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EFFECTS OF JET FUEL AROMATIC CONCENTRATION ON THE EMISSIONS OF
A T63 ENGINE

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ABSTRACT

This study consists of comparing the particulate matter (PM) from a T63 engine operated with jet fuels containing different aromatic concentrations. A natural gas derived synthetic jet fuel (synjet) was used as the baseline fuel for this investigation. Synjet provided an aromatic-free jet fuel with similar chemical characteristics (hydrocarbon range) as Jet A-1 or JP-8. A blend of three different aromatic solvents was used to replicate the mono and di-aromatic concentration in a typical jet fuel (Jet A-1 or JP-8). The jet fuel aromatic content was varied independently using on-line high precision syringe pumps. The engine was operated at two power settings to study the effects of aromatics at varying temperature and pressure conditions. The particulate emissions were characterized primarily using commercially-available instrumentation to measure particle concentration, size distribution and particulate mass emissions. In addition, PM samples were collected for off-line analysis to obtain information about the effect of the aromatics on the smoke number, carbon composition of the particles and polycyclic aromatic hydrocarbon (PAH) content. Test results for both engine conditions showed a correlation of the PM emissions to the overall aromatic concentration in the fuel. An increase and similar trends were observed in particle concentration, size distribution, mass emission, and smoke number data. The carbon composition data show an increase in elemental carbon for both engine conditions as fuel aromatics concentration increased in the fuel. However, the PAH in the soot samples did not show a clear trend with the exception of pyrene.

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CHAPTER I INTRODUCTION

Background

Studies have shown that particulate matter (PM) poses significant health and environmental risks. Acute and chronic health effects have been linked with exposure to these airborne particles (EPA, 2008). Clinical research indicates that exposure to coarse particles (PM₁₀), PM with an aerodynamic diameter between 10 and 2.5 micrometers (µm), is associated with respiratory aggravation and cardiovascular illness (Neas, 2000). However, there is increasing evidence that the existing PM₁₀ regulation (annual arithmetic mean of 50 µg/m³, 24-hour average of 150 µg/m³) is insufficient to eliminate serious health problems (Englert, 2004, EPA, 2008).

As a result, the U.S. Environmental Protection Agency (EPA) has adopted a revision of the National Ambient Air Quality Standards (NAAQS) for PM to regulate fine particles (PM_{2.5}), PM with an aerodynamic diameter smaller than 2.5 µm (EPA, 2008). The health effects associated with PM_{2.5} range from increased hospital admissions due to respiratory conditions to premature death due to lung and heart diseases (Englert, 2004, EPA, 2008). Despite legal controversies, the U.S. Supreme Court upheld the constitutionality of the EPA's decision on setting new primary standards (health based) to regulate PM_{2.5}.

PM originates from a variety of anthropogenic stationary and mobile sources as well as from natural sources. PM varies widely in chemical composition, form, and sizes.

PM can be emitted directly (primary particles such as soot) or subsequently formed in the atmosphere (secondary particles) by transformations of gaseous emissions of compounds including nitrogen oxides (NO_x) and sulfur oxides (SO_x) (Boudel et al., 1994). Aircraft emissions are comprised of both primary and secondary particles (Siegla & Smith, 1981). Modern aircraft use turbine engines as the propulsion system, which produce small particles (soot) and gaseous emissions that contribute to the air pollution (Petzold et al., 1999). The International Civil Aviation Organization (ICAO) estimated that 7.0 million pounds of solid particles are emitted each year by U.S. aircraft (Penner et al., 1999). Reduction of emissions from aircraft can provide environmental benefits to help satisfy regulatory requirements.

Problem Statement

To assist compliance with the new NAAQS for PM, all pollutant sources, including aircraft, are being evaluated for potential emissions reductions. Aircraft emissions are a growing segment of the transportation emissions inventory. This growth is occurring at a time when other significant mobile and stationary sources are drastically reducing emissions, thereby accentuating the growth in aircraft emissions (FAA, 2008).

Despite the technological advances made during the past 40 years for reducing emissions from aircraft turbine engines, the total emissions of the global aviation fleet have not decreased. This is due to the growth in the aviation industry as a result of the increased demand in global transportation services, which was projected to increase at a rate of three to five percent per year before the September 11, 2001 terrorist attacks (Penner et al., 1999). The aviation community is aware of the need to reduce aircraft emissions and is pursuing a variety of engineering and non-engineering strategies to

provide significant reductions. The engineering strategies have been used to improve the overall combustion efficiency by modifying combustor and fuel nozzle design to improve fuel/air mix and characteristics of the fuel injection (Lefebvre 1980). Non-engineering strategies (chemistry-based) are currently being studied to reduce emissions on legacy and future aircraft by reformulation of the base fuel using additives or blending with a cleaner fuel.

Justification

The United States is the largest consumer of jet fuel in the world, consuming approximately 26 billion gallons of jet fuel per year (Chevron, 2004). As the cost of petroleum crude increases and its availability declines, the available supplies of petroleum-derived fuels might need to include a broad specification or wide distillation range. Bahr (1982) and Lefebvre (1983) suggest an increase in the aromatic concentration in the jet fuel would extend its capacity to meet demand. The effect of this change could enhance the propensity toward PM formation. Though aromatics have been implicated in PM production, large-scale investigation of the dependence of the PM formation on the aromatic concentration is costly and usually not feasible.

This thesis study addresses this need by independently assessing the impacts of aromatic content in jet fuel on particle emission production of an actual turbine engine. Increased understanding on the role of aromatics in the formation of PM would greatly assist in the development of strategies to reduce these types of emissions from turbine engine combustors.

Hypothesis

Based on literature and previous testing, particle emissions will increase as aromatic concentration increase in the fuel.

Goals and Objectives

Goal

Investigate the effects of aromatic concentration in jet fuel on particle matter (PM) emissions from a jet engine. Assess the possibility to reduce PM emissions produced by a turbine engine to help meet new NAAQS for fine particles.

Objectives

- Study the effects of aromatic (mono and di-aromatics) concentration on turbine engine PM emissions characteristics (e.g. particle number density, particle size distribution, and particulate mass concentration).
- Characterize the soot emission samples for determination of smoke number, chemical composition (organic or elemental) and identification of polycyclic aromatic hydrocarbons (PAH) to establish how these are affected as fuel aromatic concentration is varied.
- Develop non-engineering mitigation strategy plan to reduce particle emissions from turbine engine combustors.

CHAPTER II LITERATURE REVIEW

From the 1970's to the 1990's, there were a limited number of comprehensive publications on particulate matter formation in aircraft engines, specifically related to aromatics in fuels. Blevins (2003) wrote an all inclusive paper capturing the most prominent available fuel-studies. She notes that the published papers focus primarily on carbonaceous material (organic or elemental) and examine the effects of alternate fuels on engine soot and smoke. As part of the research, experiments were conducted on several scales, from small test rigs to engine combustor rigs to full scale engines. Most of the fuel-effects studies were empirical in nature and emphasized attempted correlations of global parameters related to sooting tendency (smoke point, smoke number, liner incident radiative heat flux, liner temperature) with fuel properties (percentage hydrogen, percentage aromatics, H/C ratio, volatility, boiling range, viscosity, surface tension, etc.).

The most noteworthy and frequent finding, during this time, was the positive correlation between fuel carbon percentage and sooting tendency. Another important correlating parameter found was the smoke point. However, the effects of aromatic percentage were not as clear. According to some researchers this parameter had no effect, while others established it to have a secondary effect in correlation with the hydrogen content in the fuel. Among other significant findings were the consideration of naphthalene content and the conclusion that the functional dependence of engine smoke on fuel chemical composition changed with engine operating conditions. Also, two debates were initiated due to these publications which concerned the relative importance

of fuel temperature and fuel chemical composition while the other concerned the relative importance of physical and chemical effects in controlling soot formation in gas turbine combustors. The following excerpts are summarized versions of the studies Blevins references that relate to fuel property effects on emissions.

Schirmer (1972) compiled data collected using kerosene with varying hydrogen content in a “Phillips 2-inch combustor” operated at different temperatures and pressures, with temperatures between 800 Kelvin (K) (1000 °F) and 1500 K (2200 °F) and pressures between 0.1 MPa (1 atm) and 4 MPa (40 atm). Four combinations of pressure and temperature were examined to simulate engine load changes. Statistical correlations were provided for the Phillips combustor to predict optical density as a function of temperature, pressure, and fuel hydrogen content. Schirmer was the first of many researchers to show that the sensitivity of sooting propensity of fuel chemistry change with combustor operating conditions

A few years later, Butze and Ehlers (1975) performed a test using a variety of fuels in a JT8D single combustor test rig at different power settings (idle, cruise, and takeoff). They found that at cruise and takeoff, the overall engine smoke number was strongly affected by the hydrogen percentage of the fuel. That same year, Graham et al (1975) published a kinetics paper using shock tube experiments to support the theory that there are two mechanisms through which aromatics can form soot. The theory states that aromatics can either undergo direct condensation chemical reactions or they can break down into small, non-aromatic species that then indirectly form soot. According to the theory, at 1750 °K, the direct route is fast and efficient, while the indirect route is relatively slow. Above 1800 °K, the behavior depends strongly on carbon concentrations

below 2×10^{23} atoms/m³, the indirect route dominates. For higher fuel carbon concentrations, both routes proceed at similar rates. Later, Friswell (1979) called these two routes the paraffinic route and the aromatic route to soot formation.

Blazowski and Jackson performed a series of tests using single T56 combustors (Blazowski 1976, 1978, Jackson & Blazowski 1977). The combustors were operated at both idle and cruise conditions. The hydrogen contents of JP-4 and JP-5 were changed over a range of 9.9% to 15.9% by blending them with xylene and other compounds. Blazowski showed an example of a T56 peak liner temperature increasing about 75 °K (1350 °F) at cruise conditions when the hydrogen percentage (% H) decreased from 14.5% to 12.7%. Because liner temperature (defined as the average of either two or three central panel temperature) was not repeatable for different combustors and conditions, a temperature parameter was defined relative to a reference fuel. The authors found strong correlations between temperature parameter and % H for the T56 engine as well as for other combustors previously examined (J79, JT8D, CJ805, J57): The correlation appeared to be independent of the two combustor-inlet pressures employed-760kPa (7.8 atm) and 860 kPa (8.5 atm). Smoke number for the T56 engine ranged from about 40 to 80 at cruise conditions for % H between 12.7% and 14.5%. The authors noted that all of the combustors tested used pressure-atomizers; the temperature parameters of newer, air-blast-atomizer-equipped combustor showed less sensitivity to % H. The authors also examined the effects of adding different types of aromatics and concluded that % H was the dominant parameter.

Blazowski (1980) used a stirred reactor to examine the sooting propensity of several fuels in a reactor that modeled the primary zone of a gas turbine combustor. The

author varied equivalence ratio in the reactor keeping the air flow constant and found three distinct fuel group behaviors. The first group, containing hexane, cyclo-hexane, n-octane, iso-octane, 1-octene, cyclo-octane, and decalin, behaved like ethylene in that large amount of exhaust hydrocarbons were emitted with no soot. The single ring aromatic group, o-xylene, m-xylene, p-xylene, cumene, tetralin, and dicyclopentadiene, behaved like toluene in that soot was produced at the point of hydrocarbon breakthrough. For this group, the mass of soot emitted as a function of equivalence ratio was similar for all the fuels. The third group, which represent double ring aromatics and was occupied only by 1-methyl-naphthalene, produced soot at the hydrocarbon breakthrough point, generating more soot than the other fuels. Blazowski explained the results in terms of the 1975 Graham model of soot formation from aromatics and aliphatics. Blazowski was open, however, to the idea that an acetylene route for soot production could also explain the results.

In the early 1980's, Odgers also published a notable results relating to fuel aromatic content in Lefebvre's book (Lefebvre 1980). For a variety of engines, the correlation of carbon (soot) formation rate increased rapidly at 20% aromatics and then leveled off. This is in agreement with other researcher's finding that aromatic content must be high (10% -20%) to see an effect on sooting tendency (Naegeli et al, 1983 and Bowden and Pearson, 1983, 1984).

Scientists at Southwest Research Institute (SwRI) published several insightful papers on soot formation in jet engines showing clearly that the sensitivity of sooting propensity to fuel chemical properties varies with engine conditions (Naegeli and Moses, 1978, 1980, 1983; Moses and Naegeli, 1979; Naegeli et al, 1983). These researchers

focused their efforts on a Phillips 2" combustor and T63 combustor test stand. They varied operating conditions extensively in both reactors. Accepting and in most cases re-verifying that fuel hydrogen content or H/C ratio was the primary correlating factor for sooting tendency, these authors examined the changes in relative sensitivity to % H over wide ranges of pressure, inlet temperature, fuel to air ratio, and reference velocity. These parameters could be varied independently in the Phillips combustor, but they had to be changed together in the T63 engine. The parameter they used to represent sooting propensity evolved from a mass concentration derived from smoke number to the radiative heat flux from the flame to relative heat flux from the flame to relative soot concentration determined in-situ using lamp extinction. The SwRI group concluded that soot is formed by gas phase reactions rather than by liquid fuel droplet pyrolysis because their soot results did not depend on fuel physical properties. Their earliest work showed that T63 sooting tendency was proportional to H/C ratio, although the correlation was not linear. Fuel molecular structure was thought to be a secondary effect. Later work showed excellent correlations of flame radiation with %H for varying operating conditions of both Phillips and T63 combustors. Additionally, the authors used their research reactor results to show that low-smoking engines were expected to be less sensitive to fuel chemistry. In a notable SwRI paper, six fuels were blended with various components including monocyclic and polycyclic aromatics to achieve the same hydrogen contents (12.8%) (Naegeli and Moses, 1980). Surprisingly, the fuels with the polycyclic aromatics produced more soot than those with the monocyclic aromatics. Sooting propensity for these PAH-containing fuels was found to correlate with polycyclic aromatics ring carbon percentage. The relative sensitivity to aromatic content decreased

with increasing pressure and with increasing fuel to air ratio. The pressure effect was explained by the enhancement of soot formation from small fuel pyrolysis products expected at high pressure when collisions partners became prevalent. Unexpectedly, test with T63 engine involving the same six fuels showed no effect of polycyclic aromatic carbon content (Naegeli et al, 1983). The authors attempted to explain this inconsistency using the results of another study performed in the Phillips reactor. Fuels were blended to more precisely ascertain the effects of monocyclic aromatics, tetralin, and polycyclic aromatics over a range of conditions. The tetralin and polycyclic fuel blends correlated identically with H/C, while the monocyclic fuels blends showed a different correlation that was less sensitive to H/C. Differences in sensitivity were present only for high concentrations of aromatics (10% in most cases). The authors showed that the dependence of sooting on H/C decrease with increasing inlet temperature and increased with increasing reference velocity. Sensitivity of sooting to polycyclic aromatics content was shown to decrease with increasing fuel to air ratio and increase with reference velocity. The authors explained these effects by discussing the effects of each parameter on fuel pyrolysis and soot oxidation. Naegeli et al. (1983) hypothesized that the relative insensitivity of the T63 combustor to aromatics content could be explained by the T63's high fuel to air ratio and low reference conditions of most engines would show little sensitivity to aromatics content.

There was a series of articles published by researchers at Shell in their Thornton Research Center employing the "Shell Combustor" and a Rolls Royce engine combustor (Bowden et al., 1984, Bowden and Pearson, 1984, 1985). Fuels with varying chemical compositions were examined for a range of operating conditions. Several parameters

normalized by their values for a reference fuel were used to determine sooting tendency-flame radiation, pyrometric flame temperature, exhaust soot concentration determined from emission/absorption spectroscopy. In all cases, hydrogen content and smoke point provide better correlations with sooting propensity than aromatic content. In agreement with the SwRI work, the Shell researchers found that sooting related parameters are more sensitive to fuel hydrogen content and fuel aromatic type for certain engine operating conditions than for others. For example, as air to fuel ratio was decreased from 50/1 to 45/1 and then 40/1, the sensitivity to hydrogen content increased and then decreased (Bowden et al, 1984). The authors explained the result in terms of the fuel carbon concentration in the primary zone according to the kinetic proposal of Graham et al. (1975). At an air to fuel ratio of 50/1, carbon concentrations were low and soot formation rates were correspondingly low. At a 45/1 ratio, carbon concentrations were moderate, so there was strong dependence on fuel chemistry (assuming hydrogen is a marker for aromatic content). At a 40/1 ratio, carbon concentrations became so large in the primary zone that all soot formation reactions proceeded on fuel type. This effect may also explain a similar trend with fuel to air ratio sensitivity discovered by Naegeli and Moses (1980). In another example that supports Graham et al. kinetic model, one study found that fuel naphthalene content strongly affected the correlation with hydrogen content, (Bowden and Pearson, 1984) while another study found that fuel naphthalene had little effect (Bowden et al, 1984). The former study was performed at 0.35 MPa, while the latter was performed at 1.0 MPa. Because of the lower pressure of the former study, the fuel carbon concentration was assumed to be lower-placing the combustion in the regime where the direct aromatic route is fast and efficient identified by Graham et al (1975).

Combustion in the latter study was assumed to be dominated by the high-carbon regime of equal rates for both direct and indirect routes. When a family of heavy fuels (ERBS fuels from Mexican and North Sea and diesel) were outliers on the correlations, producing more soot than the other fuels, nuclear magnetic resonance (NMR) was used to identify the fuel structural features of importance (Bowden and Pearson, 1985). It was found that the outlying fuels contained more aromatic nuclei and fewer saturated side chains than the other fuels.

General Electric examined the performance of several of their engine designs (various versions of J79/CJ805, F101/CFM56, and CF6, along with single annular, double annular, and variable geometry combustors) using fuels of various hydrogen contents (Gleason and Martone, 1980). Tests were performed over a range of operating conditions ranging from idle to takeoff to cruise to dash. These studies primarily used smoke number as an indication of sooting propensity, although one focused on liner temperature (Gleason and Bahr, 1980). All of the GE studies concluded that smoke number correlated with temperature. Newer GE engines with reduced smoke design features like leaner domes and airblast atomizers showed lower sensitivity to hydrogen content than older designs. The newer engines were more tolerant of all fuel property variations than older ones (Bahr, 1982).

Vogel and Troth (1983) empirically tested twelve experimental fuels in the Allison TF41 turbofan combustor test rigs. Smoke number correlated with hydrogen content at all four conditions tested, idle, cruise, dash, and sea level takeoff. Smoke number correlated with aromatic content only for the takeoff conditions. Physical

properties (boiling range, viscosity, surface tension, vapor pressure) did not correlate with smoke number.

Clark (1981) tested seven fuels in a Purdue gas turbine combustion tunnel. Clark examined radiative heat flux from the primary zone as a function of hydrogen content, polycyclic aromatic content, and total aromatic content. Combining that data with a literature study from Naegeli and Moses (1980), the author found the best correlation to rely on a linear combination of hydrogen percent and polycyclic aromatic content raised to a power between 0.1 and 0.4. In a later paper, Clark (1984) added data from Naegeli et al (1983) and reiterated the validity of the linear hydrogen/nonlinear polycyclic aromatic correlation.

Although there were many researchers examining the effect of flame chemistry on sooting propensity, some researchers believed that physical effects were more important. Researchers found it difficult to separate the chemical from physical effects because most of the previous studies had involved varying both parameters. Rosfjord (1984 and 1987) of United Technologies Research Center (UTRC) sought to isolate the chemistry effects from the physical effects by assuring that the fuel was completely evaporated in a series of combustor test cell experiments. The author used empirical modeling to assure that the Sauter mean diameter (SMD) of his sprays was greater than a critical SMD for complete evaporation. A UTRC spray model was also executed to further demonstrate that droplet vaporization would not dominate the experiment. This author tested 25 fuels with hydrogen contents between 9% and 15%, aromatic contents between 0% and 100%, and naphthalene contents between 0% and 30%. Radiative heat flux to the combustor dome was measured and assumed to be proportional to soot loading in the primary zone.

Rosfjord correlated radiative flux with %H, aromatic percentage (%A), and naphthalene content (%N). However, Rosfjord used the radiation trends between pairs of fuels with equal %H, %A, and %N to caution that the correlations were not universal. Rosfjord used regression analyses to develop a correlation that depended on $\%H-1.2$ and $(100-\%N)-0.4$. Obringer (1985) re-examined Rosfjord hydrogen content data using regression analyses in the real plane rather than the log plane, and better correlations were found.

Using logic similar to that of Rosfjord, Rink and Lefebvre (1987) sought to study the physical effects of the spray while keeping the chemical effects constant. These authors demonstrated that reducing the mean drop size in a spray of a given fuel reduces soot formation in fuel-lean mixtures. They made the important point that the local fuel to air ratio, as opposed to the engine fuel to air ratio, was the governing parameter in soot formation.

In 1989, Gulder et al attempted to classify fuels using a procedure more sophisticated than previous ones. Instead of using hydrogen or aromatic percentage, for example, they characterized fuels using proton nuclear magnetic resonance spectrometry. They classified fuels according to carbon types that were expected to have dominant effects on soot formation in combustion, (1) carbons on mono and condensed aromatic rings, (2) carbons at α position to aromatic rings, (3) alkanic CH_2 , CH carbons including $\beta\text{-CH}_2$, CH_3 , and γ , $\delta\text{-CH}_2$ to aromatic rings, (4) C_3 , alkanic CH_3 carbons including terminal and branched and γ , δ to aromatic rings. An empirical equation was developed to relate the carbons type parameters to measured smoke points for the fuels. The authors emphasized the importance of smoke point in characterizing aviation fuels.

Attempts to correlate smoking tendency with fuel chemical properties continued into the 1990's, when Chin and Lefebvre analyzed existing data to recommend that engine smoke number be predicted by combining smoke point (SP) and naphthalene content (%N), in an empirical equation of the form $\{SP-0.92(100-\%N)-0.4\}$. These authors emphasized that the smoke point was a better correlating parameter than the hydrogen content for sooting propensity.

In 1995, Pande and Hardy used data from the Tyne and T56 combustors to evaluate numerous empirical correlations - including the single parameter correlations for smoke point, weight percent hydrogen content, and volume percent total aromatics content. Multi-parameter correlations recommended by Rosfjord, Chin and Lefebvre, and Gulder were also evaluated. Finally, other predictors such as the saturates ratio of noncyclo-paraffins to cyclo-paraffins and weighted monocyclic and dicyclic aromatic concentrations were examined. The authors concluded that the two factors that best correlated smoke data were based on (1) hydrogen content combined with monocyclic and dicyclic aromatic contents and (2) smoke point combined with monocyclic and dicyclic aromatic contents.

Toward the end of 1990's, the attention turned away from global and empirical correlations and move toward application of detailed computer models of gas turbine combustion. In the 2000, early stages of risk management research programs were developing. It appears that the new emphasis on fine particles was focus on risk management research on large sources and combustion sources of various types.

Legal Frame

At Federal level, PM emission became regulated during the Clean Air Act Amendments of 1970, where new legal standards were established as the National Ambient Air Quality Standards (NAAQS). Title I Part A Section 109 established the NAAQS of allowable concentrations in surrounding air for six major pollutants due to environmental and health threats. This section also states the need to make periodical revisions of existing air quality criteria and standards as appropriate. Upon promulgation of a new or revised NAAQS, States are required to submit a recommended list of areas for designation as attainment, nonattainment, or unclassifiable.

The areas not in compliance with the new or revised standard are designated as nonattainment. States are required, by Sections 110 of The Clean Air Act, to submit implementation plans (SIPs). These plans are designed to meet standards by reducing air pollutant emissions contributing to new or revised NAAQS within 3 years of promulgation of the standard. SIPs must detail the steps on how the State will meet with the new or revised standard.

At the state level, Puerto Rico provides a legal framework to deal with environmental issues. The Public Environmental Policy Act of 2004 clearly establishes a public policy that encourages a desirable and appropriate harmony between man and his environment. It also promotes efforts to prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man.

Moreover, Title I Part B Sections 231 of the Clear Air Act, states that study and investigation of emissions of air pollutants from aircraft will be conducted in order to determine the extent to which such emissions affect air quality in air quality control

regions throughout the United States, and the technological feasibility of controlling such emissions. It also states that from time to time, emission standards will be issued applicable to the emission of any air pollutant from any class or classes of aircraft engines which in its judgment causes, or contributes to, air pollution which may reasonably be anticipated to endanger public health or welfare.

CHAPTER III METHODOLOGY

This study consists of comparing the PM emissions from a T63 turboshaft engine operated with jet fuels containing different aromatic concentrations. The purpose of this section is to describe the experimental design, materials, study area, sampling method, instrumentation and data analyses that will be used to accomplish the following objectives:

Study the effects of aromatic (mono and di-aromatics) concentration on turbine engine PM emissions characteristics (e.g. particulate number density, particle size distribution), and particulate mass concentration.

Characterize the soot emission samples for determination of smoke number, chemical composition (elemental or organic) and identification of polycyclic aromatic hydrocarbons (PAH) in the soot sample and establish how these are affected as fuel aromatic concentration is varied.

Develop non-engineering mitigation strategy plan to reduce particle emissions from turbine engine combustors.

Experimental Design

The T63 engine was operated, for a total of four hours, at two power settings (cruise and idle) to investigate the effect of aromatics at different temperature and pressure conditions. (See Table 13) The aromatics was added independently to an aromatic-free synthetic jet fuel (synjet) at different concentrations using high precision syringe pumps to evaluate the sensitivity of particulate emissions to the total concentration of aromatics in the fuel. Particulate emissions from the T63 engine were captured and transported to the analytical instruments via oil-cooled probes installed co-

linear with the exhaust. Heated stainless steel lines were used to transport the sample from the probes to the instruments. Commercially available instruments were used to measure particle number density, particle size distribution, and particulate mass concentration. In addition, particle samples on quartz and paper filters were collected for subsequent analysis.

After an initial particulate characterization of the synjet (baseline) the aromatic blend was added to the synjet fuel using the syringe pump at the following target concentrations: 5, 10, 15, 20, and 25 percent by volume. For evaluation of the 25% aromatic concentration, the blend and synjet were premixed in an external tank due to capacity limitation with the injection pumps. Each sample consisted of three to five minutes of data collected after the engine reached stable condition. Stable engine condition was reached after one or two minutes of adding the aromatic target concentration and no significant fluctuations are observed in the analytical instrumentation.

Materials

Synjet, an iso-paraffinic synthetic jet fuel produced from natural gas via the Fischer-Tropsch process from Syntroleum, was used as the baseline fuel for this study. The synjet provides an aromatic-free jet fuel with similar chemical characteristics and physical properties as commercial (Jet A-1) or military (JP-8) fuel (Edwards, 2004) (See Table 11). To confirm this information, JP-8 and the synjet fuels were analyzed by Gas Chromatography/Mass Spectrometry (GC/MS) to provide quantitative information about the chemical composition of each (See Figure 9). The results show that JP-8 fuel is composed of 16% aromatics, 42% iso-paraffins and 20% of normal paraffins by volume.

The distribution of normal paraffins in JP-8 range from n-octane (n-C8) to n-hexadecane (n-C16), with a higher concentration from n-decane (n-C10) to n-pentadecane (n-C15). The synjet is comprised of zero aromatics, with a higher percent of iso-paraffins (82%) and lower percent of normal paraffins (18%) by volume. Noteworthy, the synjet has the same hydrocarbon range than JP-8, but with almost twice the iso-paraffins and a higher concentration of the lower molecular weight normal paraffins (n-C8 to C11).

For the aromatics, a blend formed by a combination of three different aromatic solvents produced by Exxon (100, 150, and 200) were used. This approach was employed rather than the addition of a single component since the mixture was more representative of the range of aromatic components found within actual jet fuels (See Table 12). To help determine the appropriate ratio of solvents for the aromatic blend previous laboratory analyses were conducted. An extraction of the aromatic components was conducted on two JP-8 samples using high pressure liquid chromatography (HPLC). The extractions were then analyzed by GC/MS to quantify the individual species and to determine the molecular weight distribution of the aromatic components (See Figure 10). Each solvent was also separately analyzed by GC/MS for identification and quantitation of its components. Based on this analysis, the appropriate blend ratio of the three solvents was obtained to provide an overall aromatic distribution similar to that in a typical JP-8. Overall, 25, 53, and 23 percent of the Exxon 100, 150 and 200 aromatic solvents, respectively, were found to provide the best match to the desired distribution without significantly altering the overall volatility of the mixture.

Study Area

A T63-A-700 turboshaft engine was used in this investigation to generate the particulates. The engine is located in a test cell at the Engine Environment Research Facility (EERF) in the Propulsion Directorate at Wright-Patterson Air Force Base, and is used to evaluate turbine engine lubricants, fuels, and sensors in an actual engine environment (See Figure 11). The engine operates as follows: the compressor draws atmospheric air through the inlet, compresses it via six axial stages and one centrifugal stage, and discharges it to two tubes which carry it to the combustor inlet on the aft end of the engine. The combustion gases flow forward through the combustor to two uncoupled 2-stage turbine sections. The gas producer turbine drives the compressor, and the power turbine drives the output shaft, which is connected to a hydraulic dynamometer. The engine will be operated at two conditions, designated as Ground Idle (GI) and Normal Rated Power (NRP) (also referred to as cruise condition). (See Table 13) GI is attained by a fixed fuel control setting and no load on the dynamometer. NRP is attained by adjusting the governor control and dynamometer load to maintain the intra-turbine temperature at 1280 °F (693 °C) and output shaft speed at 6000 revolutions per minutes (rpm). This approach assured the best run-to-run repeatability in these combustion tests.

The synjet was supplied to the engine from a 30-gallon external tank pressurized with nitrogen to feed the engine fuel pump. The aromatics were injected via two ISCO Model 1000D syringe pumps immediately downstream of the fuel flow meter. The required aromatic flow rate was computed from the measured fuel flow rate and the desired aromatic concentration. The syringe pump displacement was then adjusted via a

computer-controlled feedback loop to provide the required flow rate. To ensure a homogeneous mixture, the synjet/aromatic passed through a static mixer and entered the engine's fuel filter, fuel pump and the engine fuel control. The fuel control, in conjunction with the governor, meters the required amount of synjet/aromatic to the engine's pressure atomizing fuel nozzle and circulates the remaining synjet/aromatic mixture back through the fuel pump. Finally, the synjet/aromatic was injected and burned in the combustor using nominally 20-25% of the total engine airflow. For a given engine operating condition, the combined synjet/aromatic flow was held constant.

Sampling Method

Currently, there is no established methodology or instrumentation for measuring $PM_{2.5}$ emissions from gas turbine engines. An industry standard used for ground-based engine PM emissions certification is the smoke number. In this method, a known volume of engine exhaust is passed through a filter. The filter optical reflectance is measured before and after. The change in reflectance is correlated to the quantity of particulate matter collected. However, it has been found that smoke number is largely the results of large diameter particles, and that the contribution of fine particle is minimal. As such, smoke number is considered an unsuitable method for measuring $PM_{2.5}$ exhaust from turbine engines.

In this study, the methodology to be used is utilized and accepted by academia, industry and government organizations for the characterization of particulate exhaust from diesel and turbine engines. Several organizations using these techniques include: The University of Missouri-Rolla (UMR), The University of Minnesota, Air Force

Research Laboratory (AFRL), NASA Glenn Research Center, Southwest Research Institute (SwRI) and United Technologies Research Center (UTRC).

PM emissions from the T63 engine were captured and transported to the analytical instruments via an oil-cooled probe. The probe design is based on an Arnold Engineer Development Center/NASA/UMR design and consists basically of three concentric tubes with three fluid passages. The outermost passage transports the recirculating cooling oil, the middle passage provides particle free dilution air (which is injected into the sample stream at the probe tip), and the center passage transports the diluted sample to the instruments. (See Figure 12)

The probe was installed co-linear with the exhaust duct 10 inches from the engine centerline facing into the exhaust flow in the center and near the exit of the engine to help capture a representative sample coming from the engine exhaust, while avoiding dilution of the sample or contamination from the surrounding air. The exhaust sample was diluted with particle-free (dry) air at the tip of the probe to minimize water condensation, particulate loss, and to prevent saturation of the particulates instrumentation. Due to the high particulate count from this engine only 2-6% of the sample from the exhaust was used (dilution rates of 94-98%). The diluted sample was drawn into the instruments at 10 standard liters per minute (slpm) via a vacuum pump, and the air dilution and sample flows were regulated with high precision flow controllers. To maintain sample integrity, heated stainless steel lines were used to transport the sample from the probe to the instruments. The lines were heated to 50 °C to reduce particle loss due to wall-sample temperature gradients. (See Figure 13)

Instrumentation

Commercially available instruments were used to measure particle number density, particle size distribution, and particulate mass concentration. A TSI Model 3022A Condensation Particle Counter (CPC) instrument was used to provide a count of particle number (PN). The CPC uses an optical detector to count particles from 7 nm to 1 μm in diameter. The detector counts the particles in either the single-pulse mode for number densities of less than 10^4 or in the photometric mode (light scattering) for particle number densities of 10^4 to 10^7 particles per cm^3 . The sample is passed through an atmosphere saturated with n-butanol while the flow volume is rapidly expanded. Condensing butanol on the particles enlarges them to a diameter large enough to be counted by the laser and photo-diode detector. The CPC reports particle counts through an analog or a serial connection to a computer where the data are analyzed using customized software that collects and stores sample data. Data is displayed in tables, which can be exported to Microsoft Excel applications.

A TSI instrument Model 3936 Scanning Mobility Particle Sizer (SMPS) equipped with a Differential Mobility Analyzer (DMA) TSI Model 3081 was used to obtain a particle size distribution ($\#/\text{cm}^3$). This system can measure particles ranging in size from 4-1000 nm in diameter; however, for this investigation the classifier will be used for particle diameters between 4.4-165.5 nm. In the electrostatic classifier, the sample is passed through a bipolar ion neutralizer, which imparts a known charge distribution (positive, negative, and neutral) to the particles. The particles enter a DMA, which contains a high voltage rod charged to provide a precise negative potential. The particles are then separated or classified according to their mobility in the electric field, which is a

function of their size. By changing the voltage in the DMA, the particles can be separated by aerodynamic mobility and quantified using a CPC. The measured PN is then corrected using the known charge distribution. The entire system is automated. Data analysis is performed using a computer system with customized software (Aerosol Instrument Manager Software for SMPS) that collects and stores sample data. Data can be displayed in graphs and tables and can be exported to Microsoft Excel applications.

In addition, a Rupprecht & Pataschnick Tapered Element Oscillating Microbalance (TEOM) Model 1105, was used to provide direct real time measurement of the particulate mass concentration (mg/m^3). The PM-laden sample enters the TEOM and passes through a Teflon-coated filter that is fixed on the end of an oscillating tube inside of the mass transducer. The mass of the filter is increased by the PM deposition, which changes the natural frequency of the oscillation. The frequency is measured by the TEOM every 0.42 seconds. The TEOM is able to report the total mass deposited, and by using a mass flow controller to maintain a constant volumetric flow rate, can calculate the mass deposition rate and PM mass concentration. The filter element compartment is heated, which prevents capturing very volatile organics but also contributes to the noise of the instrument by evaporating semi-volatile compounds such as PAH. Windows-based software (RP1105A) allows control of the TEOM and display of the raw frequency data as well as the calculated mass data. Data reported for every 10 and 60 second averages are normally recorded by the software into an excel sheet that can be manually analyzed.

Furthermore, a custom-built smoke sampling unit was used to collect undiluted particulate samples on paper and Whatman QMA-type quartz filters for subsequent analysis. This included determination of smoke number, carbon composition of the

samples by temperature programmed oxidation and analysis of the absorbed PAH via GC/MS. The smoke sampling unit passes a gaseous sample at a preset flow rate through paper or quartz filter on which soot is collected. In collecting paper filters for smoke number analysis, the standard sample volume was set to 0.25 ft³. For the smoke number measurement, the reflectance of the filter is measured, prior collecting the sample and again after the sample has been taken. The smoke number is merely a function of the ratio of the two reflectances. The equation for determining the smoke number of a filter is where R_{blank} is the reflectance of the blank filter and $R_{stained}$ is the reflectance of the filter “stained” with soot.

$$Smoke\ Number = \left(1 - \frac{R_{blank}}{R_{stained}} \right) \times 100$$

The larger the smoke number, the darker the filter appears. The smoke number can be thought of as a qualitative measure of the amount of particulate matter in the exhaust stream.

The same approach is used to investigate the carbon composition of the samples, but instead of a paper filter the samples are collected using Whatman QMA-type quartz filters. Quantification of the sample is conducted by off-line analysis with a LECO RC-412 Multiphase Carbon Analyzer. During LECO analysis, the particulate is oxidized in the presence of excess oxygen as the furnace temperature is increased from 100 °C to 750 °C at a rate of 20 °C/min. Species that oxidize at lower temperatures (< 325 °C) are assumed to be volatile organic species (e.g., PAH), while those that oxidize at higher temperatures are assumed to be comprised primarily of elemental carbon (e.g.,

carbonatious). The PAH composition on the collected filters is determined using GC/MS.

The technique involves the thermal desorption of adsorbed PAHs from soot samples with subsequent separation and analysis using the GC/MS. This is performed by placing a 2-mg sample sectioned from the soot stained quartz filter into a chromatoprobe. The chromatoprobe is then inserted into the temperature programmable injector of the GC/MS, which is rapidly ramped in temperature (150 °C/min) from 40 °C to 320 °C. This results in the thermally desorption of the PAHs from the quartz filter and PM followed by separation and detection. It is possible to identify and quantify up to 17 separate PAHs using this technique. However, for the purpose of this investigation only nine PAHs were analyzed. Since PAH formation is known to be an initial step in PM formation, this technique can provide significant information about how the relative PM formation pathways and reaction rates are affected as a function of engine condition or fuel type. For this study, this technique will be used to investigate whether the addition of aromatic concentration altered the relative selectivity of the PAHs formed.

Data Analyses

A descriptive statistical approach was used to analyze the data in this investigation. Graphs were employed to summarize, present, and classify the data collected from the analytical instrumentation. In addition, correlations were established to describe the relationship between fuel aromatic concentration and the particle number density, particle size distribution, and particulate mass concentration data. The subsequent paragraph will explain in detail the analysis of the data.

The CPC, SMPS, and TEOM software recorded and analyzed data during the sampling process. The data were then extracted into Microsoft Excel to correct for dilution. For the CPC data, the average PN measurements for the same engine condition were used to build a scatterplot (aromatic concentration vs. particle number density) and then applied linear regression analysis to determine if there was any correlation between the two variables by computing the coefficient of determination (R^2). The same approach was employed to analyze the TEOM data, but using the 60 seconds mass concentration average to build the plot (aromatic concentration vs. mass concentration). For the SMPS data, the particle diameter measurements were used to build a size distribution plots (particle number density vs. particle diameter). In addition, the particle mean diameter data were used to build the scatterplot (aromatic concentration vs. particle mean diameter) then applied linear regression analysis to determine if there was any correlation between the two variables by computing the coefficient of determination (R^2). Smoke number data were used to build a scatterplot (aromatic concentration vs. smoke number) then applied linear regression analysis to determine if there was any correlation between the two variables by computing the coefficient of determination (R^2). The results from the temperature programmed oxidation were used to calculate the percent change of carbon composition (between elemental or organic). Finally, the PAHs mass concentration data were presented in a line chart to help identify any trends in the soot samples.

CHAPTER IV RESULTS AND DISCUSSION

This study consists of comparing the PM emissions from a T63 engine operated with jet fuels containing different aromatic concentrations. Overall, the test results for both engine conditions showed a strong correlation between the particulate emissions and the aromatic concentration in the fuel. The purpose of this chapter is to present and discuss the test results including particle number density, particle size distribution, particulate mass concentration, carbon composition, and PAH analysis. The following paragraphs will discuss the data results in details.

Particle Number Density (PND) and Particle Size Distribution

The PND represent the concentration of particles per cubic centimeter and the size distribution provides information on the number of particles of each size bin (diameters from 4.4 nm to 165.5 nm). Both of them provide insight into the mechanisms by which soot particles are formed and oxidized. The effects of aromatics on PND and size distribution are discussed below.

There was an increase in the PND at both engine conditions relative to combustion with the neat synjet fuel. These trends are in good qualitative agreement with the particle number density from the CPC and particle size distribution from the DMA. A fairly linear correlation can be established showing an increase in particle number density as function of aromatic concentration in the fuel (Figure 1 and Figure 2). Higher absolute particulate production was observed at cruise due to the higher rates of

PAH and soot formation as the result of higher combustion temperatures and pressures; however, a significant increase was notable at the idle condition in the DMA (Figure 3). This could be due to several reasons. Increased soot nuclei, initiated by the increased aromatic species in the fuel, may have passed through the combustor without completely combusting due to the lower temperatures found at idle, or the CPC may have counted fine semi-volatile particles from uncombusted or pyrolyzed aromatic compounds. The particle size distribution for the idle and cruise conditions are shown in Figures 3 and 4. The data indicate that although there was an increase in the total PND with the higher aromatic content, the relative normal distribution shape was not altered. This implies that the aromatics most likely affect the formation of the PM precursors (e.g., PAHs) and soot nucleation, but do not significantly alter the growth mechanism. The shift in the particle size distribution curves to the right as the aromatic concentration increased, suggests that the larger number of particles, underwent coagulation and growth reactions, leading to increases in the mean particle size (Figure 3 Figure 4). It should be noted that the apparent change in the normal distribution shape for the particle size distribution for cruise condition is due to an instrument artifact during the data acquisition. This artifact, however, does not alter the general PND trends observed (Figure 4).

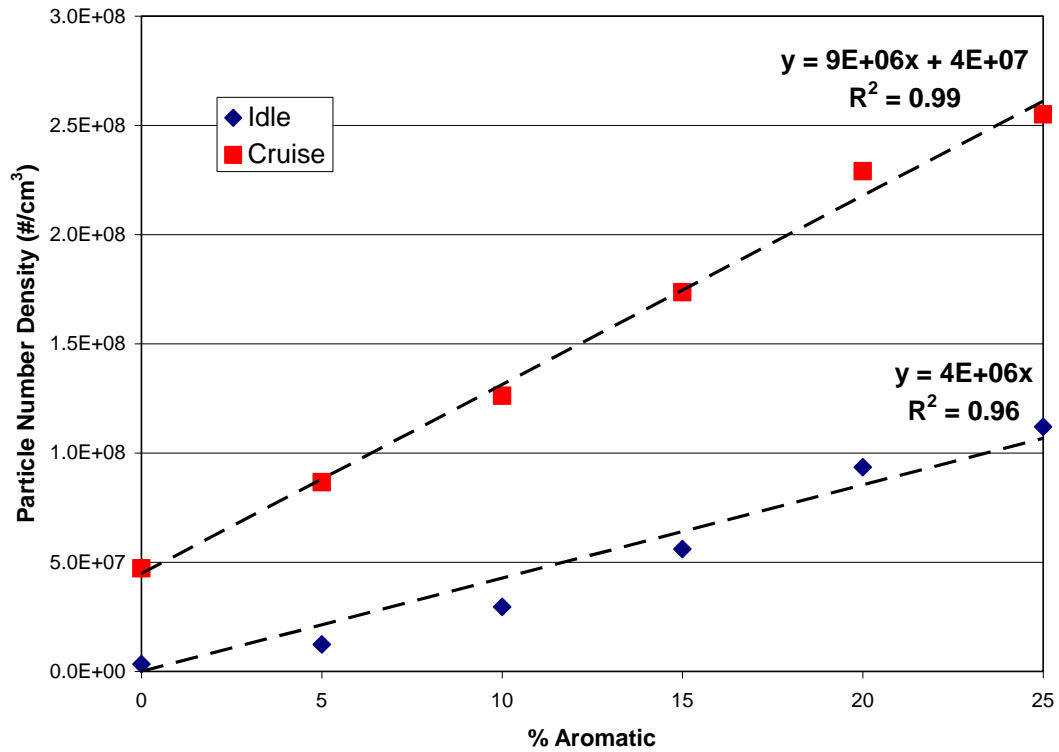


Figure 1. Linear Correlation of Particle Number Density as a Function of Aromatic Concentration

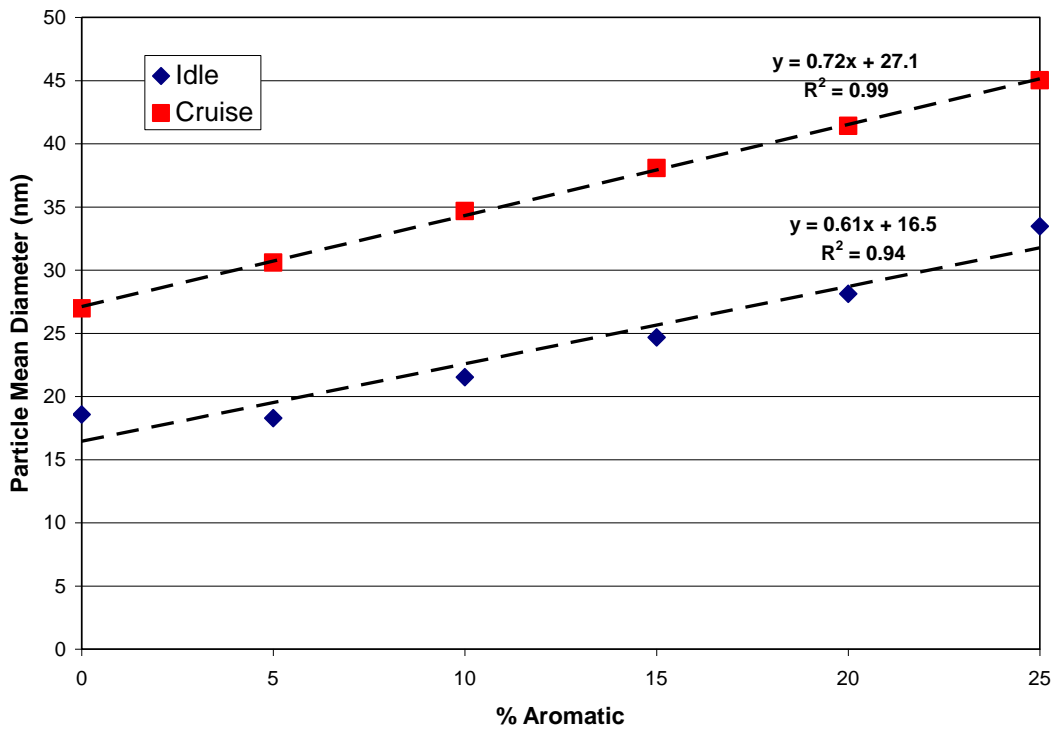


Figure 2. Linear Correlation of the Particle Mean Diameter from the Particle Size Distribution Data at Two Engine Condition with Different Aromatic Concentrations

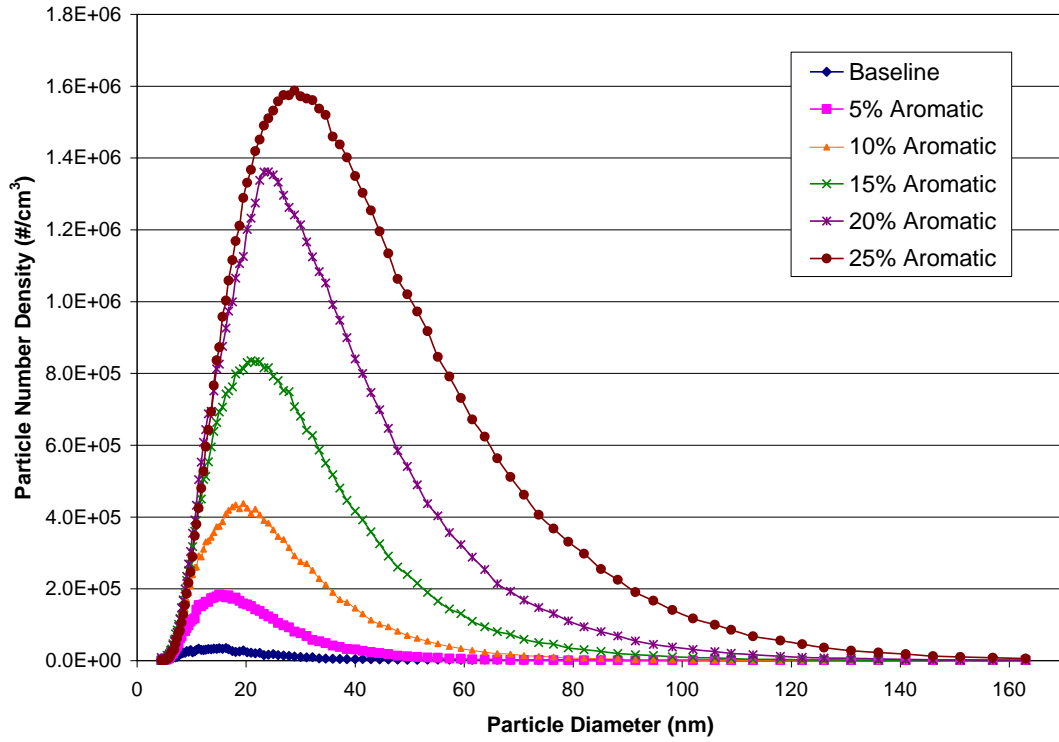


Figure 3. Particle Size Distribution at Idle Condition in a T63 Engine with Varying Aromatic Concentration

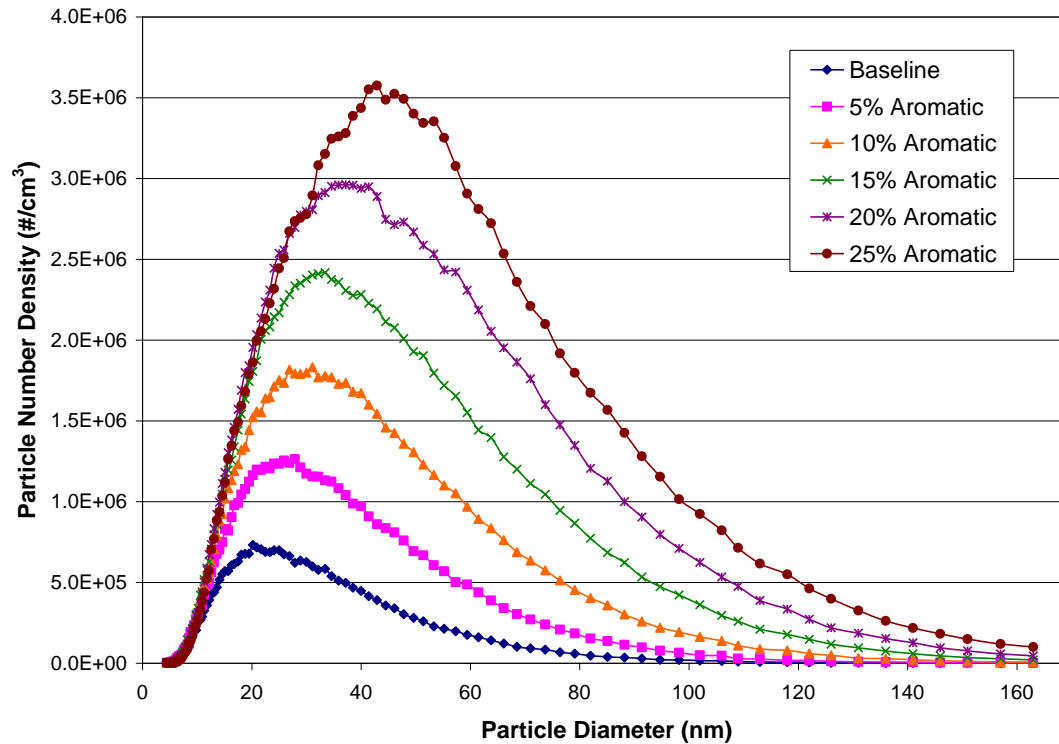


Figure 4. Particle Size Distribution at Cruise Condition in a T63 Engine with Varying Aromatic Concentration

Particulate Mass Emissions

The mass emissions correspond to the concentration of particles in milligram per cubic meter. The particulate mass emissions measured with the TEOM for the different concentrations of aromatics are shown in Figure 5. Consistent with the PND measurements, there is a higher absolute particulate mass emission production at cruise condition due to the higher rates of PAH and soot formation as the result of higher combustion temperatures and pressures. For the idle condition, although increases in mass were measured with increased aromatics, the low particle mass loading on the TEOM filter caused high uncertainty in the measurement and thus, precluded an accurate trend as a function of aromatics. This could most likely be attributed to smaller particle or fine semi-volatile particles from uncombusted or pyrolyzed aromatic compounds; which inherently contribute less to the overall mass than the larger particles.

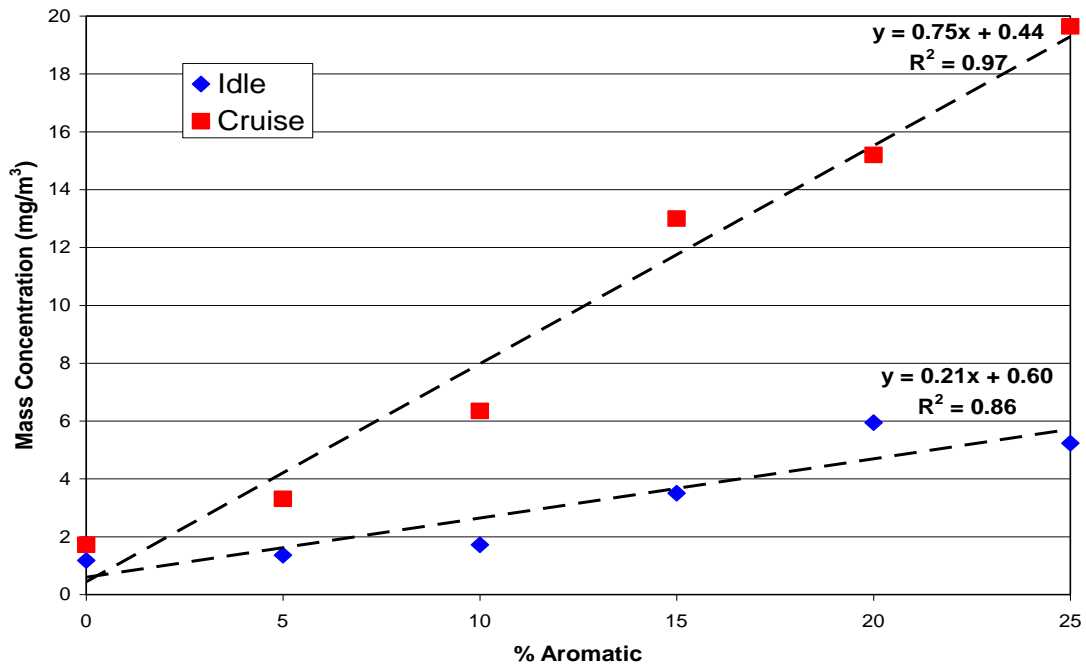


Figure 5. TEOM Mass Measurement as a Function of Aromatic Concentrations

Smoke Number

The smoke numbers as a function of fuel aromatic concentration for both engine conditions are shown in Figure 6. As expected, the smoke numbers were significantly higher for cruise than for idle. The smoke number increased linearly with the aromatic concentration for the cruise condition, and showed significant increases with aromatics at idle. Noteworthy, the trends and regression line of mass emissions as a function of aromatic concentrations are similar to those of the smoke number. These trends are in good qualitative agreement with the PND and particle size distribution data.

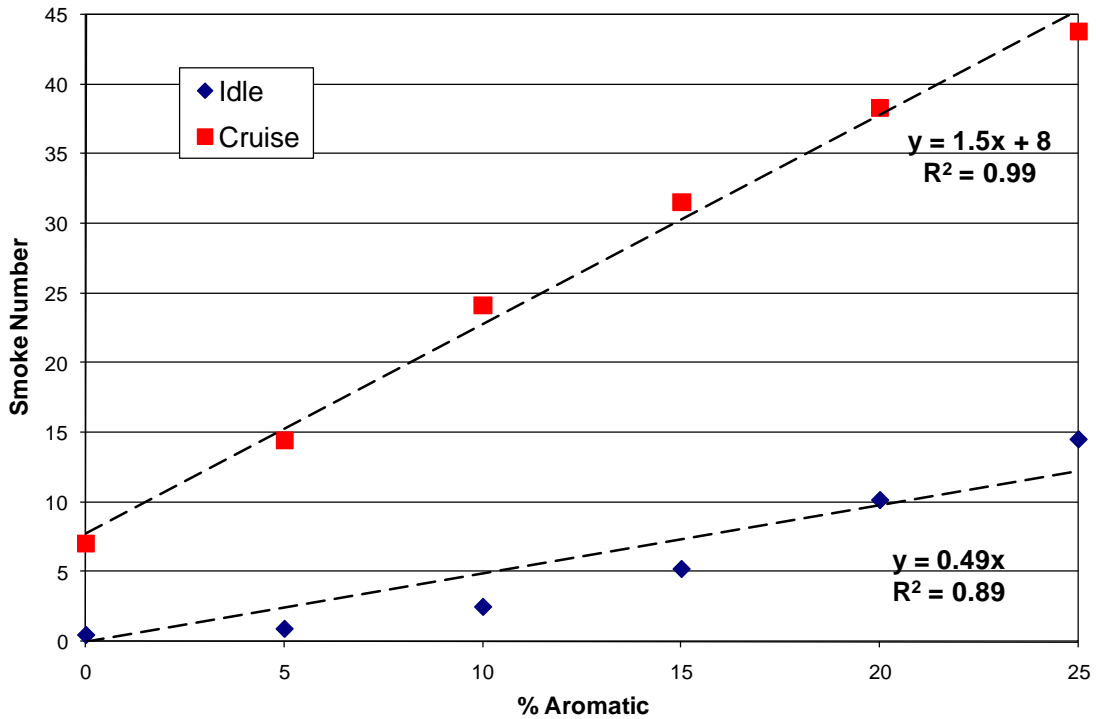


Figure 6. Smoke Number Measurement as a Function of Aromatic Concentrations

Carbon Composition Analysis

The Temperature Programmed Oxidation data help to determine the type of carbon produced (organic and elemental). Soot samples were analyzed in a LECO Multiphase Carbon Analyzer to determine the fraction of organic and elemental carbon in the sample and assess the effect of fuel aromatic concentration on the carbon produced. Figure 7 illustrates the percent of elemental carbon in the soot samples at cruise and idle conditions as a function of aromatic content in the fuel. As shown, the fraction of elemental carbon was significantly higher at cruise than at idle. For the baseline synjet fuel, greater than 60% of the carbon produced was graphitic at cruise while only 20% for idle. Evidently, the higher combustion temperatures at cruise promoted fuel combustion and the dehydrogenation of the soot PM resulting in the increased production of elemental carbon. The increase in fuel aromatics produced an increase in elemental carbon for both engine conditions. Clearly, as the aromatic content in the fuel increased, the dominant soot formation mechanism shifted from the slower aliphatic fragmentation-growth route to the faster condensation reactions of the aromatic species with C₂, C₃ and C₄ hydrocarbons leading to larger PAHs and increased soot and elemental carbon.

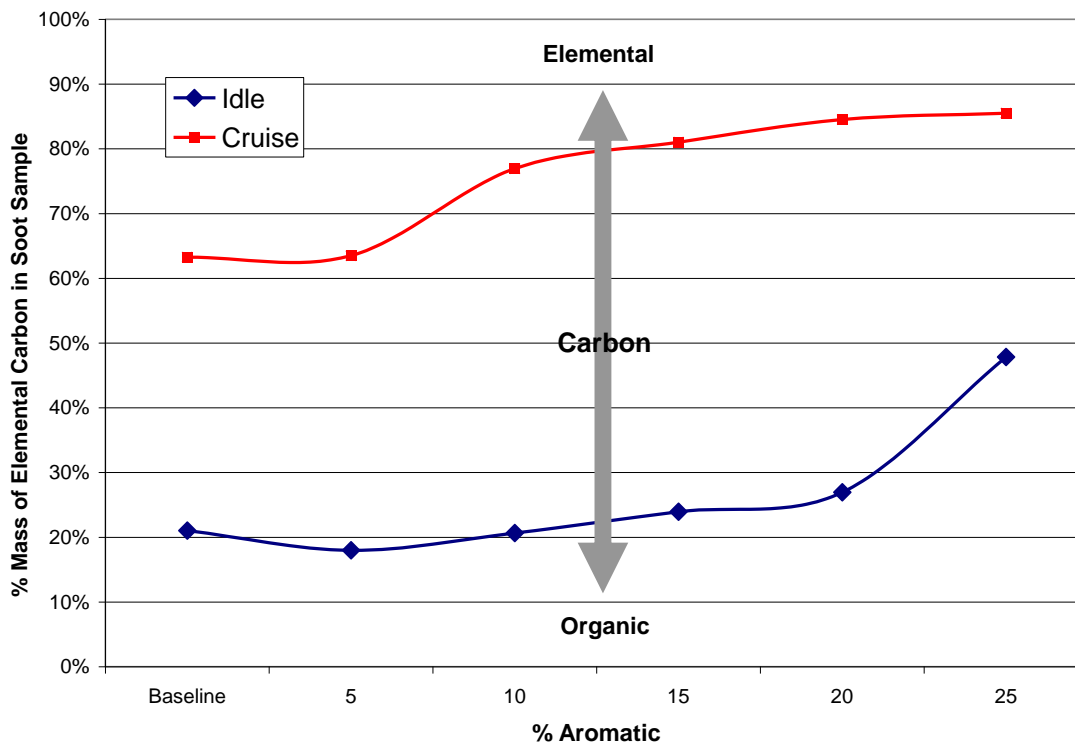


Figure 7. Carbon Composition Analysis Using Temperature Programmed Oxidation for Different Aromatic Concentrations

Polycyclic Aromatics Hydrocarbons

Soot samples were analyzed via thermal desorption and GC/MS to obtain information on the concentration of PAH compounds and evaluate their relation to aromatic content in the fuel. Results displayed in Figure 8, show that for the engine operating with the synjet fuel, the concentrations of PAH in the soot for both engine conditions were negligible (<1 ng). For the idle condition, increases in fuel aromatics produced very small increases (up to ~70 ng) in the PAH content in the soot and no clear trend of PAH content as a function of fuel aromatics was observed. For the cruise condition, higher PAH concentrations were observed with undetectable concentrations of two-ring PAHs (e.g. naphthalene) and only minor concentrations (<50 ng) of three-ring compounds (flourene, acenaphthene, acenaphthylene, phenanthrene). Negligible

concentrations of four-ring chrysene and benz[a]anthracene compounds were detected, while only fluoranthene and pyrene were measured at concentrations larger than 200 ng at the higher aromatic levels. The latter compounds were the only ones to show a trend of increased concentrations as a function of fuel aromatic levels. In general, these results support that the production of PAHs and subsequent soot is slower via the aliphatic fragmentation-polymerization reactions than through condensation and molecular growth reactions of fuel aromatic species. In the aliphatics mechanism, the first aromatic ring must be formed via fuel decomposition products and elementary reactions, while in aromatic containing fuels the aromatics are already present and grow via addition of alkyl groups into large PAH structures and eventual soot nuclei. From these results, pyrene and fluoranthene appear to be the best PAHs to estimate the soot formation tendencies of these fuels. The efficiency of the sampling and analysis methodologies used during this study likely contributed to the low yields of 2-3 ring PAHs.

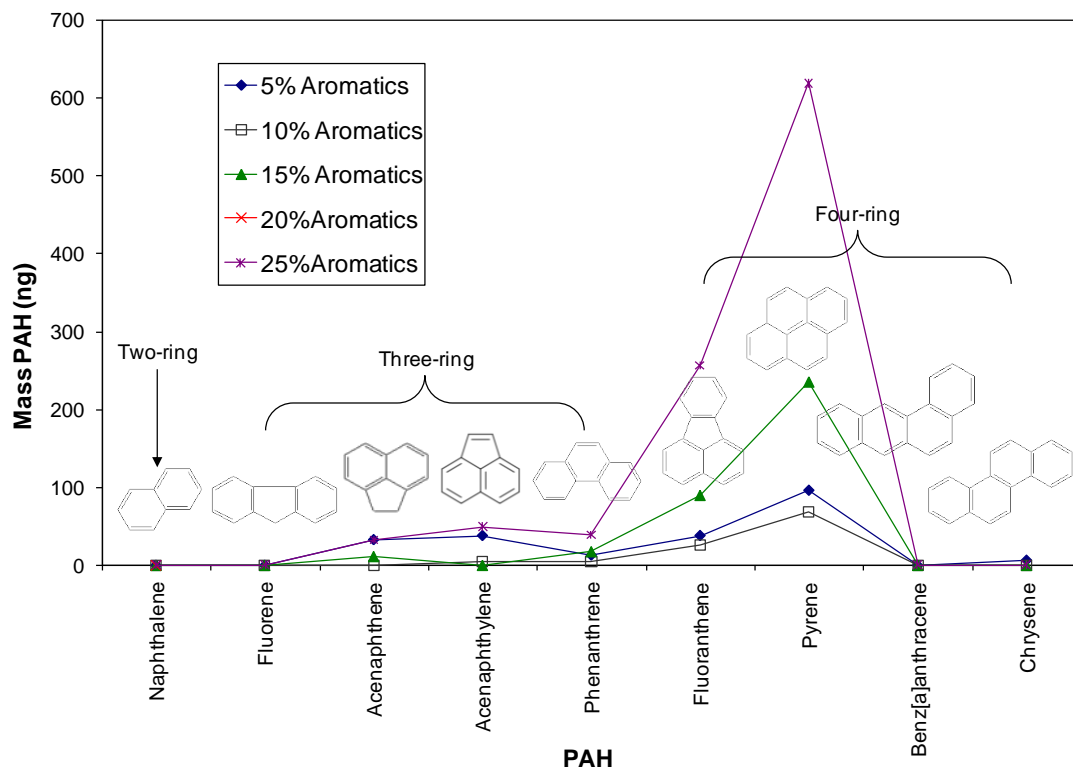


Figure 8. Chemical analysis of soot samples for different aromatic concentrations at cruise condition

CHAPTER V CONCLUSIONS AND RECOMMENDATIONS

The effects of fuel aromatic content on the PM emissions of a T63 engine were studied. As discussed on previous chapters, test results for both engine conditions showed a correlation of the PM emissions to the overall aromatic concentration in the fuel. This chapter presents the conclusions, limitations, and recommendations as a result of this investigation.

The major conclusions drawn from this study are:

- This investigation clearly shows the sensitivity of soot/particulate emissions to aromatic concentration.
- This study demonstrates the influence of aromatics on engine soot/particulate emissions on an actual turbine engine (T63).
- The methodology used in this investigation proved to be effective to measure non-volatile particle from turbine engine.
- This study presents an option for reducing PM emissions from turbine engines by using synjet or other ultra-clean fuels.

Limitations of this study that prevent the generalization of the conclusions are:

- The method used to collect the sample is still experimental.
- Only one subject was tested as part of this investigation.
- The engine was operated at only two engine conditions.
- The samples were not collected at random.

The recommendations for future studies are:

- Develop a more complex experimental design, which include multiple factors, such as different subjects (old and new turbine engines), several engine conditions (take off, cruise, landing, and taxing), and a random matrix to collect the sample.
- Investigate the effect of higher aromatic concentration in the fuel (25%, 30%, 35%, 40%, and 45%) on particle emissions.
- Conduct a material compatibility study to determine if synjet can be used on actual aircraft.

Aircraft engines produce emissions that are similar to other emissions resulting from fossil fuel combustion. However, aircraft emissions are unusual in that a significant proportion is emitted at altitude. These emissions give rise to important environmental concerns regarding their global impact and their effect on local air quality at ground level. Therefore, it is important to start addressing this issue now and not wait until later. The Table 1 shows a non-engineering mitigation strategy plan to reduce particle emission from turbine engine combustors.

Table 1

Non-engineering mitigation strategy plan to reduce particle emissions from turbine engine combustors

Problem or issue	Objectives	Strategy	Responsible organization, office or person	Approximate implementation Cost	Time frame require to implement the strategy	Expected Result
The need to reduce PM emissions from aircraft	Identify no-engineering method to address the problem	a. Legislation to include aircraft as part of the clean fuel initiative	US Congress	\$9 million	10 years	Allocate funding
		b. Develop an implementation plan	FAA, EPA	\$5 millions	6 years	Engine certification program
		c. Evaluate existing alternative fuels or fuel additives suitable for aviation purpose	DOE	\$3 millions	2 years	Down select an additive or alternate fuel
		d. Create fuel standards	Aerospace Industry	\$1 million	2 years	Establish fuel standards

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Table 2

Particle Number Data from Condensation Particle Counter

Engine Conditon	Dilution Ratio	Aromatic Concentration	Corrected Particle No. Average	Std. Deviation
Cruise	98	0	4.75E+07	8.36E+05
Cruise	98	0	4.69E+07	6.47E+05
Cruise	98	5%	8.85E+07	1.62E+06
Cruise	98	5%	8.66E+07	3.28E+06
Cruise	98	10%	1.26E+08	2.32E+06
Cruise	98	10%	1.26E+08	1.68E+06
Cruise	98	15%	1.74E+08	1.95E+06
Cruise	98	15%	1.74E+08	2.75E+06
Cruise	98	20%	2.29E+08	4.27E+06
Cruise	98	20%	2.29E+08	4.35E+06
Cruise	98	25%	2.56E+08	9.64E+06
Cruise	98	25%	2.54E+08	1.22E+07
Idle	94	0	3.39E+06	8.93E+04
Idle	94	0	3.32E+06	5.34E+04
Idle	94	5%	1.23E+07	1.70E+05
Idle	94	5%	1.25E+07	1.72E+05
Idle	94	10%	2.92E+07	3.74E+05
Idle	94	10%	2.98E+07	3.87E+05
Idle	94	15%	5.56E+07	5.71E+05
Idle	94	15%	5.54E+07	5.61E+05
Idle	94	20%	9.32E+07	9.61E+05
Idle	94	20%	9.38E+07	1.14E+06
Idle	94	25%	1.12E+08	6.45E+05
Idle	94	25%	1.12E+08	6.00E+05

Table 3

Particle Size Distribution Data from Scanning Mobility Particle Sizer and Differential Mobility Analyzer

Engine Conditon	Dilution Ratio	Aromatic Concentration	Mean (nm)	Total Conc (#/cm³)
Cruise	98	0	26.6399	5.48E+05
Cruise	98	0	27.3066	5.42E+05
Cruise	98	5%	30.4278	9.85E+05
Cruise	98	5%	30.7449	9.88E+05
Cruise	98	10%	34.8314	1.49E+06
Cruise	98	10%	34.5023	1.49E+06
Cruise	98	15%	38.0481	2.00E+06
Cruise	98	15%	38.1036	2.03E+06
Cruise	98	20%	41.3751	2.53E+06
Cruise	98	20%	41.4571	2.53E+06
Cruise	98	25%	45.1396	2.85E+06
Cruise	98	25%	44.9170	2.88E+06
Idle	94	0	18.4282	3.75E+06
Idle	94	0	18.7184	3.80E+06
Idle	94	5%	18.2606	3.50E+05
Idle	94	5%	18.3118	3.53E+05
Idle	94	10%	21.3364	9.46E+05
Idle	94	10%	21.7108	8.72E+05
Idle	94	15%	24.6509	1.82E+06
Idle	94	15%	24.7048	1.83E+06
Idle	94	20%	28.1456	2.86E+06
Idle	94	20%	28.0895	2.88E+06
Idle	94	25%	33.4888	6.45E+05
Idle	94	25%	33.4606	6.00E+05

Table 4

Particle Size Distribution Data from Scanning Mobility Particle Sizer and Differential Mobility Analyzer at Idle Condition

Diameter	Baseline	5% Aromatic	10% Aromatic	15% Aromatic	20% Aromatic	25% Aromatic
4.45	0	144.7133333	398.1875	398.1875	8189.1925	0
4.61	381.6183333	381.6183333	2289.7125	381.6183333	4640.75	381.6183333
4.78	364.9066667	1824.531667	1995.873333	1459.625	3004.916667	364.9066667
4.96	0	2533.760833	5005.366667	3479.5725	5435.014167	1739.7825
5.14	1542.274167	4455.083333	4931.95	4883.35	4057.891667	1336.4325
5.33	1402.7025	2555.305	6778.525	6778.525	4799.516667	4992.208333
5.52	1530.5925	5953.8	7116.083333	14494.71667	6747.766667	4417.725
5.73	4467.308333	5056	14139.225	13980.10833	10607.05	8093.141667
5.94	2870.825	7291.225	17495.725	19428.75	15520.23333	7578.625
6.15	5042.808333	12967.43333	24177.83333	28006.33333	22286.91667	14902.48333
6.38	7461.841667	16222.83333	33356.66667	32100.16667	28415.5	24508.08333
6.61	8257.066667	20749.75	35434.66667	46982	42723.33333	25499.33333
6.85	10340.65833	26640.66667	46488.5	58197.08333	53565.91667	31123.16667
7.1	9253.175	32042.41667	54108.58333	74261.58333	60602.16667	46674.91667
7.37	10579.2	39232.16667	75962.5	84942.16667	78566.83333	62542.33333
7.64	14488.00833	47512.83333	77254.66667	101148.1667	94669.5	76410.83333
7.91	17921.66667	62196.66667	104175.8333	117500.1667	115250.25	83629.08333
8.2	19660.33333	67551	114429.4167	145904.8333	147131	106053.75
8.51	21859.5	85675.5	128796.25	169376.6667	166775.75	128569.6667
8.82	22100.58333	82011.41667	143223.3333	187217.5	199611.6667	154581.1667
9.14	26470.83333	91015.91667	170320	223242.5	234809.1667	186480
9.47	24918.83333	98842.5	188297.5	250322.5	268731.6667	216547.5
9.82	29394.16667	107994.5	208729.1667	269183.3333	304120.8333	246360.8333
10.2	22935.41667	114528.1667	239237.5	317498.3333	354710.8333	289365
10.6	26005.66667	117918.8333	260038.3333	360123.3333	391214.1667	347430
10.9	29857.91667	141810.4167	260660.8333	390266.6667	432409.1667	379290
11.3	33231.91667	154560.1667	292098.3333	428730.8333	504065	424721.6667
11.8	29948.66667	150951	288765	449833.3333	552647.5	479935
12.2	29496.25	156697.5	310012.5	504850.8333	607669.1667	527254.1667
12.6	30304.75	163440.6667	330477.5	513001.6667	643664.1667	596127.5
13.1	32415.25	163551.5	333873.3333	553531.6667	687470.8333	642032.5
13.6	31828.66667	173427.5	343285	594738.3333	694175.8333	692806.6667
14.1	33271.58333	175551.6667	356340	638117.5	750963.3333	766520.8333
14.6	32965.58333	178580.8333	372520.8333	663080.8333	812465.8333	836390.8333
15.1	34141.66667	183880	373860	692447.5	825474.1667	872460
15.7	32695.41667	182355	386745	705868.3333	875014.1667	957741.6667
16.3	34849.08333	176022.5	408940.8333	742443.3333	925746.6667	1002350.833
16.8	31592.91667	181533.3333	418465.8333	751894.1667	973506.6667	1058495.833
17.5	26529.16667	171969.1667	428187.5	762131.6667	998991.6667	1115353.333
18.1	24270.83333	175640.8333	433629.1667	798376.6667	1065361.667	1168394.167
18.8	25550.66667	166224	423205.8333	807113.3333	1106070	1211287.5
19.5	28177.25	158810.25	437700	812685	1125422.5	1288685.833
20.2	23082.33333	156075.75	424525	830165	1200897.5	1330575.833
20.9	22077.58333	151844.6667	409307.5	835411.6667	1232317.5	1366691.667
21.7	20306.68333	142911.8333	421964.1667	832253.3333	1274564.167	1418581.667
22.5	21526.11667	137911.9167	406284.1667	832134.1667	1337348.333	1451150
23.3	15085.925	129612.0833	390208.3333	815355.8333	1360830	1489955
24.1	16264.30833	122934.1667	382780	816047.5	1361413.333	1510047.5
25	17974.94167	116162.1667	364195	791722.5	1353053.333	1531810.833
25.9	15041.59167	104794.75	345919.1667	780120.8333	1332425	1557720

Continuation of Particle Size Distribution Data from Scanning Mobility Particle Sizer and Differential Mobility Analyzer at Idle Condition

Diameter	Baseline	5% Aromatic	10% Aromatic	15% Aromatic	20% Aromatic	25% Aromatic
26.9	14299.28333	98005.58333	337030.8333	752359.1667	1295792.5	1575202.5
27.9	12949.49167	92428.33333	314774.1667	748952.5	1262213.333	1574605.833
28.9	11539.28333	80494.83333	292238.3333	707280.8333	1240995	1587126.667
30	9953.858333	76069.91667	275984.1667	680426.6667	1214034.167	1571781.667
31.1	8882.766667	68054.41667	270323.3333	641823.3333	1166009.167	1565282.5
32.2	9518.633333	57610.08333	251289.1667	627060.8333	1124295	1561069.167
33.4	6154.816667	53551	228638.3333	586330.8333	1083444.167	1537194.167
34.6	5645.041667	48611.08333	211375.8333	550022.5	1051952.5	1519496.667
35.9	4956.441667	41727.75	190200	517840	991170	1459432.5
37.2	4585.416667	37916.25	170413.8333	480434.1667	947902.5	1437269.167
38.5	4151.391667	32404.83333	161572.5	446119.1667	899328.3333	1401330.833
40	4052.8	31224.66667	146289.25	415937.5	839970.8333	1349520.833
41.4	4675.908333	26792.58333	130297.3333	391805.8333	799559.1667	1302871.667
42.9	3695.641667	23857.41667	112813.9167	358550	746622.5	1253766.667
44.5	3128.925833	20865.25	101699.5	325219.1667	698710.8333	1195592.5
46.1	3239.091667	17853.08333	94191.08333	290963.3333	646918.3333	1133815
47.8	2865.4	13627.2	81537.33333	260775.8333	584601.6667	1062798.333
49.6	2530.604167	11747.90833	70010.5	240206.6667	540515	1019834.167
51.4	2465.858333	10062.84167	62279.25	215325	489216.6667	972010
53.3	2943.158333	8460.15	53869.25	189761.6667	436817.5	917644.1667
55.2	2741.4	7800.125	46696.16667	165572	403051.6667	845886.6667
57.3	2557.079167	5382.966667	39246.33333	143768.5833	356480.8333	791049.1667
59.4	2463.558333	5004.675	33736.16667	130700.75	323161.6667	731551.6667
61.5	2057.775	3542.366667	28550.75	109209.75	288007.5	671809.1667
63.8	2724.15	2964.383333	23524.25	94064.25	253640.8333	623407.5
66.1	2258.391667	2783.541667	19672.25	80732.83333	214259.1667	563436.6667
68.5	1862.8975	1904.041667	17954.75	72610.83333	192900.8333	511290.8333
71	1826.125	1410.520833	13988.51667	59436.25	168703	461961.6667
73.7	1442.174167	1606.4025	11937.66667	50415.91667	147590.6667	405951.6667
76.4	1795.250833	999.6716667	10040.89167	45825.66667	130555.5833	367585
79.1	1893.1225	815.1983333	7594.266667	35730.41667	110456.5833	330954.1667
82	1118.234167	529.8583333	6753.175	30393.08333	94340.08333	297649.1667
85.1	1676.7675	493.8241667	4804.8	25244.91667	80530	255110
88.2	1456.335833	429.965	4399.758333	19954.41667	68602.41667	224998.3333
91.4	1416.955	243.3283333	2653.05	16343.78333	54742.25	190445
94.7	1193.803333	285.9416667	2582.758333	14139.23333	45139.33333	166668.25
98.2	929.4241667	197.3781667	2047.080833	10904.925	38047.08333	141077.75
102	922.225	299.75	1461.774167	8384.116667	30939.08333	117502.3333
106	892.8191667	149.1520833	1257.025	7328.983333	24939.41667	100053.75
109	711.5866667	118.74875	784.8433333	5375.425	20172.25	85782.25
113	761.0483333	89.045	675.8041667	3460.816667	16158.29167	67645.83333
118	607.8416667	0	672.6825	3270.966667	11940.20833	55792.75
122	467.0191667	29.53391667	585.155	1958.341667	9220.333333	45861.75
126	531.5081667	0	274.2316667	1771.4625	7558.483333	35873.83333
131	531.404	0	396.385	1307.244167	6173.958333	27382.5
136	128.4323333	0	156.0346667	822.3025	4503.675	22784.33333
141	390.6391667	0	59.29416667	713.1591667	3488.816667	17790.83333
146	260.26625	29.77875	127.08075	564.1608333	2313.591667	12491.53333
151	286.60325	29.7725	51.58141667	506.1325	1452.1	10099.00833
157	122.7933333	0	89.71566667	209.3366667	1591.996667	7852.6
163	180.2349167	24.03133333	60.07816667	378.4925	984.9691667	5555.033333

Table 5

Particle Size Distribution Data from Scanning Mobility Particle Sizer and Differential Mobility Analyzer at Cruise Condition

Diameter	Baseline	5% Aromatic	10% Aromatic	15% Aromatic	20% Aromatic	25% Aromatic
4.45	0	0	0	1194.5625	6406.95	2389.1275
4.61	1144.855	0	0	0	5724.275	1144.855
4.78	0	1094.72	0	1094.72	2189.4375	2189.4375
4.96	1043.8725	2087.7425	2087.745	1489.89	6263.225	1043.8725
5.14	6013.945	2004.645	2004.645	1576.38	1002.3225	4009.2975
5.33	5759.4325	4799.5075	1919.8075	1919.805	4799.5275	1919.805
5.52	7356.7125	9200	8294.8	6435.0625	2764.925	1843.29
5.73	9869.725	10893.275	8830.45	8986.675	6321.795	2649.135
5.94	17925.425	12145.175	12980.325	14258.05	9178.25	3386.5325
6.15	16344.075	21342.825	17559.725	10535.05	12966.225	9724.54
6.38	18608.275	31231.475	22385.4	29151.35	16137.625	14831.15
6.61	32974.55	41443.475	27626.625	22034.4	28855.125	17405.125
6.85	32664.45	43436.225	34728.925	39635.95	37142.45	28528.45
7.1	43874.575	50973.25	44618.5	51528.5	45395.65	27931.675
7.37	54610.375	59563.75	63795	70237	52105.275	43357.35
7.64	71307	85859.75	81617	72886	81305	62405.75
7.91	88201.75	95647.5	98198.25	103211.25	93754	68645.5
8.2	98172.25	106858.25	122025.75	144723.5	117510.5	84730
8.51	102970.75	155340.75	137174.5	136307	118449.25	123587.75
8.82	139030.75	192957.25	173545.25	183595.5	179838	137784.75
9.14	172579.25	193773	214253.25	216333	209386.5	167768
9.47	193956.75	236055.25	246391	230709.25	231759	218526
9.82	204504.75	272142.5	290398.75	300385.75	292141	235903.25
10.2	263234.25	306817.25	311385	339188.75	314287.25	269934
10.6	268061.75	347196	381897.5	421610.75	368432	328348.25
10.9	287665	359811.75	434793.5	442043.25	429050.25	380386.25
11.3	324596.75	423086.5	479646.75	517590	502790.75	437594.5
11.8	358192	484239.5	521760	575682.5	587520	524245
12.2	390618.25	496157.5	562977.5	628120	673392.5	570440
12.6	425593.25	561920	631910	707290	734595	703742.5
13.1	438893.25	623142.5	705667.5	793955	831950	769072.5
13.6	469355.75	676342.5	791267.5	856952.5	921432.5	882805
14.1	516542.5	703515	880540	930882.5	996115	936360
14.6	551260	749595	922617.5	1045567.5	1113217.5	1035002.5
15.1	570702.5	831430	1018835	1138115	1180430	1120237.5
15.7	570242.5	820382.5	1083490	1195035	1303625	1262985
16.3	606332.5	903370	1133040	1256897.5	1381660	1344615
16.8	613837.5	977090	1189332.5	1339980	1460242.5	1439102.5
17.5	630325	990782.5	1231912.5	1442475	1571032.5	1491722.5
18.1	671627.5	1043870	1320737.5	1543155	1689387.5	1592885
18.8	677217.5	1077542.5	1339457.5	1635897.5	1798372.5	1680660
19.5	678562.5	1122585	1443227.5	1744097.5	1840515	1788912.5
20.2	732187.5	1162980	1522317.5	1805507.5	1955170	1860487.5
20.9	717312.5	1198422.5	1558082.5	1872242.5	2033637.5	1994872.5
21.7	705767.5	1195922.5	1553395	2004830	2136147.5	2054030
22.5	689375	1216130	1639400	2059447.5	2235752.5	2129725
23.3	686222.5	1205747.5	1648482.5	2081462.5	2309057.5	2227167.5
24.1	699322.5	1235017.5	1712732.5	2144630	2444740	2317250
25	698627.5	1234887.5	1751707.5	2168665	2536615	2443745
25.9	673970	1254197.5	1735992.5	2234280	2557155	2506997.5

*Continuation of Particle Size Distribution Data from Scanning Mobility Particle Sizer
and Differential Mobility Analyzer at Cruise Condition*

Diameter	Baseline	5% Aromatic	10% Aromatic	15% Aromatic	20% Aromatic	25% Aromatic
26.9	663522.5	1239215	1817250	2282575	2660937.5	2672870
27.9	621385	1263445	1792907.5	2335692.5	2696302.5	2735825
28.9	635502.5	1211347.5	1791092.5	2352572.5	2774230	2755802.5
30	626387.5	1173002.5	1797875	2378182.5	2795632.5	2778652.5
31.1	599592.5	1154825	1832020	2401832.5	2807555	2894700
32.2	577882.5	1154605	1769302.5	2409225	2893795	3081462.5
33.4	583815	1131210	1777905	2417547.5	2911877.5	3151977.5
34.6	538735	1124347.5	1768852.5	2376517.5	2951722.5	3245605
35.9	511825	1083142.5	1729772.5	2358660	2959622.5	3259875
37.2	498115.75	1040412.5	1735840	2306687.5	2960565	3280950
38.5	467263.75	987225	1680922.5	2276462.5	2957880	3386805
40	447110.5	972577.5	1671842.5	2281455	2938525	3435907.5
41.4	414325.5	909052.5	1599825	2228140	2948850	3551632.5
42.9	391584	860010	1544475	2192590	2888305	3575565
44.5	356930	835980	1458057.5	2113782.5	2747005	3487597.5
46.1	339879.5	808945	1425232.5	2076427.5	2713817.5	3524042.5
47.8	303503.25	759427.5	1358755	2008502.5	2730502.5	3493075
49.6	280601	693507.5	1306222.5	1929075	2668592.5	3401072.5
51.4	259140	667997.5	1228822.5	1903822.5	2587577.5	3343642.5
53.3	228377.75	605925	1165457.5	1795265	2533065	3353655
55.2	213492.25	569325	1100100	1719470	2435312.5	3251955
57.3	198455.25	500768.5	1051792.5	1652880	2420947.5	3076532.5
59.4	175774.5	487857.25	968640	1551285	2307887.5	2906297.5
61.5	160115	438284	892392.5	1443822.5	2186470	2810440
63.8	141114.5	388822.5	835475	1396452.5	2054055	2723170
66.1	121249	341124.75	761595	1277127.5	1952315	2535250
68.5	102051.75	304685.25	687770	1199985	1863167.5	2359722.5
71	91674	270776.75	635737.5	1112602.5	1760370	2210252.5
73.7	83786	239690.5	575200	1045260	1600045	2099112.5
76.4	67965.25	208016.25	512255	946425	1474935	1917170
79.1	59153.25	183945.5	453826.25	865590	1348592.5	1796527.5
82	46388.225	152620	403593	772572.5	1205040	1674210
85.1	38904.375	136655	358456.25	686037.5	1126212.5	1567345
88.2	34665.25	114189	302136.25	622360	1000205	1425767.5
91.4	28873.65	97403.5	258318	533485	904270	1280940
94.7	21840.125	78086.5	219103	473881.25	797532.5	1153560
98.2	20302.15	64860	193606	422701	710185	1015272.5
102	15758.4	48392.175	162825.5	362706.5	624027.5	923245
106	13263.15	45997.3	137943.5	295955.75	533577.5	822335
109	9907.325	29165.05	108880	258969.5	476633.5	714882.5
113	7917.45	24523.875	87780.25	211143.25	388833.25	616935
118	6299.12	18994.625	78701.25	177769.5	335092.75	550585
122	4560.06	16683.525	60312	148276	272420.75	462077.75
126	2356.185	11120.625	49142.275	118118	219541	398038.5
131	2631.6575	8900.05	31950.8	95144.5	185210.25	326015.25
136	1621.62	7478.775	27307.3	74611.75	153205.25	261526.25
141	1514.505	6813.85	21184.05	59176.5	125947.25	217524.75
146	977.791	4076.425	15137.825	45464.2	94685.75	181571
151	446.5875	2815.32	11255.025	35034.075	76966.75	149283
157	448.57875	1992.78	7956.45	27927.35	57367.5	118991
163	702.91475	1153.5025	7674.7	20034.575	45369.925	100224.75

Table 6

Particulate Mass Concentration Data from Tapered Element Oscillating Microbalance

Engine Conditon	Main Flow (lpm)	Dilution Flow (lpm)	Dilution Ratio	Aromatic Concentration	Average of Corrected Mass at 60 s (mg/m³)
Cruise	4	1.20	30	0	1.73
Cruise	4	2.39	60	5%	3.26
Cruise	4	3.29	82	10%	6.43
Cruise	4	3.79	95	15%	13.12
Cruise	4	3.79	95	20%	15.20
Cruise	4	3.79	95	25%	19.52
Idle	4	1.20	30	0	1.20
Idle	4	1.79	45	5%	1.34
Idle	4	2.59	65	10%	1.68
Idle	4	1.94	65	15%	3.51
Idle	4	1.94	65	20%	5.91
Idle	4	2.79	70	25%	5.24

Table 7

Smoke Number Data from Paper Filter

Engine Conditon	Aromatic Concentration	R_{blank}	R_{stained}	Smoke Number	Average Smoke Number
Cruise	0	79.4	73.6	7.30	7.03
		79.9	74.5	6.76	
Cruise	5%	79.1	67.8	14.29	14.40
		79.2	67.7	14.52	
Cruise	10%	79.3	60.8	23.33	24.12
		79.5	59.7	24.91	
Cruise	15%	79	53.2	32.66	31.56
		79.1	55	30.47	
Cruise	20%	78.3	47.1	39.85	38.33
		79.3	50.1	36.82	
Cruise	25%	78.4	45.8	41.58	43.79
		78.7	42.5	46.00	
Idle	0	78.90	78.5	0.51	0.51
		79.50	79.1	0.50	
Idle	5%	79.00	78.2	1.01	0.95
		78.80	78.1	0.89	
Idle	10%	78.70	76.8	2.41	2.52
		79.80	77.7	2.63	
Idle	15%	79.00	74.70	5.44	5.23
		79.60	75.60	5.03	
Idle	20%	78.90	70.80	10.27	10.16
		79.50	71.50	10.06	
Idle	25%	78.2	66.7	14.71	14.50
		78.4	67.2	14.29	

Table 8

Temperature Programmed Oxidation Data from Multiphase Carbon Analyzer

Engine Conditon	Aromatic Concentration	Carbon Composition (mg)			% Mass Elemental	% Mass Organic
		Total	Elemental	Organic		
Cruise	0	0.070	0.021	0.049	37	63
		0.041	0.020	0.021		
Cruise	5%	0.045	0.017	0.027	36	64
		0.046	0.016	0.031		
Cruise	10%	0.086	0.021	0.065	23	77
		0.064	0.014	0.051		
Cruise	15%	0.084	0.016	0.068	19	81
		N/A	N/A	N/A		
Cruise	20%	0.124	0.015	0.109	15	85
		0.111	0.021	0.090		
Cruise	25%	0.173	0.024	0.149	15	85
		0.183	0.027	0.156		
Idle	0	0.078	0.061	0.016	79	21
		0.110	0.087	0.023		
Idle	5%	0.116	0.095	0.021	82	18
		0.110	0.091	0.019		
Idle	10%	0.109	0.086	0.023	79	21
		N/A	N/A	N/A		
Idle	15%	0.136	0.103	0.033	76	24
		0.128	0.098	0.030		
Idle	20%	0.131	0.096	0.035	73	27
		0.140	0.102	0.038		
Idle	25%	0.082	0.042	0.040	52	48
		0.086	0.045	0.040		

Table 9

Polycyclic Aromatic Hydrocarbon Composition Data at Idle Condition

PAHs	Aromatic Concentration					
	0	5%	10%	15%	20%	25%
Naphthalene	0	0	13.02	0	66.5	0
Fluorene	0	0	12.68	17.83	17.27	0
Acenaphthene	0	0	5.63	25.13	25.04	1.2
Acenaphthylene	0	2.77	10.57	72.17	51.81	1.5
Phenanthrene	0	0	0	0	12.95	0
Fluoranthene	0	0	0	0	0	0
Pyrene	0	0	0	0	0	0
Benz[a]anthracene	0	0	0	0	10.36	0
Chrysene	0	0	0	0	10.36	0

All Results are listed in nanograms (per total filter)
Cero (0) indicates less than 1.0 ng

Table 10

Polycyclic Aromatic Hydrocarbon Composition Data at Cruise Condition

PAHs	Aromatic Concentration					
	0	5%	10%	15%	20%	25%
Naphthalene	0	0	0	0	ND	0
Fluorene	0	0	0	0	ND	0
Acenaphthene	0	32.83	0	11.31	ND	31.99
Acenaphthylene	0	38.08	4.98	0	ND	48.99
Phenanthrene	0	13.13	4.98	17.49	ND	38.99
Fluoranthene	0	38.08	26.3	89.49	ND	256.93
Pyrene	0	95.86	68.61	234.52	ND	619.81
Benz[a]anthracene	0	0	0	0	ND	0
Chrysene	0	6.57	0	0	ND	0

All Results are listed in nanograms (per total filter)
Cero (0) indicates less than 1.0 ng

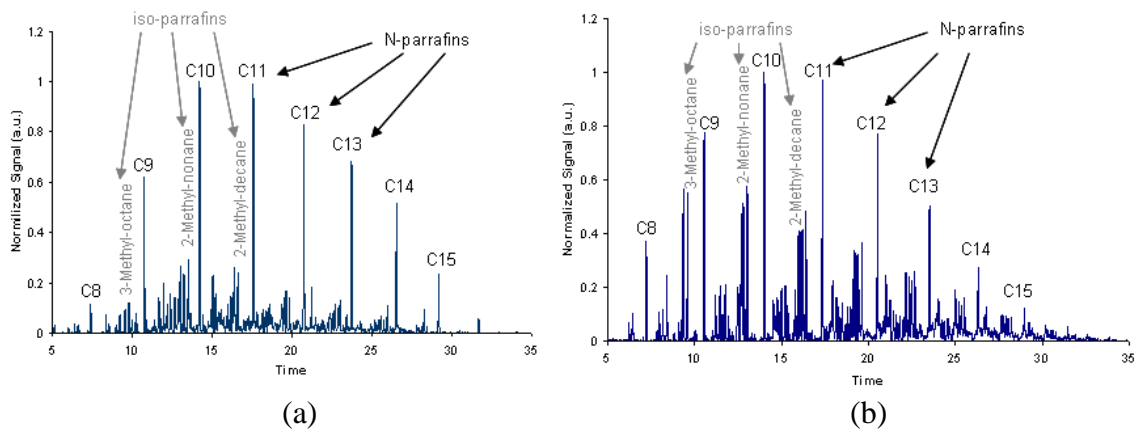
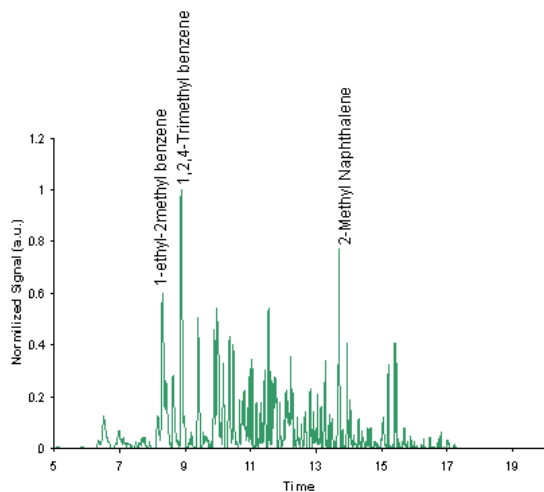


Figure 9. Gas Chromatography/Mass Spectrometry for: (a) JP-8 and (b) Synjet

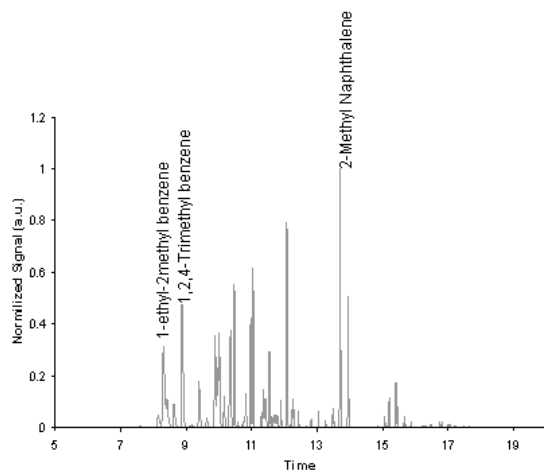
Table 11

Chemical Characteristics and Physical Properties on Jet Fuel

Property	JP-8 / Jet A-1	Synjet
Approx. Formula	$C_{12}H_{23}$	$C_{12}H_{26}$
H/C ratio	1.94	2.17
Boiling Range, $^{\circ}C$	150-256	153-271
Freeze point, $^{\circ}C$	-44	-59
Flash point, $^{\circ}C$	47	49
Net heating value, BTU/lb	18,625	18,965
Specific gravity 15.5 $^{\circ}C$	0.81	0.76
Ave Composition, vol %		
Paraffins	60	100
Cycloparffins	20	0
Aromatics	16-18	0
Olefins	2	0
Sulfur, ppm	700	0



(a)

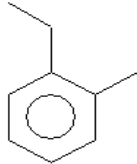
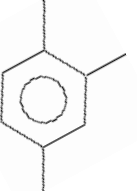
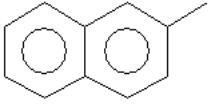


(b)

Figure 10. Gas Chromatography/Mass Spectrometry for: (a) Aromatic Fraction in JP-8 and (b) Aromatic Blend

Table 12

Comparison of JP-8 Aromatic Extraction and Aromatic Blend

AROMATICS	HPLC JP-8 Extraction	Aromatic Blend	Mayor Species	Structure
MONO-	89%	92%	1-Ethyl-2Methyl Benzene	
			1,2,4-Trimethyl Benzene	
DI-	11%	8%	2-Methyl Naphthalene	

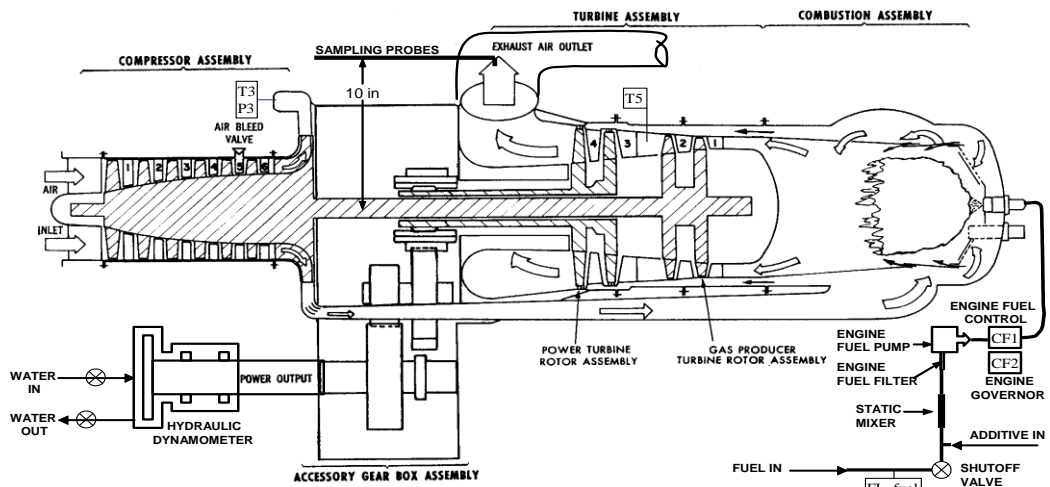


Figure 11. T63-A-700 Turbohaft Engine Setup at Environment Research Facility

Table 13

Engine Operating Conditions for T63 Engine

Power	P ₃ (psia)	T ₃ (°F)	T ₅ (°F)	SHP (hp)	Fuel Flow (lb/min)	Air Flow (lb/min)	Overall F/A ratio	Burner F/A ratio
Idle	35	251	750	8	0.89	95	0.009	0.040
Cruise (NRP)	80	498	1280	238	2.92	169	0.017	0.075

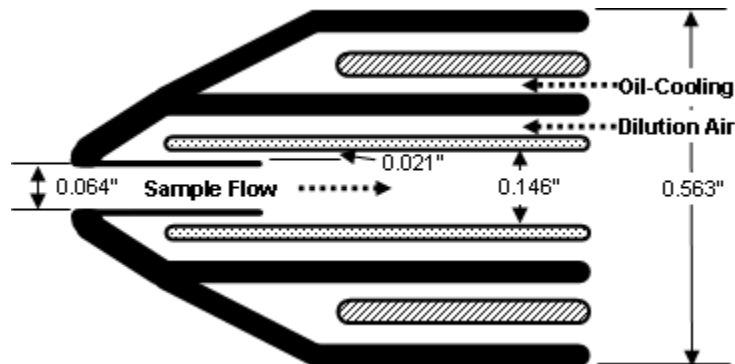


Figure 12. Particulate Matter probe design

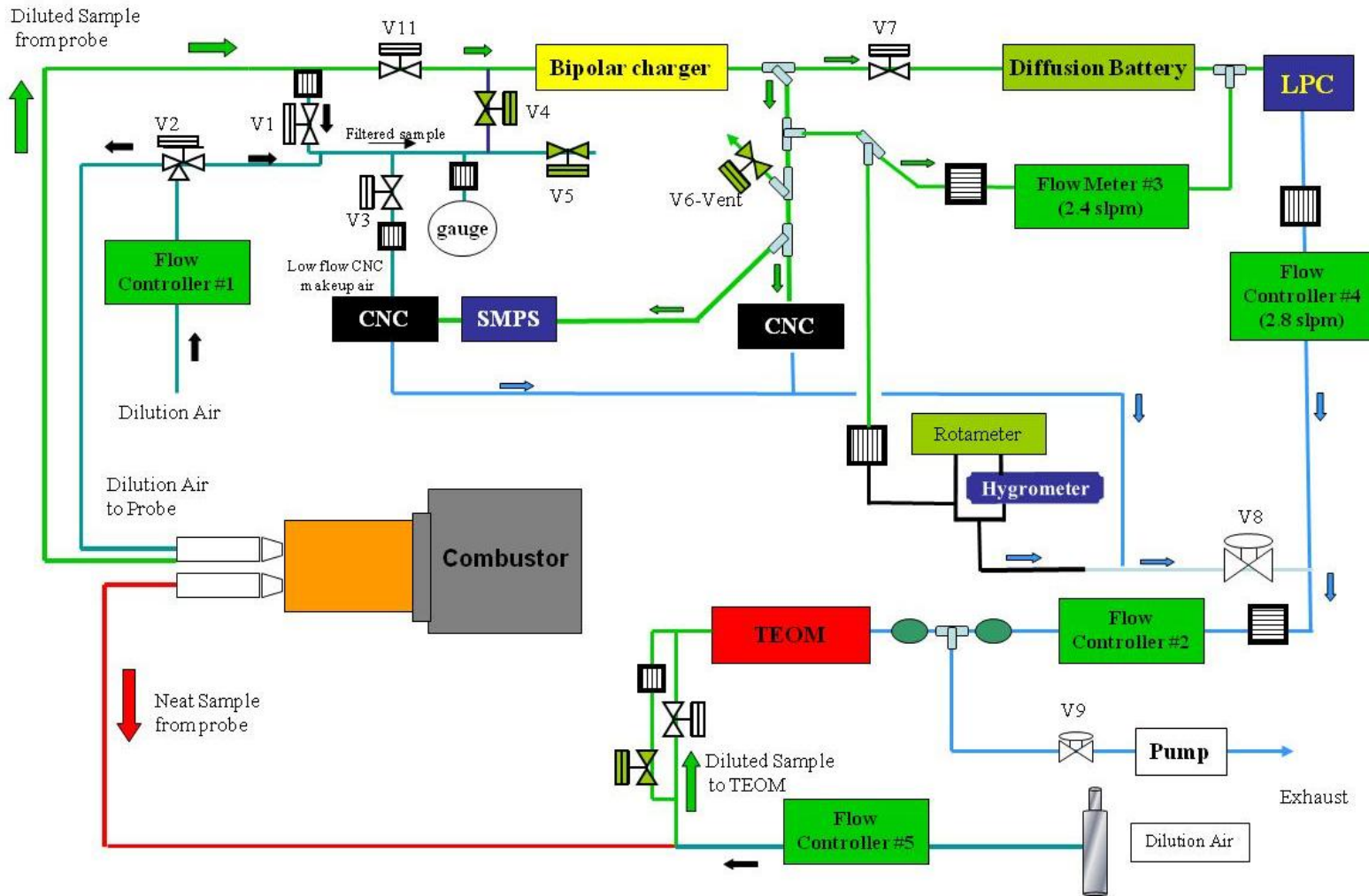


Figure 13. Particulate Measurements System Configuration