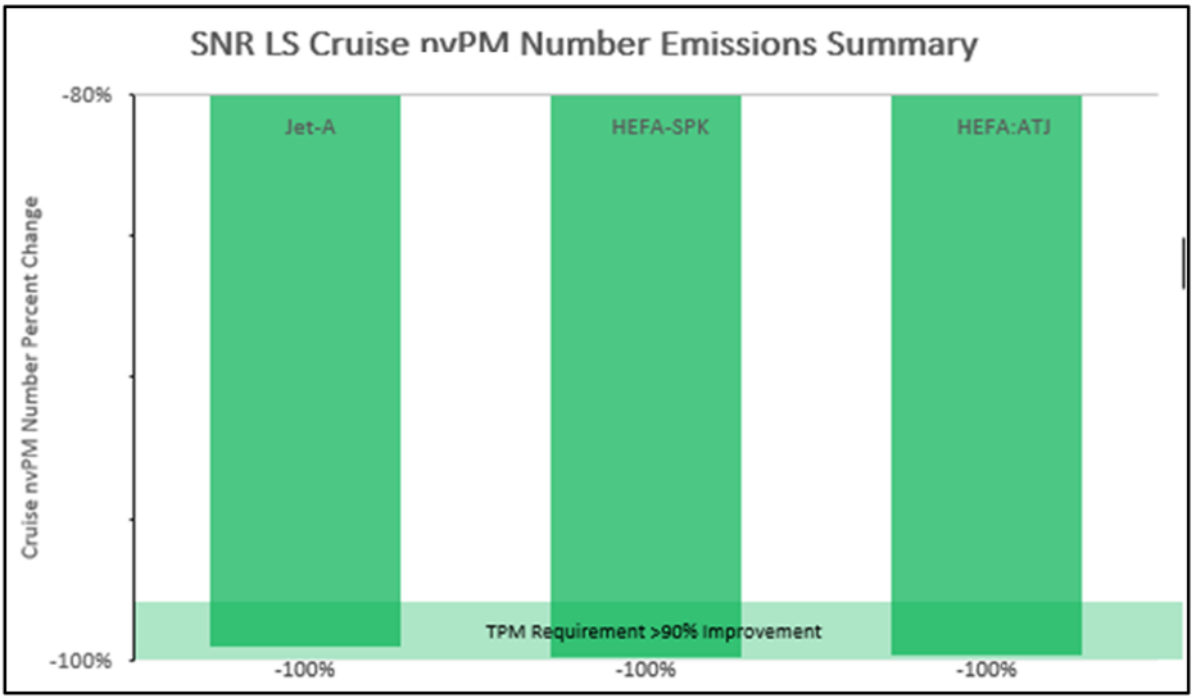


Figure 7-14 LS SNR Build 2 TPM Cruise nvPM Number Comparison

7.2.6 LS MSR TPMs

For the ignition and LBO TPM assessment for the LS combustor, see Table 7-6. The TPM assessment shows the LS MSR TPM status based on qualitative color coding and the quantitative data used for the assessment are shown in Figure 5-1. Overall, the LS MSR shows ignition occurring within the requirement for the priority ground start conditions. LS MSR ignition with SATFs also showed performance consistent with Jet A. The LS MSR successfully passed ignition TPMs for both operation on Jet A and SATFs at the conditions tested.

The LBO TPM assessment results are also shown in Table 7-6. The TPM assessment status is based on qualitative color coding, and the quantitative results are shown in Figure 5-2. Conditions 3 and 5 were tested with both Jet A and SATFs, and the plot indicates no measurable difference in LBO FAR between Jet A, 100% HEFA-SPK, and 50:50 HEFA-SPK:ATJ-IPK.

Table 7-6 LS MSR TPM Ignition and LBO

TPM Number	*TPM Compared to Baseline Engine with Petroleum-Based Jet A/A-1*	*Full Success with 100% SATF*
1	Ignition	Comparable (within 15%) or lower FAR
2	LBO	Comparable (within 15%) or lower FAR

8. REFERENCES

1. Edwards, T., Reference Jet Fuels for Combustion Testing, 55th AIAA Aerospace Sciences Meeting, Grapevine, Texas, United States, January 2017, pp. 0146

9. APPENDIX A: PROPERTY TABLES REFERENCES

Property	Method	Jet A	100% HEFA	50% HEFA 50% ATJ	90% HEFA 10% ARO150	90% HEFA 8% ARO150 2% Napth.
Standard Physical & Chemical Properties						
Certificate of Analysis Date		6/29/2023	7/30/2023	11/13/2023	7/17/2023	7/17/2023
Density @ 15°C (kg/m^3)	ASTM D4052	806	751	757	765	771
Distillation Temperature, 10% recovery (°C)	ASTM D86	185	158	167	160	162
Distillation Temperature, 50% recovery (°C)	ASTM D86	206	190	186	191	193
Distillation Temperature, 90% recovery (°C)	ASTM D86	246	246	241	248	246
Distillation Temperature, final boiling point (°C)	ASTM D86	268	261	269	268	262
Net Heat of Combustion (MJ/kg)	ASTM D3338/D3338M	43.2	44.1	44.0	43.8	43.7
Sulfur (ppm by mass)	ASTM D5453/D2622	191	<1	<1	1.9	2.1
Smoke Point (mm)	ASTM D1322	24	Not measured	43	45	45
Aromatics (% volume)*	ASTM D1319/D2425	18.8	<0.1	1.7	9.9	9.8
Freeze Point (°C)	ASTM D5972	-47	-45	-55	-59	-56
Flash Point (°C)	ASTM D56	53	40	40	42	40
Kinematic Viscosity @ -20°C (mm^2/s)	ASTM D445	4.6	Not measured	4.2	4.7	4.8
Hydrocarbon Composition Data						
Average Molecular Wt (g/mol)	GCXGC-MS @ UDRI	163	161	169	158	157
Hydrogen content (mass %)		13.9	15.3	15.3	14.8	14.6
Total n-paraffin, mass %		19.5	16.0	9.0	13.9	13.9
Total iso-paraffin, mass %		25.0	76.2	84.3	69.2	66.2
Totoal cyclo-paraffin, mass %		35.3	7.4	5.8	6.7	7.8
Total aromatics, mass %		20.2	0.4	0.2	10.1	12.1
Monoaromatics [alkylbenzenes], mass %		11.9	0.3	0.2	8.5	8.5
Diaromatics [Napthalenes, etc], mass %		1.0	0.0	0.0	0.6	2.5
Cycloaromatics, mass%		7.3	0.0	0.0	1.1	1.2
Additional Physical Properties						
Derived Cetane Number	ASTM D6890	47.4	58.4	43.3	54.8	53.6
Enthalpy of Vaporization (est), kJ/mol	Estimation mthd**	59.1	56.3	58.9	56.3	56.2
Enthalpy of Vaporization (est), MJ/kg		0.36	0.35	0.35	0.36	0.36
Surface Tension -10°C, mN/m	ASTM D1331C	28.1	25.9	25.4	26.2	26.3
Surface Tension 22°C, mN/m		26.2	24.1	23.6	24.4	24.7
Surface Tension 40°C, mN/m		24.8	22.7	22.4	23.2	23.3
Thermal Conductivity 0°C, W/mK	ASTM D7896	0.122	0.125	0.111	0.125	0.125
Thermal Conductivity 10°C, W/mK		0.120	0.122	0.109	0.123	0.122
Thermal Conductivity 20°C, W/mK		0.118	0.120	0.107	0.120	0.120
Thermal Conductivity 30°C, W/mK		0.116	0.120	0.106	0.118	0.118
Thermal Conductivity 40°C, W/mK		0.114	0.116	0.104	0.116	0.116
Thermal Conductivity 50°C, W/mK		0.112	0.113	0.102	0.114	0.114
Specific Heat @ 0°C (J/g/K)	E1269***	1.86	2.17	2.17	2.08	2.09
Specific Heat @ 25°C (J/g/K)		1.94	2.25	2.27	2.16	2.18
Specific Heat @ 75°C (J/g/K)		2.13	2.46	2.51	2.38	2.37
Specific Heat @ 100°C (J/g/K)		2.24	2.58	2.63	2.49	2.50

* Defer to GC x GC "Total aromatics" for more accurate measurement

** estimate derived from avg molecular weight and aromatics mass fraction (R. Xu, H. Wang, M. Colket, T. Edwards)

*** correction factor of 11% increase from base measurement applied. Factor derived from reported deviation of the dodecane standard