2019

The Investigation of Noise, Vibrations and Emissions of Aero-Gas Turbine Combustion with Synthetic Kerosene Fuels

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The Investigation of Noise, Vibrations and Emissions of Aero-Gas Turbine Combustion with Synthetic Kerosene Fuels

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in *Mechanical Engineering.*

By
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Under the mentorship of *Dr. Valentin Soloiu, Professor*

ABSTRACT

Climatic changes from aviation emissions are complex and include effects of greenhouse gases such as: CO2, NOx, and aerosols. For that reason, the objectives of this study were to investigate the noise, vibrations and emissions characteristics of synthetic kerosene combustion in an aerospace gas turbine to reduce the engine's environmental impact. Sustainably produced synthetic kerosene is known for having low soot emissions due to little to no aromatics (compounds that create particle pollutants), and for being a sustainable alternative fuel source to imported oil. The noise and sound levels were collected using Bruel & Kjær microphones to measure various mid to low range frequencies of the gas turbine at the combustion chamber and exhaust plume. A triaxial accelerometer was utilized to measure axial vibrations during combustion, and a MultiGas FTIR Spectroscopy analyzer to measure 25 different species of gaseous byproducts in the exhaust fumes from the turbine engine. Jet A and IPK exhibited similar noise and vibrations characteristics, while the emissions results found that Jet A produced less emissions than IPK, most likely due to variances in the ambient conditions during each collection process. The additional analysis of S8 synthetic fuel and thrust measurements of Jet A, IPK, and S8 can provide a more comprehensive analysis of the sustainability and efficiency of synthetic fuels available for use in the aerospace field. In the future, these results can be validated using combustion and flow analysis simulation of the S-30 model using ANSYS.

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December 2019

Department of Mechanical Engineering
University Honors Program
Georgia Southern University

ACKWNOLEDGEMENTS

I would like to thank my faculty adviser, Dr. Valentin Soloiu, for his guidance and commitment to ensuring my capabilities and knowledge to complete this research and for pushing me to work hard for all of my success and accomplishments. I would also like to thank all of the lab members who have helped me complete experimental trials, especially Cesar Carapia and Aliyah Knowles. Their commitment and contribution to this project was crucial to the emissions system implementation and collection.

I would like to thank the Department of Mechanical Engineering and faculty for their support, guidance, and knowledge they have provided me during my time here at Georgia Southern. Through the good times and the hard, I have found them in my corner, pushing me to succeed by any means possible.

Finally, I would like to thank my friends and family for their continued belief in my ability to successfully push through the obstacles life threw at me and their support of me and my dreams.

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NOMENCLATURE

ASTM	American Standard for Testing and Materials
CPB	Constant Percentage Bandwidth
FAA	Federal Aviation Administration
FFT	Fast Fourier Transform
F-T	Fischer Tropsch
GHG	Green House Gas
GWP	Global Warming Potential
IPK	Iso-Paraffinic Kerosene
NASA	National Aeronautics and Space Administration
PA	Paris Agreement
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
CO	Carbon Monoxide
CO_2%	Carbon Dioxide
CH_4	Methane
H_2O%	Water
SO_2	Sulfur Dioxide
NO_x	Nitrous Oxides
THC	Total Hydrocarbons

1. INTRODUCTION

The objective of this study was to investigate the vibrations and gaseous emissions of synthetic kerosene combustion and its effects on noise, in an aero-gas turbine. The fuel properties of Jet A and Iso-Paraffinic Kerosene (IPK) synthetic fuel were analyzed and compared to experimentally determine noise, vibrations and emissions characteristics.

1.1 EMISSIONS – Sources and Climate Impacts

Greenhouse gasses occur through a multitude of sources, included but not limited to manufacturing, residential, and transportation. As greenhouse gasses are dispersed, they become trapped in the earth's atmosphere. The greenhouse effect moderates atmospheric and surface temperatures; important to sustain life on Earth [1]. In response to the emission of higher-levels of greenhouse gasses resulting from increased human activity over the past 200 years, the United Nations (UN) created the IPCC that assesses scientific, technical, and economic data regarding the effects of climate change [1]. If left unrestricted, the effects of climate change can have serious negative effects such as rising sea levels, coastal flooding worldwide, more droughts and heat waves, an increase in intensity of hurricanes and storms, and more.

International aviation and maritime transportation account for approximately 5% of the global total greenhouse gas emissions and are growing and expected to grow exponentially [2]. In the U.S., The Federal Aviation Administration (FAA) forecasts that the domestic commercial aviation alone will serve over 1 billion passengers yearly by 2021. The FAA also predicted that from 2008 to 2025, the fuel consumption of U.S. based airlines will increase an average of 1.6% per year [1]. Even still, the political commitment to emissions reduction is weak, and faces pushback from major political and industrial companies [2]. Although international legislation like the Paris Agreement (PA) and the Kyoto Protocol (KP), named by the United Nations Framework Convention on Climate Change (UNFCCC), have been put into place, actual implementation and regulation is slow due to difficulties in interaction, coordination, resource allocation, law-making, and regulation of international aviation and maritime transport between different regimes [2].

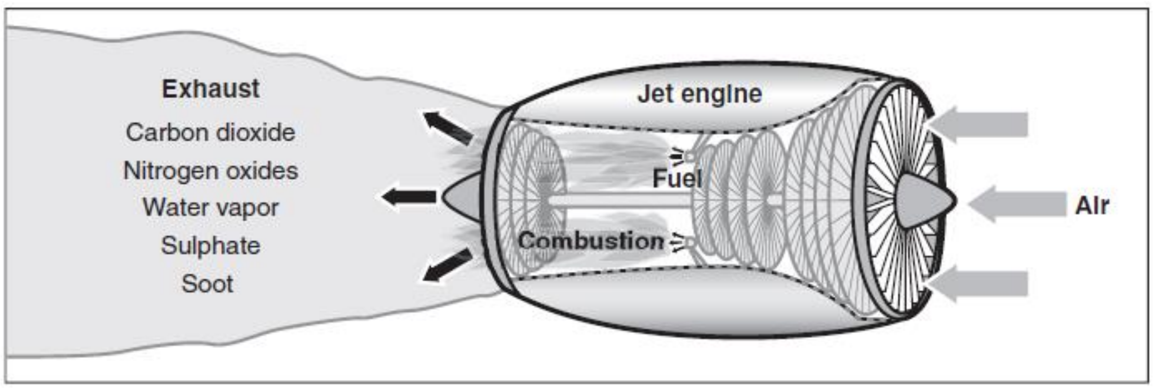

Figure 1. Greenhouse Gas and Other Emissions from Aircraft at Cruising Altitude [1]

Climatic impacts of aviation emissions are complex and include effects from carbon dioxides, nitrogen oxides, emitted aerosols, soot, and water vapor [3]. Figure 1 depicts the types of emissions a jet turbine engine emits at cruising altitude. For every gallon of jet fuel burned, approximately 21 pounds of carbon dioxide are emitted. Similarly, water vapor emissions can lead to the formation of contrails that induce the creation of cirrus clouds; both believed to have a warming effect on the earth's atmosphere [1]. The Global Warming Potential (GWP) of a species of gas was developed to compare the impacts of different gases that affect global warming. By definition, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over, usually, 100 years relative to 1 ton of carbon dioxide [4]. The following explains in further detail the effects and components of carbon dioxide, methane, and nitrous oxide.

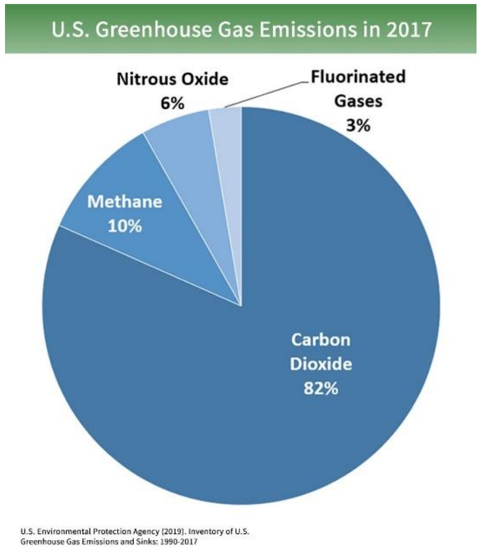

Figure 2. US Green House Gas Emissions in 2017 [4]

Carbon Dioxide, then, by definition, has a GWP of 1, and remains in the climate system for thousands of years. Carbon Dioxide is the primary greenhouse gas emitted through human activities, as seen in Fig. 2, in which 34% and 33% of the total GHG emissions can be attributed to the transportation and electricity sectors, respectively [16]. For every gallon of jet fuel burned, approximately 21 pounds of carbon dioxide are emitted [1].

Aircrafts emit little to no methane directly into the atmosphere, but soot emissions initiate the destruction of methane molecules that create a cooling effect. However, the effect of climate warming from ozone formation outweighs its cooling effects [1]. Methane has an estimated GWP of 28-36 and lasts approximately one decade in the atmosphere [4]. Methane, however, absorbs much more energy; this net effect is reflected in its GWP [4]. Pound for pound, methane has an impact 25 times greater than that of carbon dioxide [5]. Figure 3 below shows methane trends through 2030 for North America as of 2017.

Transportation only accounted for 1% of methane emissions while agriculture and fossil fuel use accounted for 40%, each. Even with mitigation efforts, the overall emission of methane into the atmosphere will not be drastically reduced. More efforts will have to be focused on specific sectors to make a greater difference in methane emissions.

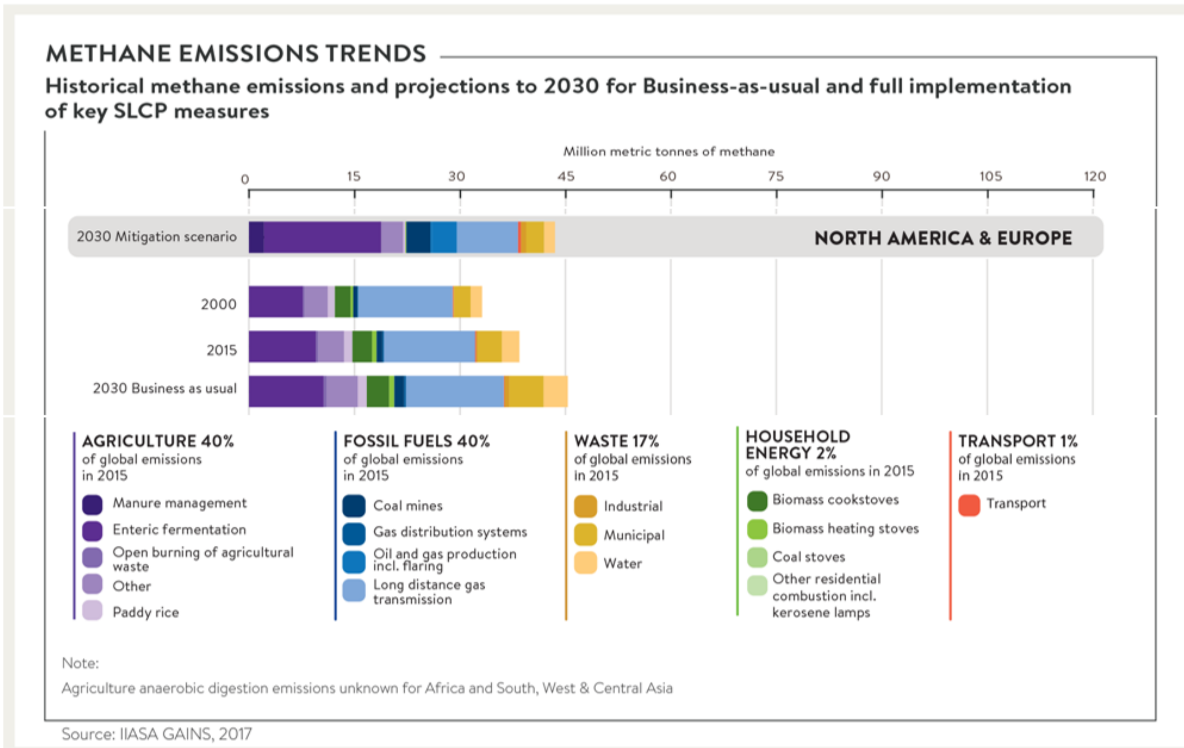

Figure 3. Methane Trends and Projections [6]

Nitrous oxides are produced when air passes through high temperature and pressure combustion, resulting in oxygen and nitrogen combining to form NOx [7]. These emissions do not contribute directly to global warming but affect the ozone that produces a warming effect on the climate [1]. Nitrous Oxide has a GWP of 265-298 times that of carbon dioxide and can remain in the atmosphere for more than a century [4]. The impact of one pound of nitrous oxide on the atmosphere is almost 300 times that of carbon dioxide. The transportation sector is only responsible for approximately 5% of all nitrous oxide emissions in the atmosphere [5].

Water vapor emissions can lead to the formation of contrails that induce the creation of cirrus clouds; both believed to have a warming effect on the earth's atmosphere. Aircraft operations trigger the formation of contrails that cool the climate through increased reflection of solar radiation, but still trap heat, and their magnitude of their effect is uncertain. The same can be said for cirrus clouds formed by aviation; the exact quantifications are unknown and are therefore not included in the IPCC estimations of aviation's contribution to emissions [1].

1.2 FUEL ANALYSIS – Production and General Characteristics

Gasoline is the driving force in the development and magnitude of the petroleum industry and is directly linked to the growth and development of transportation. In the U.S. alone, 46% of oil by volume goes to the production of gasoline, while 31% goes to the creation of distillates for diesel fuel, jet duel, and fuel oils. In 2010, the US consumed 27% of the worldwide demand of jet fuel, averaging to approximately 5.2 million barrels per day [8]. With spikes in the price and consumption of petroleum, economic and environmental interest have also grown.

Currently, there are five certified conversion processes to produce alternative fuels for aviation. The scope of this paper will focus on the Fischer-Tropsch (F-T) process. Alternative fuels can be derived from coal, oil shale, tar sand, plants and animal fats, and offer the potential to reduce aviation's impact on air quality by reducing the amount of pollutants being emitted during combustion based upon their base feedstock and production process [8-9]. Specifically, synthetic jet fuels are derived from fossil feedstock such as coal and natural gas [9].

Synthetic Kerosene is known for having characteristically low soot emissions levels due to little to no aromatics (compounds that create particle pollutants [3]), and for being an alternative fuel source to imported oil. Synthetic kerosene is most commonly derived from the Fisher-Tropsch process depicted below in both Fig 4. Raw material is first gasified to produce a mixture of carbon monoxide and hydrogen (synthesis gas), before that gas is converted to liquid hydrocarbons through F-T processing. The F-T process is the conversion of syngas to paraffinic hydrocarbons in the presence of an iron- or cobalt-based catalyst [10]. These fuels will have similar characteristics, independent of feedstock type. Variations in the fuel properties are associated with operating conditions including the type of catalyst, temperature, and pressure within the synthesis reactors, and the products of that synthesis are treated and processed [10].

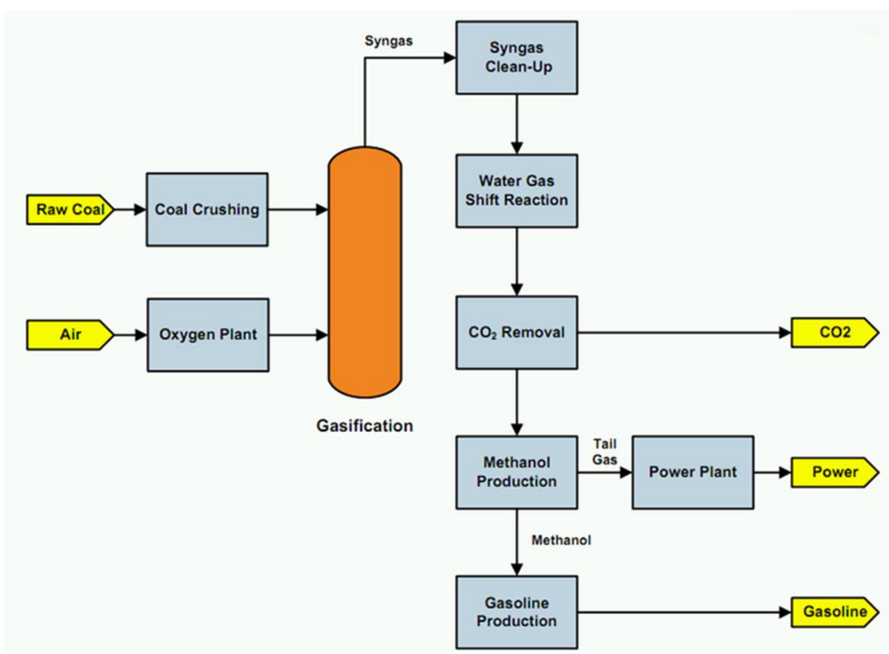

Figure 4. IPK Processing Flow Chart

Fuel properties such as the liquid density, viscosity, surface tensions, and normal boiling point all have an impact on fuel atomization and ultimately combustion efficiency, with emissions being dependent on the volatility and aromatic content of the fuel [20]. According to the American Standard for Testing and Materials (ASTM), alternative fuels should have a heat combustion no less than 42.8MJ/kg, a flash point no less than 38°C, a freezing point no greater than -47°C, and a minimum density of 775kg/m^3 [9]. Table 1 shows specific fuel properties for Jet A, S8, and IPK, with only Jet A and IPK being used in these experiments.

In a report gathered by the FAA, NASA, and Transport Canada, it was determined that F-T fuels could provide aviation with a 10-50% reduction in emissions that contribute to global climate change. Currently, there are six airports that are regularly distribution blended alternative fuels. Still, less than 150,000 commercial flights have used a blend of alternative fuels [11].

Table 1. Fuel Properties [12] [13]

Property	Jet A	S-8	Sasol IPK
POSF number	4658	4734	5642
Composition			
n-Paraffins(wt%)	28	17.7	2.1
Iso- paraffins (wt%)	29	82	88
Cycle-paraffins (wt%)	20	<0.4	9
Aromatics (wt%)	20	<0.1	<0.5
Flash point (°C)	47	49	44
Freezing point (°C)	-49	-59	<-78
Density @ 15°C (kg/m^3)	806	757	762
Viscosity @ -20 °C (mm^2/s)	4.1	4.6	3.6
Neat Heat of Combustion (MJ/kg)	42.8	44.1	44
Smoke point (mm)	21	>43	>40
H/C molar ratio	1.957	2.152	2.119
Molecular weight (g/mol)	142	168	156
Autoignition Temp (°C)	210		

1.3 NOISE AND VIBRATIONS – Types, Sources, and Dangers

Airplane noise is the major noise source that has caused widespread pushback from society because of its negative effects on quality of life. Most noise is generated by the mechanical components of a system caused by forces acting on the components. Noise generated from aircraft generally stem from the engine: specifically, the fan/propeller, compressor, turbine, combustor, and jet exhaust, and from the airframe, including noise generated from airflows around lifting and control surfaces such as flaps, slats, and landing gear [14].

In the U. S., the FAA and NASA are the primary regulators of aviation noise. NASA focuses its efforts on the noise source, such as the aircraft engines and airframes, while the FAA focuses on the impacts of these noises on communities [14]. Airframe noise is generated by an aircraft flying without the propulsion system operating, and is produced from the airflow around the aircraft. Specifically, noise is generated as a result of the landing gear and lift components. The noise generated from these locations is due to the turbulent, unsteady, separated flow around the components [15]. Illustrations of these noise locations on an aircraft and wing can be seen in Fig. 5, below.

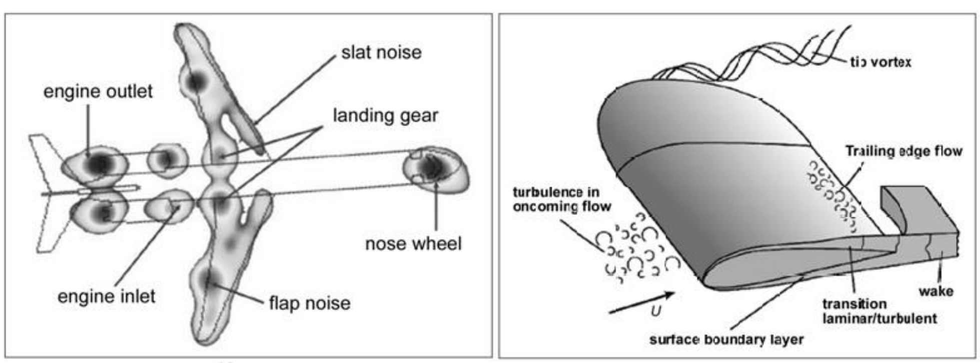

Figure 5. Noise Source Locations on an Aircraft and Wing [15]

Noise produced by the turbine engine is the other main source of noise generation by aircraft. Noise from the engine is produced in all sections including the fan, compressor, combustor, turbine, and exhaust, with the fan and exhaust generating the most noise of all the components [16]. Fan systems produce sounds that can be classified in two categories: tonal and broadband. Tonal sound is a sound of noise recognizable by its regularity, while broadband sound is a noise whose energy is distributed over a wide section of audible range [16]. Figure 6 visualizes the noise generated by the different components of a turbine engine, as well as their magnitude and general direction.

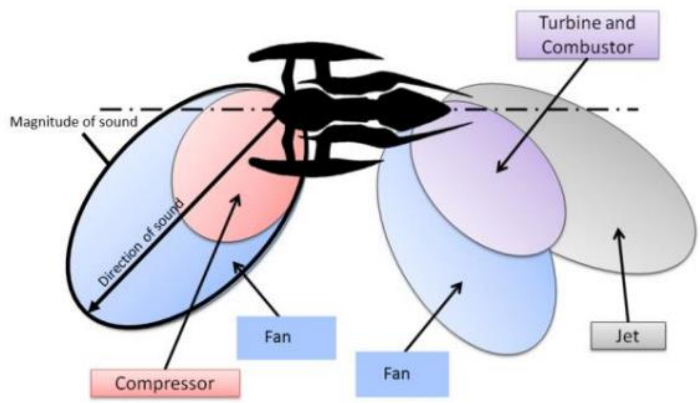

Figure 6. Turbofan engine with Major Noise Components [16]

Jet exhaust noise is a broadband sound caused by the turbulent mixing of the exhaust gases with the atmosphere and is influenced by the shearing action caused by the difference in speeds between the exhaust jet and the atmosphere [17]. As seen in Fig. 7, turbulence at the exhaust exit causes high frequency noises, while the downstream exhaust turbulence creates low frequency noises. Shock waves also form at the exhaust exit due to the velocity of the exhaust exceeding the speed of sound [17].

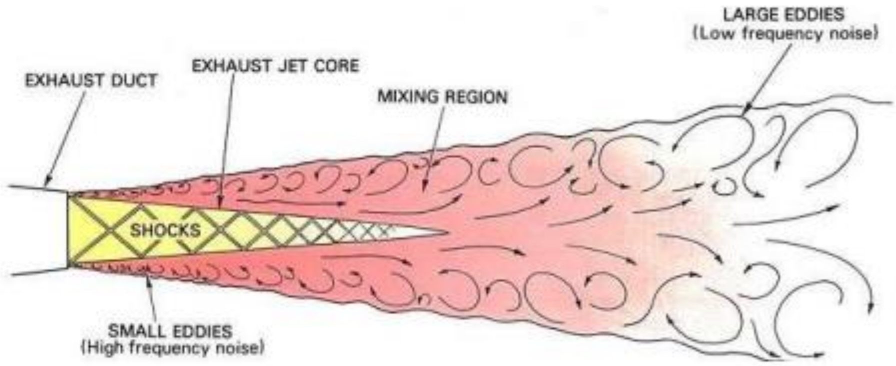

Figure 7. Jet Noise Spectrum [18]

Alternative fuels not only have varying emissions characteristics, but their physical and chemical properties also create a variance in combustion characteristics, which has a direct effect on jet exhaust noise. While there is a plethora of literature detailing combustion using alternative fuels for automotive engines, literature detailing the results in a turbine engine are scarce.

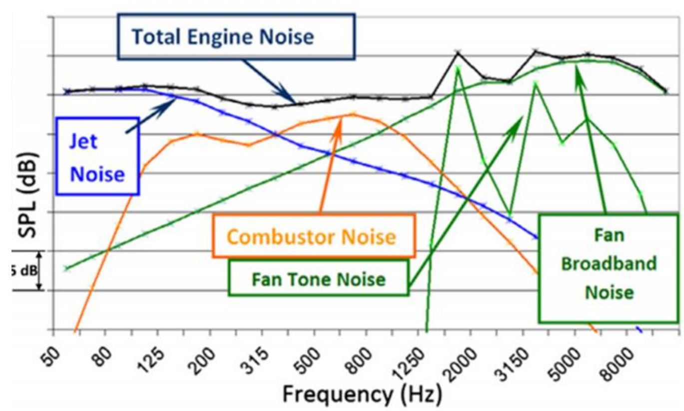

Figure 8. Noise Sources According to their Frequencies [19]

Combustion noise has been identified as the third dominant noise factor behind fan and exhaust noise, as seen in Fig. 8. Direct noise sources can be attributed to the process of volumetric expansion and contraction due to the fluctuations of the heat release rate associated with the chemical reaction of fuel burning in the combustion chamber [19].

Indirect combustion noise is generated when a fluid with a non-uniform entropy or vorticity distribution is accelerated through the engine. Examples of both direct and indirect noise sources can be seen in Fig. 9 below. Danger arises when combustion instability causes pressure waves that reflect at the boundaries of the combustor. Should these oscillations begin to magnify due to self-excitement, high noise levels and severe pressure oscillations can cause structural damage to engine components like fatigue cracking of combustor liners [19].

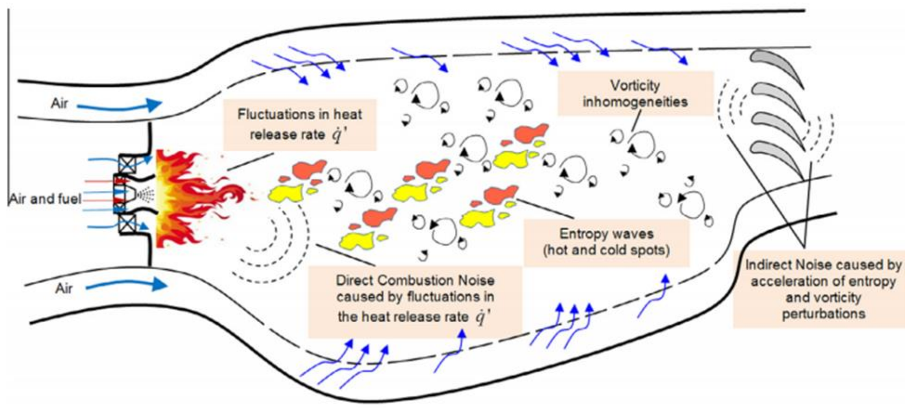

Figure 9. Direct and Indirect Combustion Noise Sources in a Gas Turbine [19]

2. LITERATURE REVIEW

2.1 EMISSIONS – Reduction Analysis

The worldwide supply of alternative fuels to the aviation industry presents multiple advantages including environmental benefits, alleviation of petroleum dependence, stabilization of fuel prices, and economic development in more diverse regions of the globe [20]. Currently, the ASTM has approved five production pathways for alternative aviation fuels, including the Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK).

In a numerical study conducted by [20], a variety of steady-state off-design conditions and transient conditions were investigated to assess the performance and environmental impact of alternative fuel use in commercial aircraft [20]. Results concluded that the alternative fuels improved the engine performance compared to conventional Jet-A, with specific fuel consumption savings of up to 4%. Due to the higher hydrogen-to-carbon ratio of alternative fuels, substantial reduction of soot emissions was seen, as well as a reduction of approximately 10% for NOx. Significant reductions were also seen in CO emissions for a wide range of operating conditions [20].

An experimental study conducted by NASA compared neat and blended versions of FT alternative fuels with standard military fuel JP-8. It was determined that both pure and blended FT fuels not only dramatically reduced soot emissions (reduction in mass of 86% averaged over all powers for neat and 66% for blended) when compared to baseline JP-8 but produced smaller soot particles as well due to the decreased sulfur and aromatic content. It was noted, however, that some benefits of FT fuels may be offset by the increased CO2 emissions during fuel production [21].

While the lower content of aromatics in alternative jet fuels has been a key feature of the fuels content in its capabilities to reduce emissions, it can also pose problems for commercial and military aircraft. Aromatics contribute to the lubricity of the fuel and enhance the material compatibility that prevents leaks in the seals of aircraft [22]. Experiments have found that the lower aromatic content of the pure alternative fuel resulted in insufficient seal swell behavior, and therefore had to be blended with ASTM approved jet fuels to meet requirements for commercial use. Even with the use of the blended standard and alternative jet fuels, a mass reduction of particle mass and number was achieved in terms of emissions particulates [23].

2.2 NOISE AND VIBRATIONS – Mitigation Technologies

For the past 50 years, interest in how aircraft noise affects the quality of life of communities has grown, especially regarding the relationship between environmental noise exposure and the subjective reaction of residents. Other studies, however, have evaluated the effect of exposure on more specific attributes such as increased stress levels, decreased measurements of health, sense of vitality, and mental health, as well as psychological responses to noise annoyance that affects cardiovascular health [15]. Studies have also found that children can be physically affected by aircraft noise exposure, leading to impairments in reading comprehension and long-term memory [16]. Figure 7 below illustrates the magnitude of reaction from communities and their annoyance levels as the average sound level increased. As the outdoor day-night average sound level increased, community reaction and the annoyance level increased. It has been reported in 2017, in Reference [15], that there are no published reports on intervention techniques for individuals.

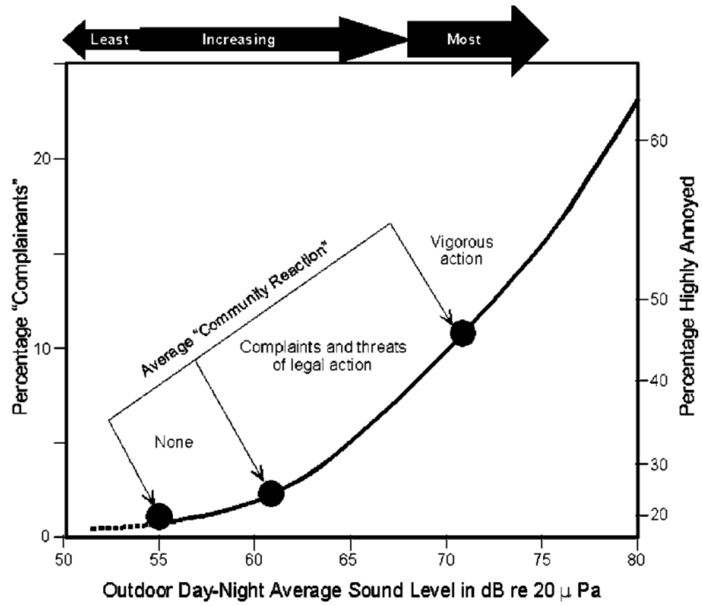

Figure 10. Effects of Noise on Community Reaction [24]

Noise reduction technologies can be classified into two categories: passive and active methods. Passive methods include reducing radiated noise through energy absorption while active control focuses on the mitigation at the source. As previously seen in Fig. 6, fans in the turbine engine are responsible for the most noise during take-off and approach. Some technologies to reduce this noise include scarf inlets, forward swept fans, swept and leaned stators, fan trailing edge blowing, and acoustic treatment. In most cases, implementation of one or more of these technologies resulted in a reduction in noise by at least 10dB [25].

Other technologies include the recycling of vibration and noise energy to reduce noise and vibration pollution. In a study conducted by [26], vibrational energy was converted to electricity through piezoelectricity to then be reused. The principle behind the use of this energy recycling is through converting mechanical energy (vibrations) to electrical energy. According to [26], based on the energy conservation principle, this type of system would achieve noise and vibration reduction in aviation. Implementation of one or many of these systems can help to mitigate noise pollution and hazardous vibrational energy throughout an aircraft.

3. METHODOLOGY

The experimental gas turbine is equipped with five pressure sensors and five K-Type thermocouples throughout the turbine engine, and fuel flow rate transmitters at the inlet and outlet. The locations of these sensors can be seen in Fig. 11. This data, along with the speed and thrust, is collected by a National Instruments analog output (NI6218) and displayed to the MiniLab software for live readings.

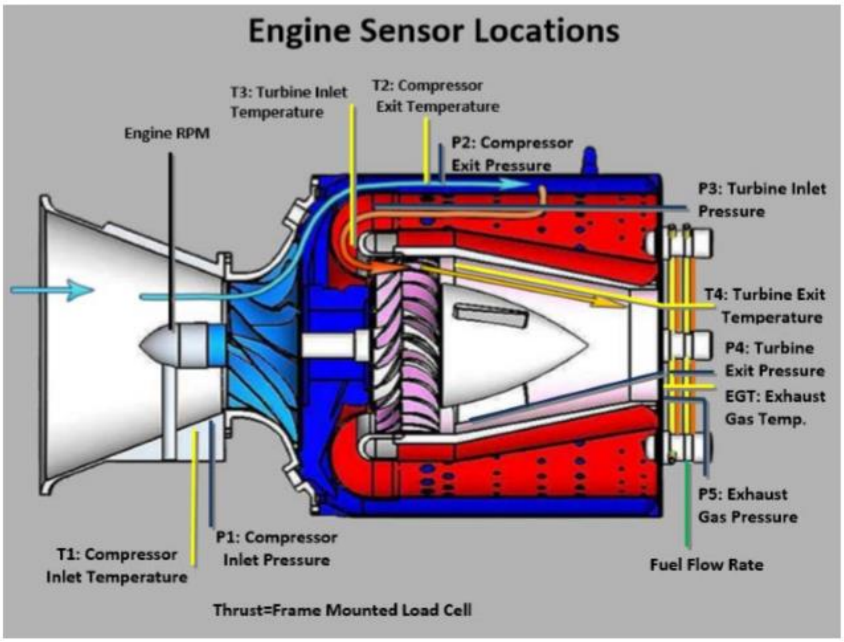

Figure 11. Engine Sensor Locations for SR- 30 Turbine Engine [27]

The maximum operating conditions versus the conditions used in this experiment can be seen in Table 2, below.

Table 2. Maximum and Operating Conditions of the Turbine Engine [27]

	Maximum	**Experimental**
RPM	77,000	65,000
Inlet Temp (°C)	870	160
Exhaust Temp (°C)	720	489
Air Pressure (KPa)	1,103	999
Oil Pressure (KPa)	482	138
Ambient Temp (°C)	41	37

3.1 EMISSIONS – FTIR Spectrometer Setup

To collect emissions, a MultiGas FTIR Spectrometer was used to collect 25 different species of particulates and post process them using the MKS MG2000 software. During data collection, the MultiGas software continuously acquires and processes spectra while computing concentrations of gasses. To achieve conditions within acceptable error tolerances for the MKS to accurately analyze the exhaust gas, multiple steps had to be taken to modify the environment in which the MKS operated in.

An in-house exhaust gas transfer and heating pipe system was designed to allow for the exhaust gas to travel through multiple loops before entering the sampling line of the MKS. As seen in Table 2, the exhaust temperature reached readings close to 489 °C, however, the maximum temperature the gas can be analyzed at is 191°C to prevent the melting of the O-rings sampling line intake valve and due to temperature constraints of the laser housing. Thermal analysis of the piping-system was conducted to determine how many loops the gas needed to travel through before cooling to an acceptable temperature for intake into the MKS.

Additionally, experimental runs had to be conducted during specific weather conditions to ensure the accuracy of the MKS. The standard operating temperatures can be seen below in Table 3. With a dry nitrogen purge, the MKS can be operated between 10% and 90% relative humidity, non-condensing. The humidity levels have been further narrowed down to between 40-60% for the optimal operating range, with 80% being the absolute maximum based upon experimental results from previous runs of our specific MKS.

Table 3. Operating Conditions for the MKS [28]

	Operating Temperatures (°C)
Optimal	20-30 (maximum performance rang)
Extreme	10-32 (loss in signal-to-noise possible)
Optimal Variation	+/- 3 (no loss of performance, minimum baseline drift)

The weather conditions on each day of the run are listed below in Table 4. All tests occurred between the times of 12pm and 6pm, therefore, an average of the humidity levels during just those hours was calculated for more accurate humidity data during the run of the actual experiment. Morning humidity levels are statistically higher than daytime and nighttime, and therefore cause outlier data not accurate to the average humidity during setup, runtime, and breakdown of the experiment. Past weather conditions were collected from Time and Date, a top-ranking website for time and weather and can be seen below.

Table 4. Weather Conditions during each run [29]

DATE	**AVERAGE TEMPERATURE (°C)**	**DAY AVERAGE HUMIDITY (%)**	**AVERAGE HUMIDITY FROM 12PM – 6PM (%)**
November 16, 2018	15.5	83	58
March 7, 2019	15	67	26
April 17, 2019	19.5	74	50

3. NOISE AND VIBRATIONS – Microphone and Accelerometer Setup

To collect noise and vibration data, the immediate surrounding areas were purposed to achieve a free field condition to minimize sound reflective surfaces using Bruel & Kjær (B&K) microphones, as they can adjust to environmental conditions at present. The experiment was conducted outside with no reflective surfaces to disturb the noise collection process and all moving objects (such as people) were removed from the field during noise data collection.

One B&K free field microphone (Type 4189-A-021, 14.6-146dB, 6Hz–20kHz) was used to measure various mid to low range frequencies at the combustion chamber of the aerospace gas turbine at 1 meter away from the engine housing. One B&K multi field microphone (Type 4961, 20-130dB, 5Hz-20kHz) was placed at the exhaust chamber to measure the noise produced downrange of the engine. The microphone taking measurements at the combustion chamber was angled to be perpendicular to the chamber, while the exhaust microphone was angled at approximately 45° from the z-axis of the exhaust, both one meter away from the outer casing of the gas turbine. A schematic of this setup can be seen in Fig. 12.

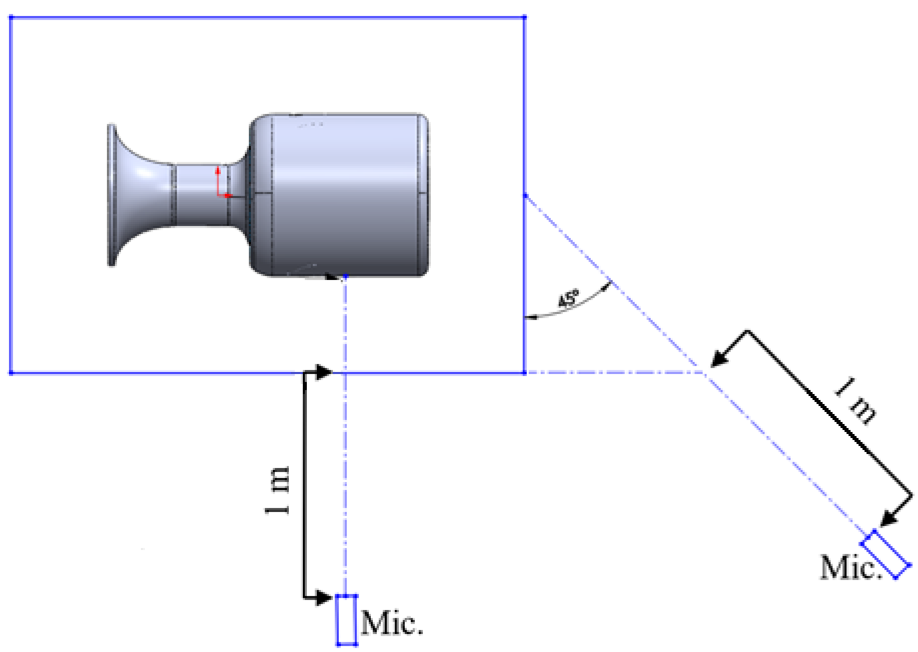

Figure 12. Microphone Experimental Setup Schematic

A B&K triaxial accelerometer (Type 4527, -60-180℃, 0.3Hz-10kHz) was used to measure axial vibrations during combustion and due to mechanical vibrations. The accelerometer was placed on the support plate with the axes positioned so that the x-direction followed the axis of the turbine shaft and remained perpendicular to the ground. Figure 13 shows a schematic of the accelerometer placement and axis orientation.

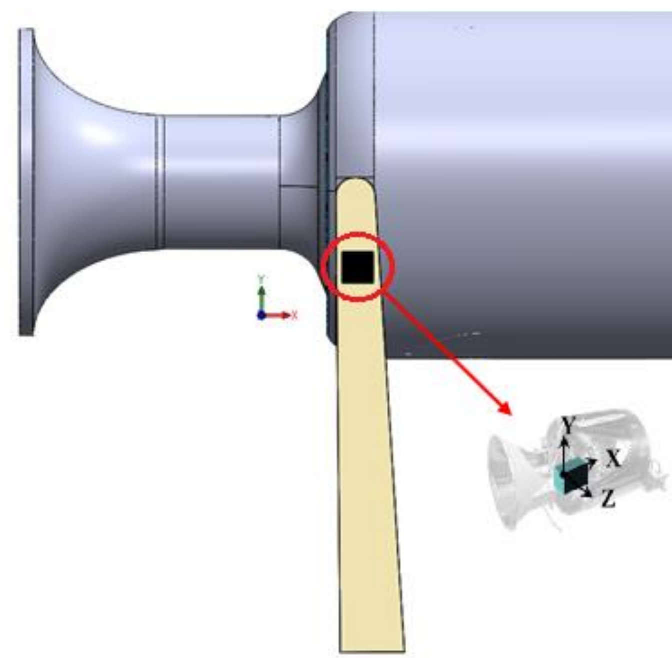

Figure 13.Accelerometer Experimental Placement Schematic

A full schematic of the turbine engine, noise and vibrations equipment, and emissions equipment modified from [30], and their relative locations can be seen in Fig. 14, below.

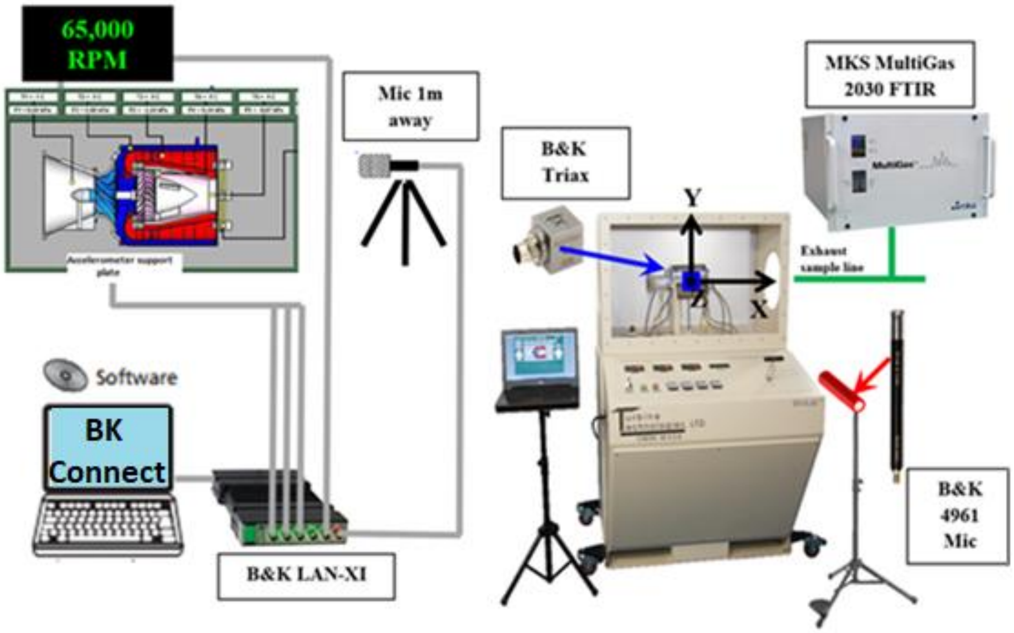

Figure 14. Experimental Engine and Noise, Vibrations, and Emissions Instrumentation [30]

4. RESULTS AND DISCUSSION

4.1 NOISE AND VIBRATIONS – Mechanical and Combustion Analysis

The noise, vibrations, and emissions data of neat Jet A and IPK were recorded and processed to produce the results seen below. From the overall vibrations FFT and CPB, the noise and vibrations produced from the fuel combustion and from mechanical sources can be determined. Two trials of Jet A (conducted during the same run on a single day), and two different runs (conducted on two different days) using IPK were averaged to produce one FFT and CPB curve for Jet A and IPK, each.

Mechanically, there were no differences between the two fuels. As seen in Fig. 15, Jet A combustion produced less vibrations between approximately 4K and 8kHz, with no significant changes elsewhere on the frequency spectrum. For there to be any worthwhile change in noise levels produced, a minimum difference of 3 dB must be seen between the two fuels. There were two areas of difference between the two fuels, as seen in Fig. 16, at approximately 300 and 8K Hz. These differences, however, were not of the magnitude of 3 dB and are therefore insignificant.

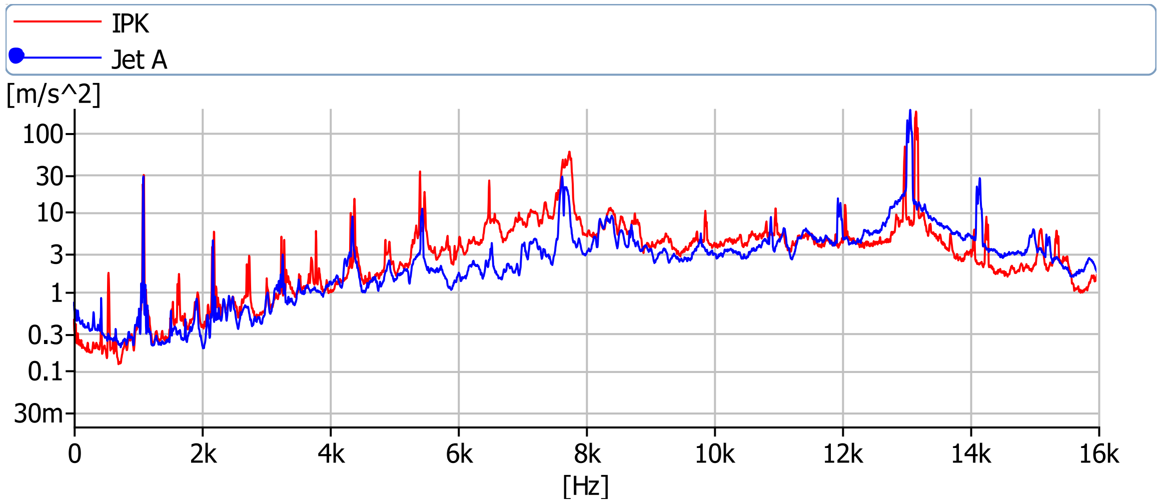

Figure 15. Full FFT comparison of Jet A and IPK

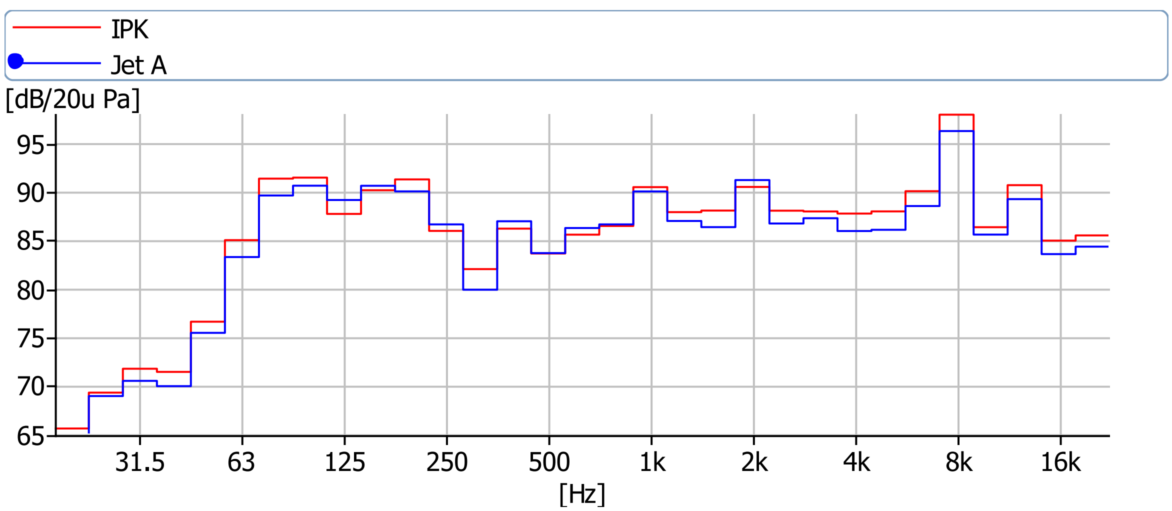

Figure 16. Full CPB comparison of Jet A and IPK

From the FFT graph, Fig. 15, the frequencies of different mechanical components can be determined. Using the conversion rate of 1 RPM being equivalent to 1/60 Hz, the operating frequency can be converted to Hertz as seen below. Due to the symmetry of the engine and its rotation around a singular shaft, this operating frequency can be multiplied by the number of mechanical components, like the compressor blades, present in the gas turbine to determine the frequency at which these components vibrate. The mathematical operating frequencies and the experimental operating frequencies of IPK and Jet A were determined for the rotational operating frequency, the 3 struts on the exhaust nozzle cone, and the 12 compressor blades. These results can be seen in Table 5, below. The experimental frequencies for each mechanical component were within acceptable error ranges to prove accurate. The vibrational peaks of each component have been isolated and shown with their respective values in Figures 17, 18, and 19.

$$Operating\ Frequency = \frac{65K\ RPM}{60\ HZ} = \ 1.083\ Hz$$

Table 5. Mechanical Components of the Aero-Gas Turbine and Corresponding Frequencies

	Calculated Frequency (kHz)	**Graphical Frequency (kHz) Jet A**	**Graphical Frequency (kHz) IPK**
Operating Speed (65K RPM)	1.083	1.088	1.082
3 Struts	3.25	3.266	3.264
12 Compressor Blades	13.0	13.064	12.982

By isolating the peaks of the operating frequency, exhaust cone struts, and compressor blades, the vibrations signature of Jet A and IPK can be fully analyzed. As can be seen in Figures 17, 18, and 19, IPK has two peaks compared to Jet A’s one. This may be due to the autoignition characteristics of IPK and its consequential effect on the vibrations throughout the turbine engine. It is unclear what causes IPK to have two, close range, frequency peaks as these specific frequencies and at other frequencies along the spectrum. Most, if not all, of the double peaks occur after the operating frequency, and are therefore most likely caused by some type of mechanical vibration.

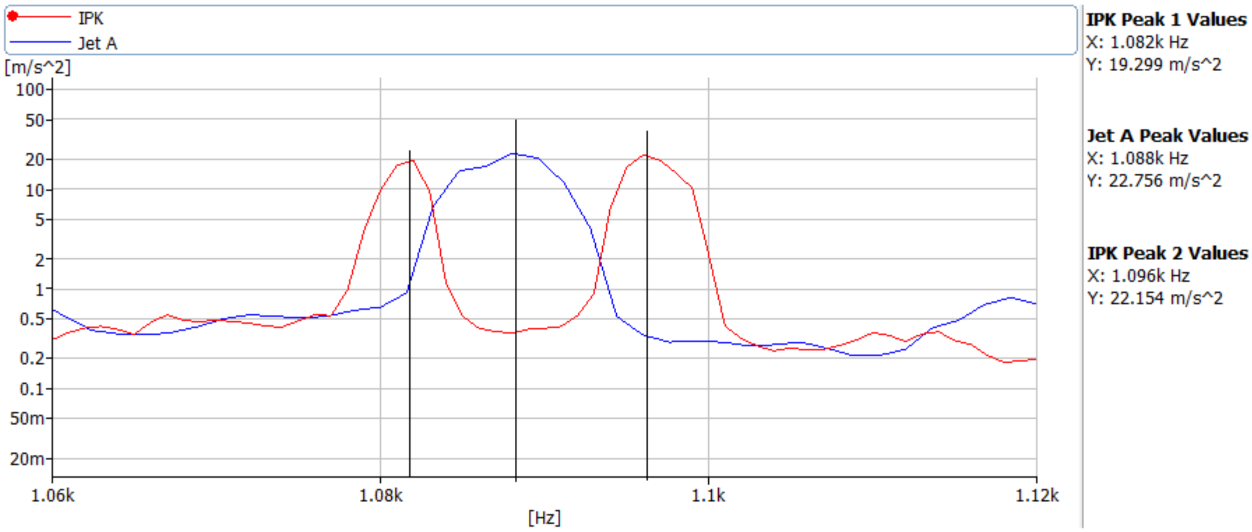

Figure 17. Operating Frequency Comparison of Jet A and IPK

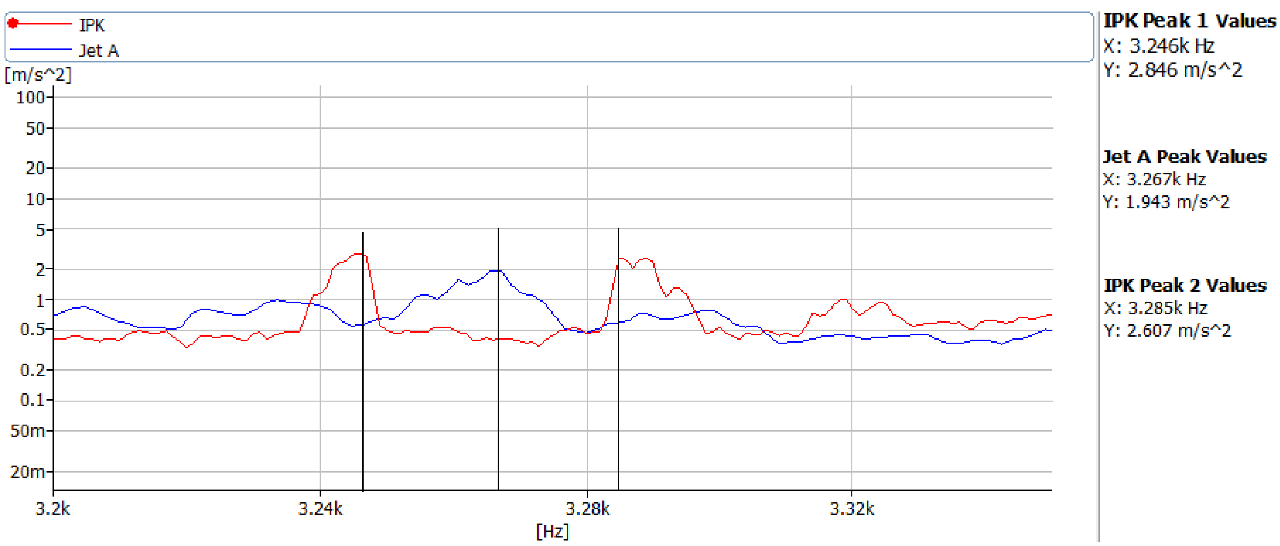

Figure 18. Exhaust Cone Strutt Frequency Comparison of Jet A and IPK

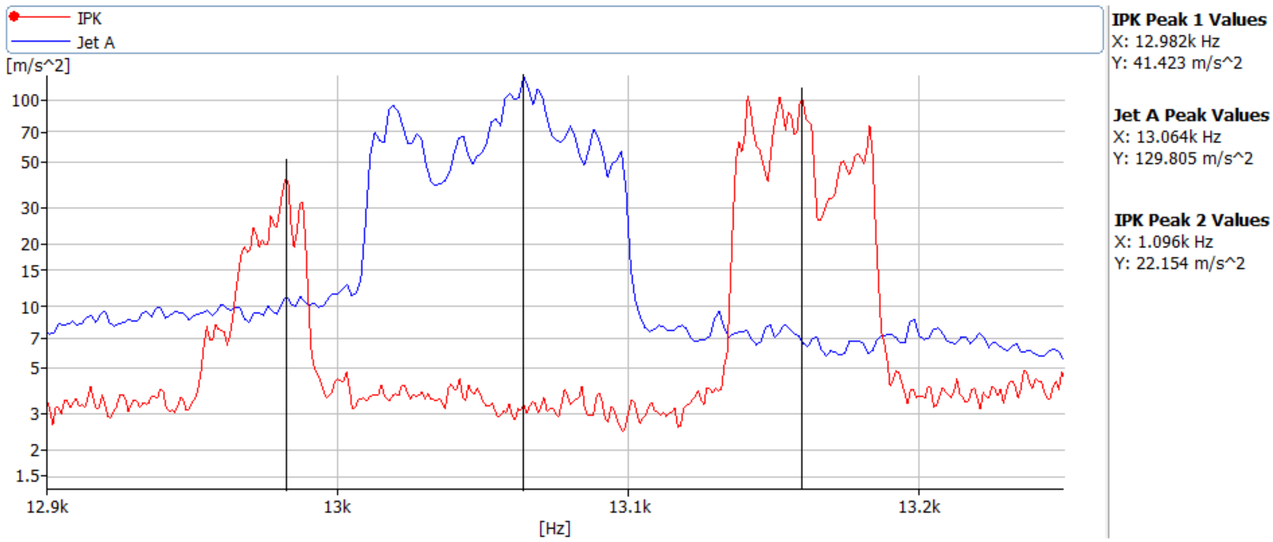

Figure 19. Compressor Blade Frequency Comparison of Jet A and IPK

Combustor noise generally occurs from the 200 to 600 Hz range, as seen in Fig. 17. This range of the FFT and CPB plots were analyzed to better see the differences in the noise and vibrations caused by Jet A and IPK. Jet A caused higher magnitudes of vibrations (Fig. 20) than IPK, meaning that more vibrations were produced during combustion of Jet A than IPK. At 550 Hz, IPK experienced a large spike in vibrations that was not mirrored by Jet A, most likely due to the difference in chemical characteristics of the fuels. This particular area could represent a second ignition event, which could support the theory behind the double peaks as discussed above in Figures 17 through 19. This spike in vibrations, as seen in Fig. 20, however, did not cause an increase in noise. There was no significant difference between the noise produced between IPK and Jet A despite the differences in the magnitude of vibrations that occurred with Jet A, which can be seen in Fig. 21.

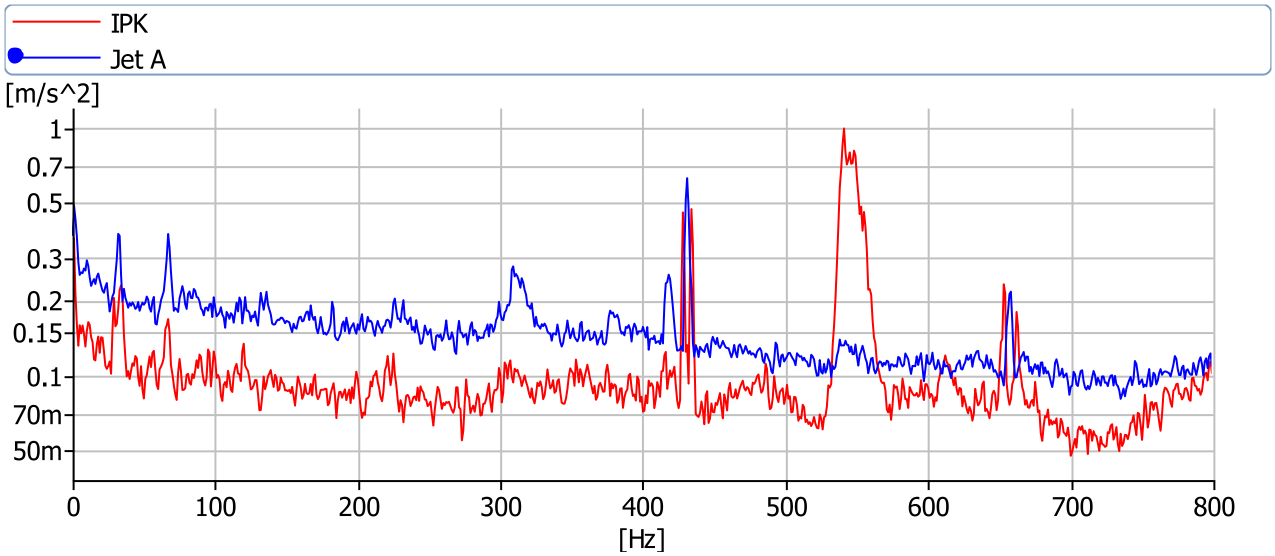

Figure 20. Combustion FFT Comparison of Jet A and IPK

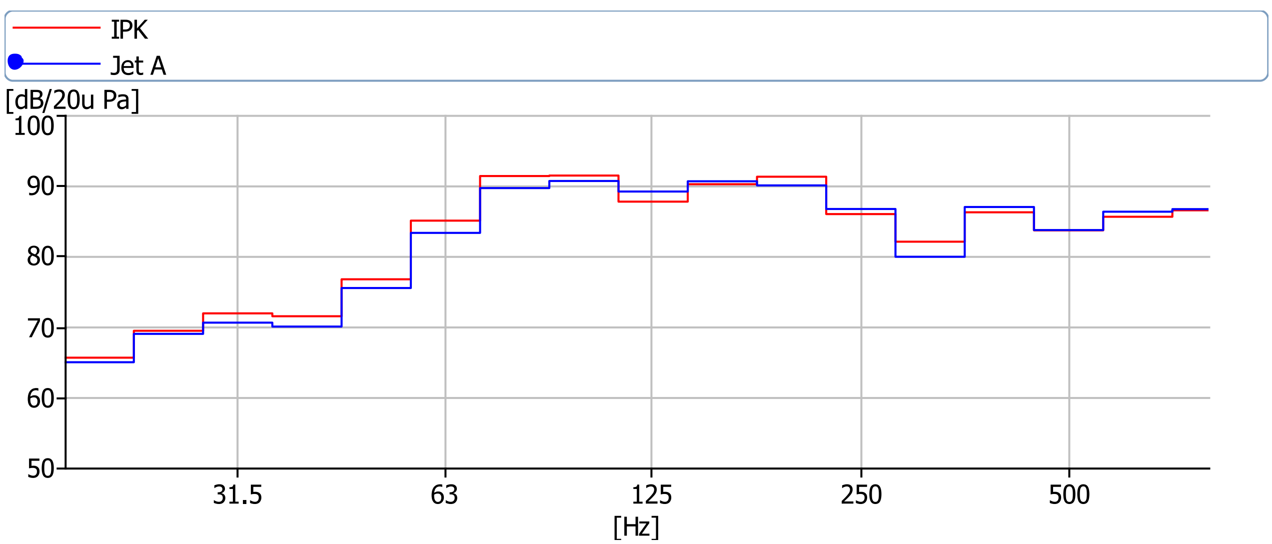

Figure 21. Combustion CPB comparison of Jet A and IPK

IPK was run twice on different days, meaning that the ambient parameters may have varied slightly causing unexpected differences in the emissions, noise and vibrations results. Figure 22 shows the differences during combustion for both IPK trials. Trial 2 showed much more variation in the vibration signature than Trial 1. It is possible that the combustion during Trial 2 was more unstable or experienced greater fluctuations than during Trial 1. More data will need to be collected to determine if this is the case. It is also believed that if the combustion vibrations signatures in Fig. 23 represent fluctuations out of the norm, that the differences in the emissions data collected during the trials of IPK (Table 6) could also represent these vibrational anomalies.

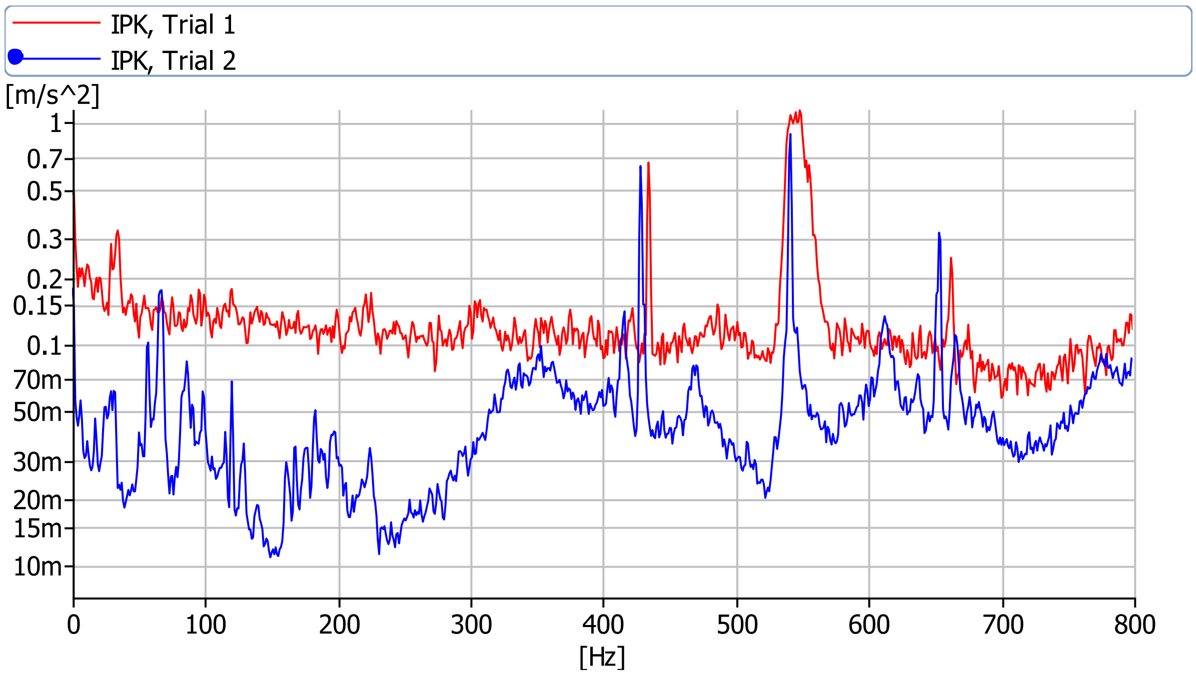

Figure 22. FFT Comparison of both IPK Trials

4.2 EMISSIONS – Particulate Emissions Analysis

The emissions of Jet A and IPK were measured at the exhaust and analyzed using a MultiGas FTIR Spectrometer, and these results can be seen in Table 5. As an alternative fuel, IPK is derived from coal using the Fischer-Tropsch process and is known for having little to no aromatics, at least 19% by weight than Jet A, making it, in theory, a fuel less detrimental to the atmosphere as far as its emission of greenhouse gasses. The specific species chosen for analysis in this experiment were based off literature reviews which designated these compounds as the most crucial to monitor and mitigate in jet fuel exhaust.

Table 6. Emissions Results for Jet A and IPK

Species		Jet A (ppm)	IPK (ppm)		
		Trial 1	Trial 1	Trial 2	Avg
1	H_2O	39300	29900	116100	73000
2	SO_2	6.72	1.32	1.80	1.56
3	CH_4	23.90	39.02	24.57	31.8
4	CO	843.91	814.91	560.41	687.66
5	CO_2	32800	24200	16100	20200
6	NOx	36.76	31.90	67.37	49.63
7	THC	639.88	1019.61	837.79	928.70

The average of both IPK trials were calculated with results favoring decreased emissions highlighted in green, and the IPK results not showing reduced emissions in red. Looking at individual trials, Trial 1 of IPK produced better results than Jet A did compared to Trial 2 VS Jet A. The drastic differences between the two IPK trials have skewed the results to favor Jet A over IPK in 4 out of 7 categories. According to the results, Jet A produced better emissions results in the percent of H_2O, CH_4, NOx, and THC emitted. These experimental results do not correlate with the emissions results found in other literature; more runs of both IPK and Jet A must be conducted to create a greater data pool for more accurate analytical analysis.

5. CONCLUSIONS

This research investigated the differences between Jet A and IPK aviation fuels to analyze the difference in noise, vibrations, and emissions and mitigate their effects on noise and air pollution. Vibrationally, Jet A and IPK exhibited no significant differences in signatures. The same can be said for the noise profile of each fuel, as well. IPK, however, exhibited characteristically different vibration signatures than Jet A during combustion due to its chemical composition and autoignition characteristics.

The emissions of Jet A and IPK showed variability in their magnitudes. With only one trial of Jet A, there is no data to compare and confirm the precision of the results. Two trials of IPK allowed for comparison between each trial, which saw extreme variances. This may be due to the weather conditions at the time of the run, or of possible combustion instability as seen in the vibrations signature for Trial 2. With the data collected, IPK only showed more desirable results in 3 of 7 species. This trend does not follow trends predicted in other literature, which predicted a significant reduction in emissions from IPK. More data must be collected to determine any trends and broaden the data pool for more accurate statistical analysis in the turbine engine.

6. FUTURE WORK

The future of this work continues with the collection of emissions data using Jet A, an IPK to confirm repeatability and the accuracy of the results and incorporate S8 as another alternative fuel. Once that has been achieved, thrust measurements will be analyzed to determine the efficiency of each fuel and make further analytical comparisons of the feasibility and sustainability of alternative fuels. Finally, blends of these fuels will be tested in accordance with ASTM to make further applications to the commercial and military industry. Mitigation and experimentation can then occur to determine solutions and technologies to assist in the reduction of emissions, noise, and vibrations from the fuel and engine.

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