Center of Excellence for Aerospace Particulate Emissions Reduction Research

Final Report

The Development of Exhaust Speciation Profiles for Commercial Jet Engines

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Abstract

This study reports the emissions of CO, CO_2, NO_x, Particulate Matter (PM) mass, speciated PM and speciated hydrocarbons at six thrust settings: 4%, 7%, 30%, 40%, 65% and 85%, measured from both engines on four parked 737 aircraft at the Oakland International Airport. The engine types were selected to represent both old and new technologies. Tests were performed to determine whether or not all engines studied were operating in a representative manner. Of the 8 engines studied, only one was found to have performance deterioration and it was excluded from the engine average results. Size distributions from 5nm to 1µm were measured for all test points and associated aerosol shape parameters, and mass and number-based emission indices were evaluated along with real-time chemical speciation for some hydrocarbons. This work was conducted by the University of Missouri-Rolla and Aerodyne Research Inc. The bulk of the Total Organic Gases (TOG) speciation was pursued using off-line filter sampling approaches conducted by the University of California - Riverside. **After the field campaign was completed it became apparent that a leak had occurred in the sampling system for the sub-set of filters designated for light hydrocarbons (C_1-C_{12}) and carbonyls, and the Summa canister data was lost for unknown reasons. The emission indices for these species are not quantifiable.** Despite this loss of data this study has resulted in the first quantitative values obtained using state of the art techniques of engine emission factors for PM and some TOG for the most common classes of gas turbine engines currently operating in the US domestic fleet. The data from this test will serve to improve air quality prediction models used in Environmental Impact Statements and Reports for airport expansion projects, and for developing effective State Implementation Plans.

Executive Summary

This report represents the specific CARB funded deliverable for ARB contract number 04-344: The Development of Exhaust Speciation Profiles for Commercial Jet Engines.

Airport traffic is expanding and yet information is scarce on the exhaust speciation profiles of both total organic gases (TOG) and particulate matter (PM) from modern commercial jet aircraft using current fuels. The lack of chemical source profiles makes it almost impossible to produce accurate statewide inventories and Environmental Impact Report (EIR) efforts in regions heavily impacted by commercial jet aircraft. The objective of this project was to develop TOG and PM speciation profiles for engines used in newer Boeing 737-type commercial aircraft burning Jet A/A-1 turbine fuel using the latest analytical equipment. These aircraft were specifically chosen since they represent >70% of the aircraft currently in operation in the domestic commercial fleet. Furthermore, the primary engine type employed (CFM-56 series) has such a strong presence in global aviation that CFM claims an aircraft with their engines takes off every four seconds, every day. These facts being considered, the B737/CFM-56 combination is an excellent starting point for the development of a database that accurately represents commercial aircraft emissions. The successful completion of this project will facilitate informed decision-making and accurate modeling of B737 type commercial jet engine exhaust emissions for inventories and ozone estimation as well as detailed chemical speciation/source apportionment to assist in health risk assessments during the EIR process for airport expansion projects. It should be noted that the data presented in this study are engine/airframe specific and do not necessarily represent gas turbine engine emissions in general and should not be applied to other engine/airframe types.

The primary objective of project JETS APEX2 was to collect and develop exhaust speciation profiles from modern commercial jet engines. To achieve this objective, CARB had initiated discussions with Oakland International Airport (OAK) and Southwest Airlines (SWA) to provide access to in-service commercial B737 aircraft for such measurements since SWA operates exclusively with B737s and is the major airline operating out of OAK. With the appropriate coordination of expertise and resources, this CARB project, with significant expansion, provided a measurement venue required to meet the critical National PM Road Map milestones that followed Project APEX (APEX1 - April 2004) and Project Delta-Atlanta Hartsfield (UNA UNA - September 2004). In the spring of 2005, Project JETS APEX2 emerged as a multi-agency (CARB, NASA, FAA, EPA, UMR, UCR, UCF, AEDC, GE, Boeing, SWA, OAK and ARI) funded study with the following objectives:

1. Produce the first measurements with state-of-art analytical equipment of speciated total organic gases (TOG) and particulate matter (PM) from engines on typical in-use Boeing 737-type commercial aircraft [ARB contract number 04-344 deliverable].
2. Provide data to address critical science questions/issues arising from the 2004 APEX1 and UNA UNA studies [an objective of the broader multi-agency project not reported here].

These data will also be used, where possible, to develop chemical source profiles needed to make informed decisions during the Environmental Impact Report (EIR) process for airport expansions.

Custom-designed probes and extensive support equipment were used to sample jet exhaust in the on-wing position and were analyzed with state-of-the-art instrumentation. Emissions of CO, CO_2, NO_x, PM mass, speciated PM and speciated hydrocarbons at six thrust settings: 4%, 7%, 30%, 40%, 65% and 85% were measured from both engines on four parked 737 aircraft.

Particle-laden exhaust was extracted directly from the combustor/engine exhaust flow through the probe, transported through a sophisticated sample train, distributed to the different research groups, and analyzed in each group's suite of instrumentation. Sampling probes were located at different positions downstream of the engine exit plane: 1m, 30m and 50m on the starboard side and at 1m on the port side of the aircraft. In this report the 1 and 50m data are presented. These aircraft engine emissions measurements were performed at the Ground Runup Enclosure (GRE) at OAK during August 2005. The engine types were selected to represent both old (-300 series) and new (-700 series) technologies. Realtime PM physical characterization was conducted by UMR. Size distributions from 5nm to 1μm were measured for all test points and associated aerosol parameters e.g. geometric mean diameter, geometric standard deviation, total concentration, and mass and number-based emission indices were evaluated are presented below.

Realtime measurements of gaseous emissions were made by ARI using 1) Tunable Infrared Laser Differential Absorption Spectroscopy (TILDAS) based on both lead-salt diode and quantum cascade laser sources for several important trace species emissions and 2) Proton-Transfer Reaction Mass Spectroscopy (PTR-MS) for hydrocarbons, and 3) chemiluminescence measurement (NO). These measurements were converted to Emission Indices using CO_2 measured with a non-dispersive infrared absorption of that major combustion product. Chemical composition of the particle emissions was quantified using an Aerosol Mass Spectrometer (AMS) in concert with a Multi-Angle Absorption Photometer (MAAP, for Black Carbon mass) and particle size and number measurements.

Measurement of TOG, PM mass, metals and ion concentrations were conducted on the exhaust products collected on filter membranes by the University of California - Riverside Center for Environmental Research and Technology. The analytical methods employed are considered standard methods for such measurements and are described in detail in the methodology sections to follow. After the field campaign was completed, analysis of the DNPH cartridges and SUMMA canisters revealed anomalous CO_2 concentrations which were attributed to a leak in a sub-system of the sampler. Also, C_4-C_{12} hydrocarbon values based on the concentrations measured from the Thermal Desorption Tubes (TDS) were much lower than expected from APEX1 and other research. Since this leak introduced an unquantifiable dilution in these sub-systems, the emission factors for the light hydrocarbons and carbonyls could not be calculated.

The results of these measurements represent the heart of this final report and are presented in the results section as a series of speciation profiles by mode for each of the eight engines studied. Details of experimental methods and limits of detection are also provided in the tables.

The major conclusions from this study are as follows. Size distributions for engine exit plane were generally lognormal. Strong and sometimes non-linear dependencies were observed on engine power settings. The onset of gas-to-particle conversion was apparent at 50m for low to medium powers. In this data non-lognormal size distributions were often observed, where the mean sizes decreased and EIn increased relative to the 1m size distributions. Consistently, the aerosol Soluble Mass Fraction was found to increase with distance from the engine exit plane implying that as a result of processes such as gas to particle conversion soluble material present in the gas phase at the engine exhaust exit is being taken up by non-volatile soot as the exhaust plume expands. Its value was negligible at the engine exit plane and was ~10% at 50m. It should be noted that the aerosol properties in this study were calculated for the entire aerosol size distribution and not individual modes.

Measurement of NOx indicated that the general emissions performance of the engines was in keeping with certification measurements for the subject engine models. Measurements of individual hydrocarbon species suggest that most of the major species decrease with increasing engine power in proportion to each other and, in specific, with formaldehyde, which is one of the most plentiful emitted hydrocarbons and can be measured accurately. The particle composition includes both sulfate and organic volatile fractions at downstream distances, adding to the carbonaceous aerosol that is present already at the engine exit plane. The sulfate contribution has little dependence on engine power, while the organic contribution is greatest at low engine powers.

With respect to the TOG for which samples were obtained and analyzed, the relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with previous work. Chromium (VI) results for all but one of the engines studied were as expected. From DNPH analysis, the major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone. Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions.

At this time, the implications of this work for the CARBs relevant regulatory programs are limited. The State of California has no authority to regulate aircraft engine emissions or ground operations, so this project has few direct implications in those areas. However, the resulting improvements in inventory accuracy and detail will carry into other areas. Included would be improvements in air quality prediction used in Environmental Impact Statements and Reports (EIS and EIR) for airport expansion projects, and for developing effective State Implementation Plans (SIP). Of course, health effects impacts, such as those on airport neighbors, will need health risk factors to be developed. But climate change work would benefit from the improved quantification of such greenhouse emissions as NOx, CO_2, and particulate matter.

Upon the completion of this study, the Principal Investigators make the following recommendations for future work concerning aircraft emission characterization:

- The results of this study proved that accurate emission factors can be acquired in a cost effective manner. Since the data is clearly engine/airframe specific, studies of this nature should now be performed on other important engine/airframe combinations e.g. B747/CF6-80.

- The ideal testing conditions afforded by the GRE at Oakland leads to the recommendation that it should be considered a high priority venue for any future engine tests.

- Since the mix of transports routinely operating in and out of Oakland will limit the range of engines/airframes that can be studied, for future studies where B747, B757, B767, and B777 and the larger Airbus transports A320, A340 etc. are anticipated test vehicles, it will be necessary to consider attracting other aircraft to the Oakland test site or using GREs located at other airports, provided appropriate weather conditions prevail.

- In future tests it is recommended that high frequency data acquisition be employed for engine operating conditions such N1, N2, EGT and Fuel flow rate. This may be difficult for older airframes but straight forward for newer additions to the commercial fleet that digitally record engine operating conditions.

- Much of the data was gathered and initially analyzed in real-time. However, this was not the case for the UCR VOC samples that were analyzed off-site post test. For future studies efforts should be expended to assure that the analysis could be undertaken for these samples on-site. This would provide quasi-real-time feedback on the integrity of such samples.

- Engine to engine variability is difficult to estimate when the engine sample size is small (in this study ≤ 4 engines per model). The value of accurately estimating this parameter warrants the consideration of a longer period of study.

- Valid measurements for TOG and multiple significant speciated VOCs were not obtained because of sampling and laboratory issues for the light hydrocarbon and carbonyl analyses. These measurements should be repeated at a future engine test, when the opportunity arises, to get better estimates of TOG and speciated VOCs.

The objectives of the JETS APEX2 study were to produce a comprehensive data set of emission factors for total organic gases and PM for old and new technology CFM56 class engines operating out of a medium size hub airport in the State of California (i.e. Port of Oakland). This study was successful in producing the first state of the art measurements for PM physical characterization of in-service CFM56 type engines. Unfortunately, as a

result of the failure of some of the off-line sampling systems the TOG analysis was limited and from that perspective not all of the objectives set out in the proposed effort were accomplished. **However, even with the limited TOG data this study represents the first extensive physico-chemical analysis of a series of in-service commercial engines and as such is an extremely valuable dataset.** This study is part of a greater multi-agency effort that includes emissions measurements downwind of an active runway at Oakland during normal airport operations, and the results presented here are essential for the interpretation of the downwind measurements. The downwind studies were publicly released at the APEX Conference held in Cleveland, OH, November 29-December 01, 2006.

1.0 Background

1.1 Introduction

The growth of commercial air traffic over the last decade has led to an increased contribution to the local inventory of gaseous and particle emissions from the operations associated with airports, e.g. ground support equipment (GSEs) and aircraft engines. Recent studies have shown an increasing number of environmental effects from aviation related activities such as impact on climate (Penner et al., 1999) and local air quality (Waitz et al., 2004). An additional concern, primarily in the vicinity of airports, is the contribution of aircraft emissions to the formation of photochemical smog and the delivery (through inhalation) of highly concentrated irritants into human beings (Samet et al., 2000; Dutton, 2002).

The lack of EPA aircraft engine standards for PM and speciated hydrocarbons and the scarcity of information about the emissions associated with airport operations have heightened the concerns of communities living around airports. Furthermore, Federal statutory and regulatory framework prohibit states, like California, from setting emission standards for aircraft engines, regulating the number of takeoffs or landings at airports, limiting flight procedures or controlling types of planes used at airports. As a consequence, airports find it increasingly difficult to evaluate the potential contribution and health effects of all airport-related emissions during the environmental review process.

1.1.1 Regulated Emissions from Commercial Jet Engines

Lister (2003) published a comprehensive review of the background, history and development of the current aircraft engine emissions certification regime, up to the publication of Annex 16, Volume II, 1st Edition in 1981 and a brief overview of the main developments. His review is based on historic archive records of the development of the current certification methodology, which were available to the NEPAIR partnership (New Emissions Parameter covering all flight phases of AIRcraft operation).

In the United States, the United States Environmental Protection Agency (US EPA) is required by Section 231 of the Clean Air Act Amendments of 1990 to regulate aircraft engine emissions and has adopted aircraft engine emission standards recommended by the International Civil Aviation Organization (ICAO) as the applicable federal standards. The ICAO and its Committee on Aviation and Environmental Protection (CAEP) continue to coordinate development of consistent international standards for aircraft engines worldwide that “encourage the development of less polluting, more efficient aircraft engines and more aerodynamic aircraft bodies will result in aircraft that pollute substantially less, operate more quietly, and consume less fuel than today’s airplanes."

The US EPA issued its current rule in 1997 on the control of aircraft air pollution, including standards for exhaust emissions for carbon monoxide (CO), nitric oxides

(NO_x), and smoke number (SN). The EPA regulation also incorporated the emission test and measurement procedures from the U.N. International Civil Aviation Organization (ICAO), bringing the U.S. aircraft standards into alignment with international standards. Quantification of the regulated emissions - carbon monoxide (CO), oxides of nitrogen (NO_X), total hydrocarbons (THC) and smoke number (SN) - can be found in the ICAO database (ICAO 2006). It should be noted that usually only one engine is tested in triplicate in order to represent an engine family and that very few multiple engines from the same family are tested.

While most investigators use the standard SAE methods to measure the emissions, several researchers have explored other methods, especially applied to in-use emissions from aircraft operating on the ground. For example, Popp (1999) tested remote sensing at London's Heathrow Airport and in two days made 122 measurements of 90 different aircraft in a mix of idle, taxi-out, and takeoff modes. The work found aircraft at idle exhibited little nitric oxide emissions and at higher thrust levels were somewhat consistent with values from the ICAO Databank. Heland (1998) applied FTIR spectroscopy to the determination of major combustion products such as CO_2, H_2O, CO, NO, and N_2O in aircraft exhausts and compared them with values published in the literature. He reported the measured CO emission index at idle power of a CFM56-3 engine was about 27% lower than the value given by Spicer and about 27–48% higher than the ICAO data for the whole span of CFM56-3 engines. The CO emission index (EI) measured at idle power of a CFM56-5C2 engine of an Airbus A340 was about 30% less than the ICAO value. One observation from Heland's work is the magnitude of the variation found when different investigators make the measurements.

Herndon (2004) measured the NO and NO_2 emission ratios from 30 individual in-use commercial aircraft during taxi and takeoff at JFK Airport in New York City. NO and NO_2 concentrations were measured with one-second time resolution using a dual tunable infrared laser differential absorption spectroscopy instrument. The authors reported that the field-measured emission ratio to the ICAO EIs for three aircraft engines agreed within the expected engine-to-engine variability, aging effects, and experimental uncertainty for three somewhat different engine types.

1.1.2 Non-Regulated Emissions from Jet Engines

As previously discussed, the people living near airports are concerned about their exposure to the combustion products from jet engines and a number of groups are interested in learning more about how much aircraft emissions contribute to the inventory of a basin. Combustion of jet fuel results in CO_2, H_2O, CO, SO_x, NO_x, particulate matter (PM) and hundreds of organic compounds. Most data are on the regulated emissions and information is lacking on the speciation of the hundreds of hydrocarbon compounds and PM necessary to inventory the contribution of aircraft operations to the total area loading. In order to inventory aircraft operations emissions, a detailed emissions database with speciation is required, and historically, tests to obtain speciated engine emissions data are very expensive and involve many hours of engine operation. These tests are quite rare

and almost non-existent. Current efforts to model commercial jet exhaust, as well as EIR's, are relying on results from testing of military aircraft performed in the 1980's or earlier. Data, which are available, such as in EPA's AP-42 Emission Factor report, come from measurements made around 1980.

Spicer (1992) is usually credited with being the first person to have developed comprehensive speciation profiles of the hydrocarbons in jet exhaust. His first paper reported on emissions for the F-101 and F-110 military engines using JP-4 while operating from idle to intermediate power. His primary focus was the detailed organic speciation and his methodology for sampling and analysis of the hydrocarbon species is similar to that carried out in the work reported here. However, current analytical equipment is far more sensitive and allows lower detection limits. In a second paper, Spicer (1994) reported on the chemical composition and photochemical reactivity of exhaust from two engines. One was an older TF-39 engine that was not designed with emissions in mind, and the other was the newer technology, low-emission CFM56-3 engine. Both engines were tested at three power settings using fuels meeting the JP-4, JP-5 and JP-8 specifications. Results with kerosene-based JP-5 showed the hydrocarbon emission index of the CFM56 engine was about half that of the TF-39 engine. Spicer points out that the core engine of the CFM56 is essentially the same as the F-101 used and reported on in his earlier tests.

Petzold (1999) reported a comparison of the characteristic parameters of black carbon aerosol (BC) emitted from jet engine during ground tests and in-flight behind the same aircraft. They found that the total BC number concentration at the engine exit was in good agreement with the in-flight measured number concentrations of non-volatile particles. A comparison between total number concentration of BC particles and the non-volatile fraction of the total aerosol at the exit plane suggested that the non-volatile fraction of jet engine exhaust aerosol consists almost completely of BC. BC size distribution features included a primary modal diameter at D~0.045 μm and an agglomeration mode at D<0.2 μm.

In 2000, Dewers described AERONET, "*Identification of aircraft Emissions relevant for Reduction Technologies, as a cooperative network set up within the European Communities 4th Famework Programme of Research.*" AERONET Thematic Network was created as a platform where stakeholders meet and exchange information, views and experiences gathered in different European projects. The complexity of the issues can be witnessed by the size of the stakeholder group: including aircraft and engine manufacturers, operators, fuel suppliers, airports, and air navigation providers. Each stakeholder has a keen interest to ensure that its products, aircraft and air transport, are environmentally acceptable.

As part of the AERONET effort, Petzold (2001) provided a comparison of the various analytical measurement methods for monitoring various emissions from aircraft engines either airborne or on the ground. The measurement of particulates is the most interesting section of his review. He points out that the smoke number method is not able to accurately reflect the presence of emitted particles in terms of their size. He concludes: "there is an urgent necessity to establish standard methods for engine exhaust aerosol

characterization which correspond better to present knowledge on the atmospheric impact of aircraft emitted particles."

Wilson (2004) presented an overview of the goals and achievements of another AERONET effort: the European PartEmis project (Measurement and prediction of emissions of aerosols and gaseous precursors from gas turbine engines). PartEmis focused on the characterization and quantification of exhaust emissions from a gas turbine engine. His summary table reviews current knowledge about measurement techniques and gaseous and aerosol parameters. Of interest is their quest to measure non-methane hydrocarbons (NMVOCs -C_2–C_{10}) and partially oxidized hydrocarbons, specifically carbonyl compounds and organic acids. More than 100 NMVOCs (aliphatic and aromatic hydrocarbons, carbonyls and acids) were found and quantified but not yet published. For example, they report the emission indices of organic acids were about 10 times higher than for carbonyl compounds. Review of the aerosol phase revealed that the formation of volatile particles in jet engine emissions was the result of cooling and dilution of exhaust gases.

Tesseraux (2004) reported on the risk factors of jet fuel combustion products. Her research was motivated by the increase in air travel and the scarcity of information known about exposure to the vast number of organic compounds, including carcinogenic substances, to the people living in the vicinity of airports. Her review indicates that no hydrocarbon (HC) compound was found to be a characteristic indicator for jet engines. A key aspect of her review is the comparison of research comparing organic compounds in the emissions of jet engines with emissions from diesel vehicle engines as partially shown below in Table 1.

Table 1: Example of Volatile Organic Compounds in Jet Engine and Diesel Engine Emissions—Aromatic Hydrocarbons (see references in Tesseraux)

	Jet Engine					**Diesel engine (mg/m^3)**
	CFM-56-3 (ppm) (Spicer)			Averaged test run (mg/m^3) (Eickhoff)		(Eickhoff) (running)
	Idle	30%	80%	CF6 50C2/E2	CFM56-3B1	
Benzene	4.13	0.02	0.02	0.69	0.06	2.12
Toluene	1.56	0.01	BDL	0.26	0.07	0.53
Ethylbenzene	0.42	BDL	BDL	0.18	0.01	0.64
m-p-Xylene	0.68	BDL	BDL	0.45	0.02	-
Styrene	0.76	0.01	BDL	0.09	0.01	-
o-Xylene	0.40	BDL	0.01	0.35	0.01	-
Phenol	0.40	BDL	BDL	0.66	0.04	1.12
C_4-benzene	0.52	BDL	BDL	0.23	0.01	
C_5-benzene	0.50	BDL	BDL			
Naphthalene	1.35	BDL	BDL	0.42	0.01	1.98
2-Methylnaphthalene	0.51	BDL	BDL	0.38	0.01	2.26
1-Methylnaphthalene	0.61	BDL	BDL	0.24	0.01	1.29

BDL – below detection limit

Recently, Gerstle (2002) published a series of internal reports as the product of a 5-year series of emissions testing of seventeen military aircraft engines, two helicopter engines and two auxiliary power units (APUs), all burning military fuel, JP-8. Testing included regulated emissions and selected non-regulated emissions, such as the carbonyls and Volatile Organic Compounds (VOCs). Their data for the carbonyls and VOCs might be useful references.

1.1.3 Effects of Unburned Jet Fuel

A growing body of information is available about the physical properties and chemical composition of unburned jet fuel. These references are germane given the interest of some staff at ARB on the speciation and health effects of unburned jet fuel and its fumes. An excellent reference is the 2003 report of the National Research Council entitled: "*Toxicological Assessment of Jet-Propulsion Fuel 8.*" The NRC report and numerous references within dealt with the health effects of fuel vapors and liquid fuel.

1.2 Recent NASA Missions

1.2.1 Experiment to Characterize Aircraft Volatile Aerosol and Trace Species Emissions (EXCAVATE- 1999)

Most of the recent measurement data on aircraft emissions is from the National Aeronautics and Space Administration (NASA) but is unpublished. The EXCAVATE mission sampled aircraft emissions at 1 and 35 meters behind the NASA Langley 757 parked on the tarmac. The project used the NASA Langley sampling system and laboratory for measurement of regulated gaseous emissions and PM particle diameter and number distributions. Aerodyne Research Incorporated (ARI) data showed that organic carbon (OC) and sulfate emission factors both increased with distance behind the plane, likely reflecting increasing condensation with increasing plume age and cooling. The ARI Aerosol Mass Spectrometer (AMS) results agreed well with concurrent DMA number distribution measurements, which indicated that the small particles disappeared when the aerosol inlet was heated to 150°C, consistent with observed particulate sulfate composition. Both AMS and DMA results showed increasing aerosol loading with increasing distance behind the plane and lower emission factors with increasing engine power. In contrast, the AMS, the only particle sampling system with a time resolution of seconds, resolved transients of particulate matter (PM), OC with loadings up to 1000 times higher than at high power operation during shifts between idle and high power.

The AMS spectrometer provides chemically resolved size distributions. Figure 1 shows the observed external mixture of sulfate and organic particles in the Boeing 757 aircraft exhaust as a function of downstream aging. Chemically-resolved aerodynamic size distribution data, in combination with the electrical mobility diameter size distributions obtained by NASA Langley, greatly enhanced their understanding of the aircraft exhaust

PM formation mechanisms and chemistry. The ARI mobile laboratory was a cost-effective and time-efficient technique for characterizing EPA-required emission factors for aircraft, while simultaneously providing chemically resolved particle size distributions and the ability to observe and identify potentially large transient emissions events.

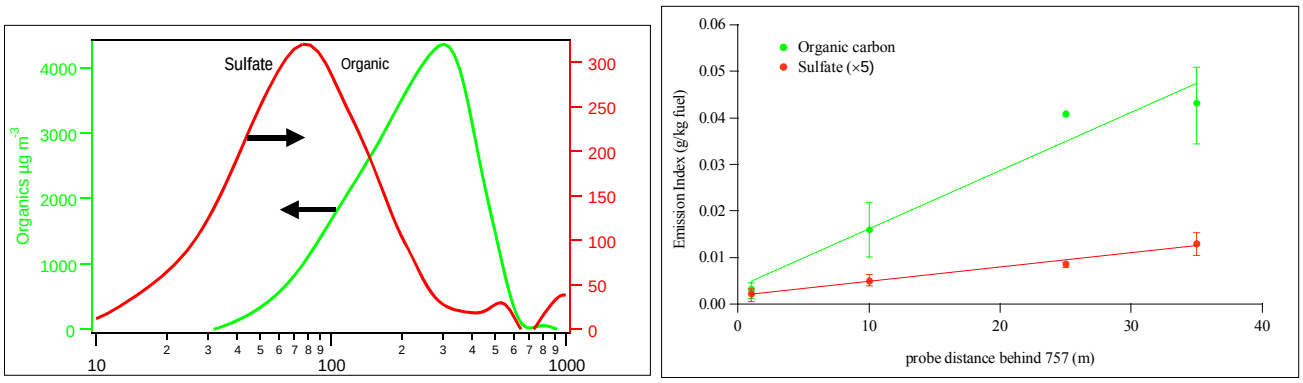


Figure 1a: Aerodynamic Size Distributions (nm) for Organic and Sulfate Particles in Aircraft Exhaust at 25 Meters. Figure 1b: Particulate Emission Indices Measured as a Function of Distance Behind the Engine.

ARI used their Tunable Infrared Laser Differential Absorption Spectrometer (TILDAS) for real-time analyses of some regulated and non-regulated gaseous emissions. By selecting appropriate laser sources for the instruments, the spectral range measured important exhaust species such as NO, NO_2, HONO, SO_2, CO_2, and H_2O. Other species have been measured in diesel engine exhaust and/or in atmospheric measurement, including HCHO (formaldehyde) and HNO_3 (nitric acid). Like the AMS for particles, their TILDAS has a rapid response, limited only by the flow times in the sampling system. The combined measurement of gaseous species in concert with the particle parameters proved critical for understanding the total emissions performance of the engine, including transient phenomena and mixing and dilution at downstream probe locations.

1.2.2 Aircraft Particle Emissions eXperiment (APEX1-2004)

APEX1 was the second NASA test of aircraft emissions and involved a multi-agency commercial aircraft mission characterization and technology demonstration with a goal of characterizing particle and trace gas precursor species from the NASA aircraft DC-8 with CFM56-2C1 engines at the engine exit plane as well as at 10 and 30 meters downstream of the engine. The goal of APEX1 was to advance the understanding of particle emissions and their evolution in the atmosphere from a current in-service turbofan engine. NASA wanted to define the physical and chemical properties of particle emissions (including transient due to throttle change and start-up) from the engine at the exit plane as a function of engine operating parameters and fuel properties and to further probe the physical and chemical properties of particle emissions from the aircraft at selected

downstream locations to advance the knowledge of particle transformations in the atmosphere during operations in and around airports. Others involved in the testing included University of Missouri-Rolla (UMR), University of California-Riverside (UCR), Aerodyne Research Inc. (ARI), Environmental Protection Agency (EPA), several Department of Defense (DoD) entities and the Federal Aviation Administration (FAA). Detailed analysis of the APEX1 data set has been completed and can be found elsewhere (Wey et al. 2006; Lobo et al. 2007; Yelvington et al. 2007; Knighton et al. 2007;Onasch et al. 2007).

Figure 2: Picture of NASA Aircraft and Multiple Test Labs with Supporting Equipment

The APEX1 data set includes information on speciated hydrocarbons and PM. Specific information was collected on the following gas phase species:

- Regulated emissions- continuous: NO_x, CO, total hydrocarbons (THC),
- Additional gases-continuous: SO_2, NO, NO_2, HONO, CO, N_2O, CO_2, H_2O
- Additional gases-non-continuous: from VVOCs like methane (C_1) to VOCs, including carbonyls, to semi-volatile organic compounds (SVOCs), including naphthalene and PAHs

The testing also gathered specific information on particulate matter:

- Total number concentration, size distribution, hydration properties, morphology
- Non-refractory aerosol size, selected number density, and composition
- Smoke Number
- Non-volatile mass
- PM mass/number concentration, particle size distribution, and total non- volatile PM
- PM elemental/organic carbon and semi-volatile organic compounds
- PM water-soluble ions and elemental composition

Knowledge gained from APEX1 will clearly advance the scientific understanding of speciated compounds and particulate matter and the new instruments that were used for the first time to characterize PM size distribution in real time. However, these data

recorded were for one engine, and much more research is needed in areas related to modern engines as found on the Boeing 737 aircraft. Such data is reported here.

1.3 JETS APEX2

Put in perspective, past and recent work, including the latest NASA missions, have directed most effort towards advancing the understanding and expanding the database related to regulated emissions and some new scientific approaches for measuring PM. None of these data are included in the current ARB profiles. Instead, ARB's current profiles were developed using older fuels and engine technology, mainly based on older military use fuels and engines from the 1980's. Accordingly, significant uncertainties exist in ARB's projects when quantifying speciated hydrocarbons and speciated PM emissions from current airport sources. ARB's uncertainties exist because:

- The currently employed emissions data were collected for limited and outdated military aircraft engines with military fuels and other operations from the 1980s,
- The measured compounds, overall methodologies, and test equipment used, limit the usefulness when applied to current commercial jet engine speciation profiles, and
- Very few emissions tests have been conducted since the 1980s for speciated hydrocarbons and PM on actual commercial aircraft engines, so there was no opportunity to update the ARB database.

Obtaining data on aircraft emissions is complicated and no single entity has all the resources and expertise needed to meet ARB's multiple goals. Accordingly, the approach was to use multiple teams, consisting of executive and technical members. The executive team consisted of the ARB, Federal Aviation Administration (FAA), the UMRCOE, Southwest Airlines (SWA) and the Port of Oakland (OAK).

The technical team consisted of researchers from the University of Missouri-Rolla (UMR), the University of California-Riverside (UCR), and Aerodyne Research Inc. (ARI). This team had the resources necessary to carry out a complex project of this nature in order to deliver the desired information to ARB. The field-ready, proven equipment included instrumentation for sampling and measuring CO, CO_2, NO_x, PM, and detailed chemical species emissions data from engines on modern commercial aircraft. Additionally, the South Coast Air Quality Management District analyzed the very volatile organic carbon gases (VVOCs, like methane) and the metals with their ICP-MS. As on past projects, representatives from Boeing and GE participated as advisors in the project. Roles of the various team members are shown below in Table 2 and the list of instrumentation and data acquired are reported in Table 3.

Table 2: Roles of Various Team Members

Project sponsor: ARB	***Manage contract, coordinate with FAA, airline, airport and principal investigator, verify deliverables are met***
Executive Team	
FAA	Aircraft contracts, operation & fuel costs
SWA	Provide aircraft
OAK	Space & security issues
UMRCOE	Principal Investigator, coordinate tech team members
Technical Team	
UMR	Sampling setup/probes
UMR/ARI	Measure real-time (RT) regulated gases
UMR	Measure RT PM size, number, penetration
UCR	Measure speciated hydrocarbons
UCR	Measure PM mass, EC/OC, metals, ions
ARI	Measure RT PM size/composition, selected gas species
South Coast AQMD	Analyses of light hydrocarbons & metals
Air Toxics Ltd.	Analyses of DNPH samples (upwind and downwind of test location)
Alta Analytical Laboratory, Inc.	Analysis of dioxin
Bay Area AQMD	Analysis of VOC samples (upwind and downwind of test location)
Desert Research Institute	Analysis of ambient PM samples (upwind of test location)
Frontier Analytical Laboratories	Analysis of dioxin
Boeing/GE	Technical advisors

Table 3: List of Instruments/Media to be Deployed for the Chemical and Physical Characterization of the Non-regulated Emissions in the Engine Exhaust

Analyzer/Sample Media (Lead)	Information collected
Mass Aerosol Sampling System (UMR)	Number and size distribution of PM
Cambustion DMS500 (UMR)	Real-time (RT) PM number & size distribution
Aerosol Mass Spectrometer (ARI)	RT PM chemical composition
TILDAS (ARI)	Up to four species: NO, NO_2, CO, SO_2, & trace species: HONO, HNO_3, & formaldehyde in real-time
Quartz substrates (UCR)	EC, OC, speciation of PM organics
Teflon substrates (UCR)	PM mass, ions, metals, Cr(VI)
SUMMA canister (SCAQMD)	C_1-C_8 organic HC speciation
Multi-bed traps (UCR)	C_4-C_{12} organic speciation
PUF/XAD cartridges (UCR)	C_{10}-C_{30} organic speciation
DNPH cartridges (UCR)	Carbonyl analysis

2.0 Materials and Methods

2.1 Aircraft Engines

Aircraft emissions vary with the engine type, the engine load/test cycle, ambient conditions, and the fuel used. Aircraft engines tested in JETS APEX2 were those attached to the Boeing 737 series of aircraft as these engines are used extensively for commuter service within California and neighboring states. The goal was to measure the emissions from B737-300 and B737-700 aircraft, from the commercial fleet of SWA, with engines made by CFM International. CFM International is a 50/50 partnership formed over 30 years ago between General Electric and French engine-maker Snecma Moteurs. Considerable detail on engine performance and market share can be learned from the CFM web page[1]. The CFM engines are the market leaders in every category in which they compete with 390 global customers and more than 14,200 engines in service. CFM claims an aircraft with their engines takes off every four seconds, every day. Table 4 lists the aircraft and number of CFM engines being used today.

Table 4: CFM56 Fleet Statistics (through October 2006)[1]

Aircraft	Engine	In-Service
E-3/KE-3/E-6	CFM56-2A	193
KC-135/RC-135	CFM56-2B	1,962
DC8-70	CFM56-2C	524
B737-300/-400/-500	CFM56-3	4,498
A319/A320	CFM56-5A	1,183
A318/A319/A320/A321	CFM56-5B	2,384
A340	CFM56-5C	1,090
B737NG	CFM56-7B	4,403
	Total	**16,237**

In APEX1, a DC-8 aircraft with CFM56-2C1 engines was tested. At JETS APEX2, engines that were newer and more representative of those in current commercial service were studied. Put in perspective, the CFM56-3 engine followed the CFM56-2 and was last manufactured in 1999. The newest engine, CFM56-7 was certified in 1994 and is being used because of its higher thrust, improved efficiency, and lower maintenance costs. It is the newest engine and the sole engine being installed on the newest 737's. Both the –3 and the –7 are much newer and more representative of current aircraft engines as the in-use numbers in Table 4 indicate.

A list of engines tested in the current study and associated airframes are listed in Table 5. Each aircraft had two engines that were tested giving a total of 8 engines sampled. This was the first test campaign involving simultaneous sampling from multiple engines on the same airframe. The measurement activities were performed during the late night hours of 9pm – 5am, since this was the time period for aircraft availability.

[1] http://www.cfm56.com/index.php?level2=engines&level3=1037

Table 5: List of engines tested and associated airframes

Date	Aircraft Tail No	Airframe	Engine
August 23, 2005	N435WN	B737-700	CFM56-7B22
August 24, 2005	N353SW	B737-300	CFM56-3B1
August 24, 2005	N695SW	B737-300	CFM56-3B1
August 25, 2005	N429WN	B737-700	CFM56-7B22

2.2 Location for On-wing Sampling

The location selected for carrying out testing of these aircraft engine emissions was the Ground Runup Enclosure (GRE) at Oakland International Airport (see Appendix A). The GRE shown in Figure 3, completed in 2002, is a $4.5M, three-sided facility that dramatically reduces the effects and propagation of jet engine run-up noise that occurs during engine maintenance work. This location proved to be an ideal setting in which to carry out the measurement activities without hindering normal airport operations. This venue offered other features that proved useful for emissions measurement. The side walls of the GRE reduced cross-wind plume deflection away from the downstream sampling probes. A typical problem with engine emission sampling is the variation of ambient conditions (temperature, pressure, humidity, wind, etc.) on engine performance, since these tests usually require long periods of testing (e.g. 8 hours). If variations in the emissions associated with changing ambient conditions are large, they will interfere with observations of emissions for predefined test matrix engine condition changes (fuel, power setting, engine type, engine on-time, etc.). This problem was greatly relieved for JETS APEX2 project since ambient conditions were very stable for Oakland Bay Area in August 2005. In particular, the prevailing wind direction was ideally situated with respect to the open face of the GRE facility as shown in Figure 4. Detailed wind roses generated from data collected by ARB during the test are included in Appendix B. The prevailing winds ensured a continuous exchange of air through the GRE and no evidence of engine exhaust recirculation was observed throughout the entire testing period. Also, Appendix C lists the DNPH cartridge sample results for various carbonyls. These samples were acquired at three locations – Upwind of the GRE, Downwind of the GRE and at the ARB trailer and values were less than 5ppb at all locations. Appendix D lists the results of the ambient canister sample analysis for Hydrocarbons. It is evident from the DNPH cartridge and HC canister analyses that the ambient levels of VOCs were negligible.

Figure 3: View of the GRE

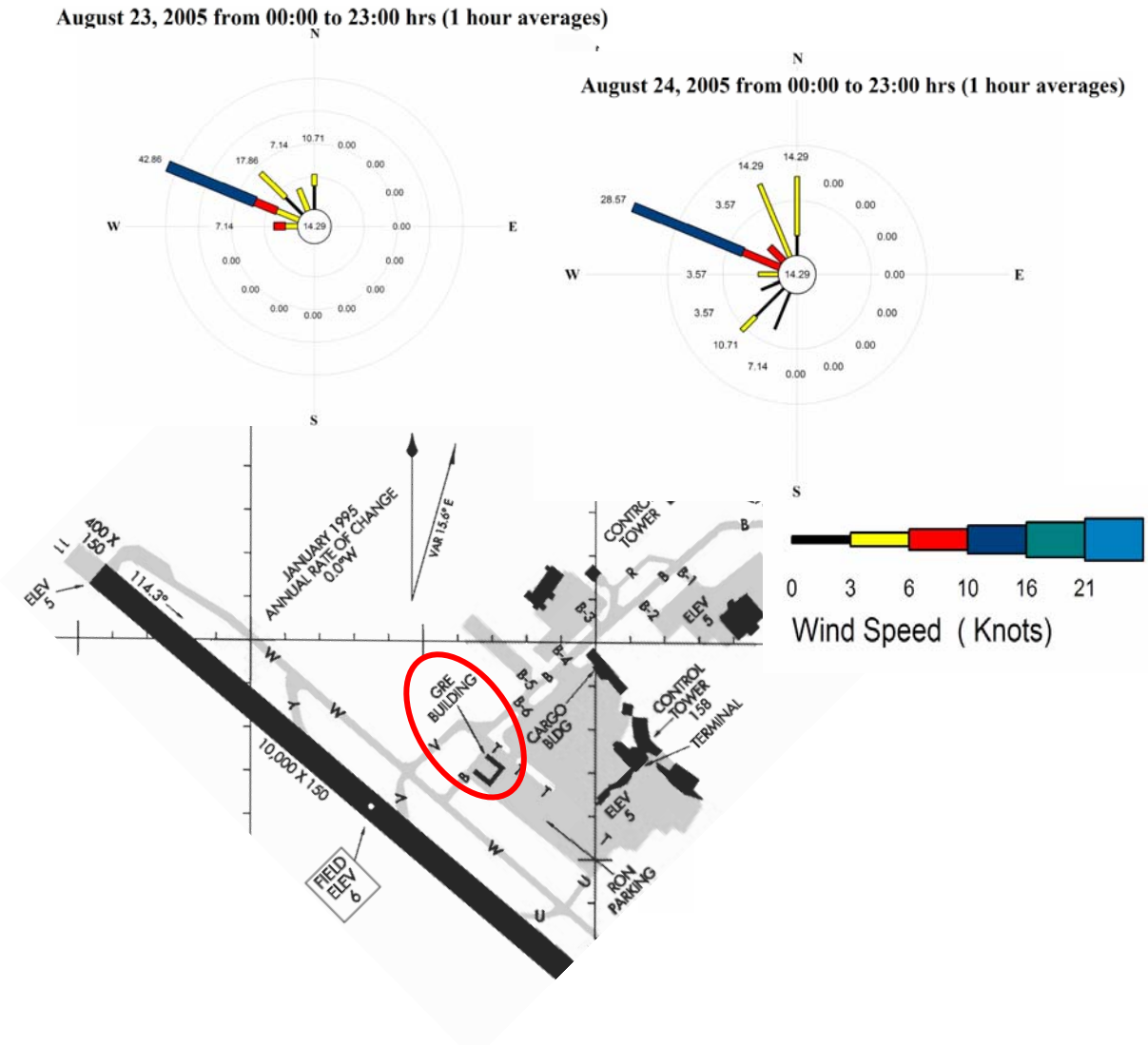


Figure 4: Wind-rose diagram giving prevailing wind orientation with respect to Runway and GRE facility

The orientation of the aircraft, sampling probes and mobile laboratories within the GRE are shown in Figure 5.

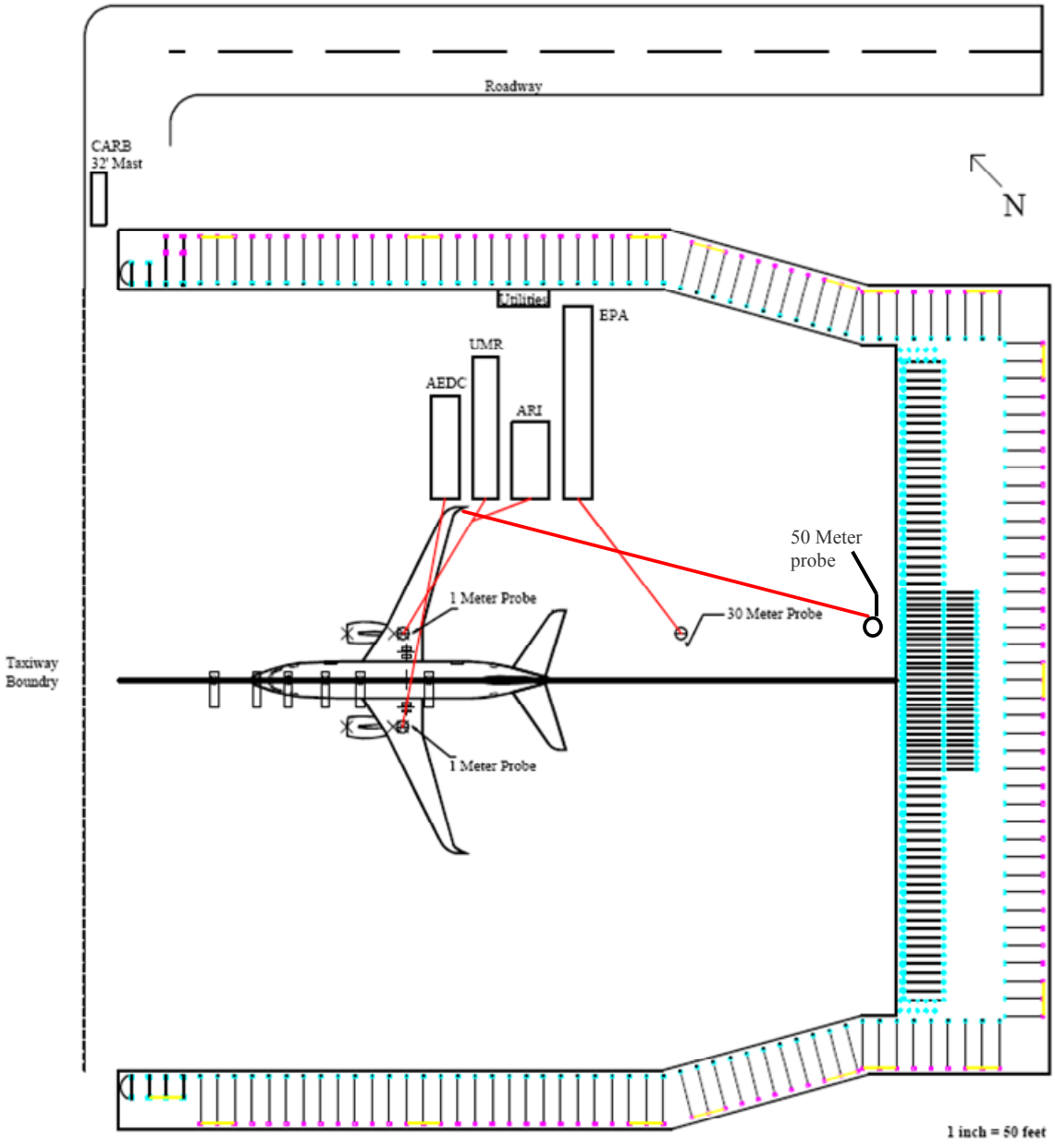


Figure 5: Layout within the GRE

2.3 Equipment for On-wing Sampling

Sampling jet engine exhaust for a parked aircraft is not a trivial exercise. Custom-designed probes and extensive support equipment were used to sample jet exhaust in the on-wing position. Particle-laden exhaust was extracted directly from the combustor/engine exhaust flow through probes and supplied to the measurement devices. The primary probe for collecting samples and data was positioned within 1 meter of the exhaust nozzle exit plane, as this position is representative of the engine signature and the certification data in the ICAO database. At this test, two primary sampling probes, one on the starboard side and the other on the port side of the aircraft, were used. Figure 6a shows an example of the starboard sampling rake system and Figure 6b gives a close-up view of the rake itself with the protective sample line shielding removed. More sampling rake details are given in Appendix E.

Figure 6a: Starboard sampling probe stand (left). Figure 6b: Probe rake with different probes (right)

The PM probes (see Figure 7) are designed to provide both probe tip and downstream (0.09 meters from tip) dilution flows, thereby reducing and/or eliminating probe effects. The rake quadrant and probes are water cooled to protect them from thermal degradation during testing. The dilution flows are drawn from particle-free, dry air sources located in the mobile laboratories and conducted to the probes through 0.006-meter (inside diameter) flexible gas lines. The sample for PM measurements are conducted to the mobile laboratories through a ¾" SS sample line for which line losses have been calibrated.

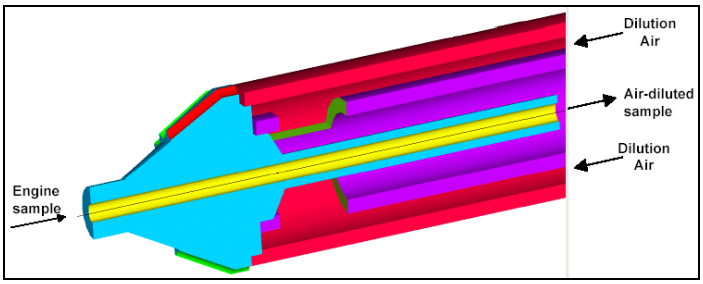


Figure 7: Particulate Sampling Probe

The gas samples are conducted to the mobile laboratories through heated sample lines which are designed in accordance with Aerospace Recommended Practice (ARP) 1256. The mobile laboratories are typically located near the aircraft wing tips (Figure 5). Even on the largest transport aircraft, the sample lines between probes and laboratories are typically ≤30 meters long. A sophisticated sample probe and sample train was needed to collect the exhaust sample and deliver it to each experimental group's suite of instruments. Figures 8 and 9 both present the probe and sample train systems, with Figure 8 emphasizing the sample train and Figure 9 the probes.

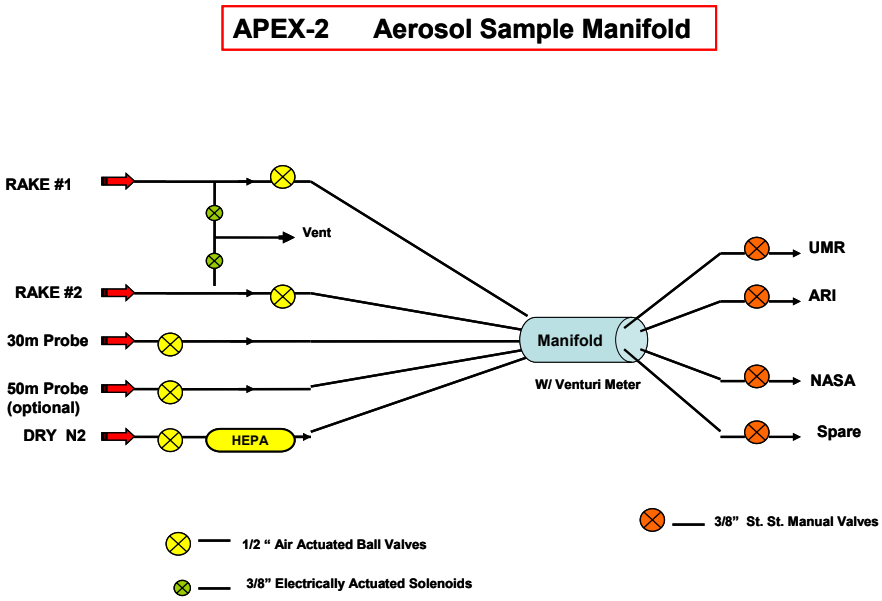


Figure 8: Aerosol sample manifold

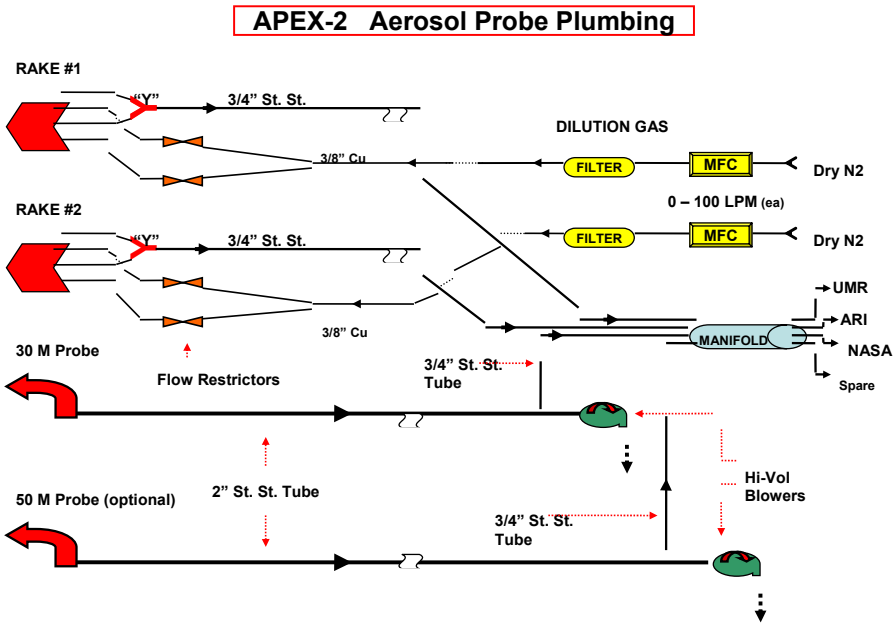


Figure 9: Aerosol probe plumbing

Four probe rakes were employed, with one probe rake located 1m behind the starboard engine, one 30m and another 50m downstream of this engine, plus one 1m behind the port engine. In this report, data from the 1m and 50m locations are presented. The PM physical characterization of the 30m aerosol was not possible since the line loss function was not available. In order to collect sufficient sample flow from the 1m rakes, two probes were always coupled. Dry nitrogen for dilution was introduced into the flow at the probe tips on the 1m rakes. The dilution was used to suppress particle-particle interactions and gas-to-particle conversion. The amount of dilution gas was controlled by observing the CO_2 concentration in the sample line and keeping it at a desired level. Typical dilution ratios were in the range 10-40. Both aerosol and gas samples received the same dilution. No diluent was provided at the 50m location since sufficient dilution with ambient air was found to have occurred naturally in the plume. In order to maximize the amount of data acquired per unit of engine run time, it was necessary to avoid spending time to flush stale air from the 1m sample lines that aged during times when that line was not being used. This was accomplished by always running fresh sample through the lines and dumping sample when it was not being analyzed. The lines and valves leading to the vent shown in Figure 8 were used for this purpose. No line switching was done on the 50m sample train, so this was not an issue at that location. As shown in Figures 8 and 9 the sample was first delivered to a manifold, located in the UMR trailer. From there it was delivered in separate sample lines to each instrumentation group (UMR, ARI, and NASA).

2.4 Test Cycle

The test cycle for the EPA procedure is specified in 40CFR Part 87, Control of Air Pollution from Aircraft and Aircraft Engines, and was derived from traffic surveys at major U.S. commercial and general aviation airports: Los Angeles International, Chicago O. Hare, New York John F Kennedy, Washington National (now Regan National), Van Nuys, CA and Tamiami, FL. As is evident in Figure 10, the test procedure represents the four modes in the landing and takeoff (LTO) cycle: approach, taxi/idle-in, taxi/idle-out, takeoff and climb-out.

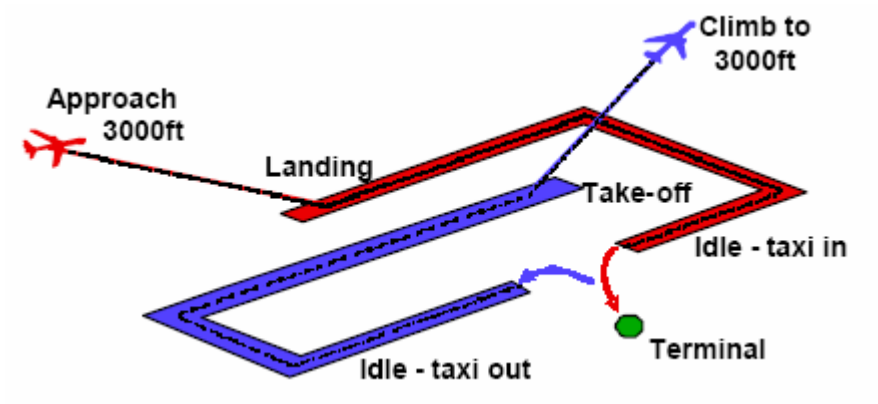


Figure 10: Schematic diagram of the Landing and Take-Off cycle

EPA considered operations below 3000 feet altitude to be a reasonable approximation of the atmospheric mixing height over major U.S. metropolitan areas. The actual thrust setting (percentage of rated thrust) and weighting factors (times) for the LTO cycle are shown in Table 6 below.

Table 6: EPA's LTO Thrust Settings &Time-in-Mode

Operating Phase	Thrust setting (% of rated thrust)	EPA Time in Mode, minutes
Taxi/idle	7%	26
Takeoff	100%	0.7
Climb-out	85%	2.2
Descent*	NA	NA
Approach	30%	4

*Descent not used in EPA cycle

For this test, the EPA protocol was used as a guide and testing at six thrust settings: 4%, 7%, 30%, 40%, 65%, and 85%, was performed. The intermediate points were added to allow a careful definition of the point at which the Emission Index for the PM rapidly increases more than 10-fold. Rather than collecting one sample over all modes in the LTO cycle, UCR measured PM and other species at each thrust setting and determined

individual modal mass emission rates. This approach will allow ARB and FAA to calculate the emissions appropriate for any airport of interest. Data for the operating aircraft and the atmospheric conditions were recorded during the test.

Figure 11 illustrates the test matrix used in this campaign. The test matrix was designed for 10 minutes of stable engine operation at each test point with the exception of the 85% test point which was limited to 2 minutes due to engine operations constraints recommended by Boeing and required by SWA.

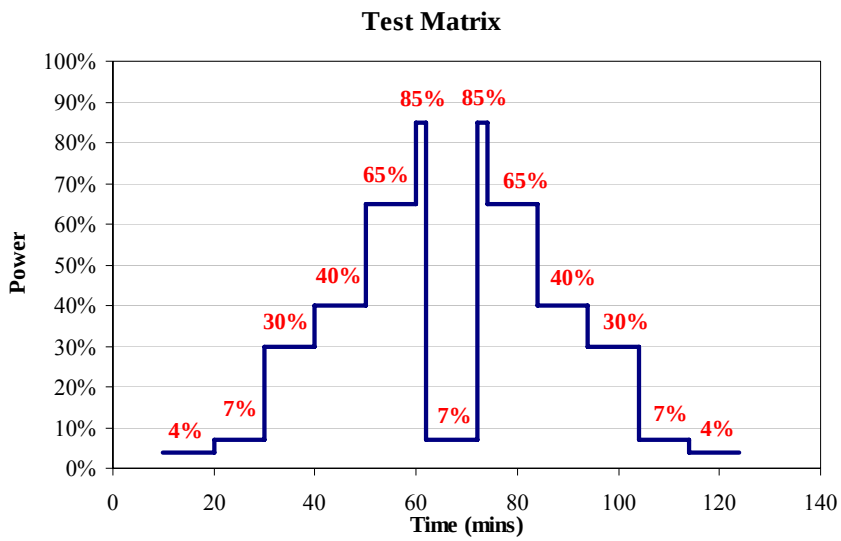


Figure 11: Test Matrix used at JETS APEX2

2.5 Fuel

Fuel for the test was that generally used in the aircraft (Jet A) and samples were taken for subsequent analysis by ARB for aromatics and sulfur content (see Appendix G). The hydrogen/carbon ratio was obtained since this ratio is needed to interpret the combustion data (see Appendix H). A sample of the lubricant was also taken by EPA, but these have yet to be analyzed.

2.6 ARI Methodology

The measurement instrumentation and sampling scheme used during JETS APEX2 were similar in concept, though different in many details, to those which were used in the NASA/Qinetiq (Whitefield et al. 2002), EXCAVATE (Anderson et al. 2005), and APEX1 (Wey et al. 2006) test programs. A suite of particle and trace gas measurement instruments was housed in the Aerodyne Mobile Laboratory, a panel truck specially modified for this purpose (Figure 12). A single probe tip from the port or starboard 1 m rake or one of the downstream (30 or 50 m) probes was selected for measurement. A sample line entered the truck, and the sample flow was split isokinetically into two halves: one directed to the suite of particulate characterization instruments (AMS,

MAAP, CPC), and one to the trace gas instruments including the TILDAS, chemiluminescence, and PTR-MS instruments. Carbon dioxide (CO_2) was measured in both flows using separate NDIR CO_2 measurement instruments. The particle instruments were located on the left-hand-side of the truck and isokinetically sampled aerosol behind a PM2.5 cyclone. All instruments in the mobile lab sampled from the same inlet line.

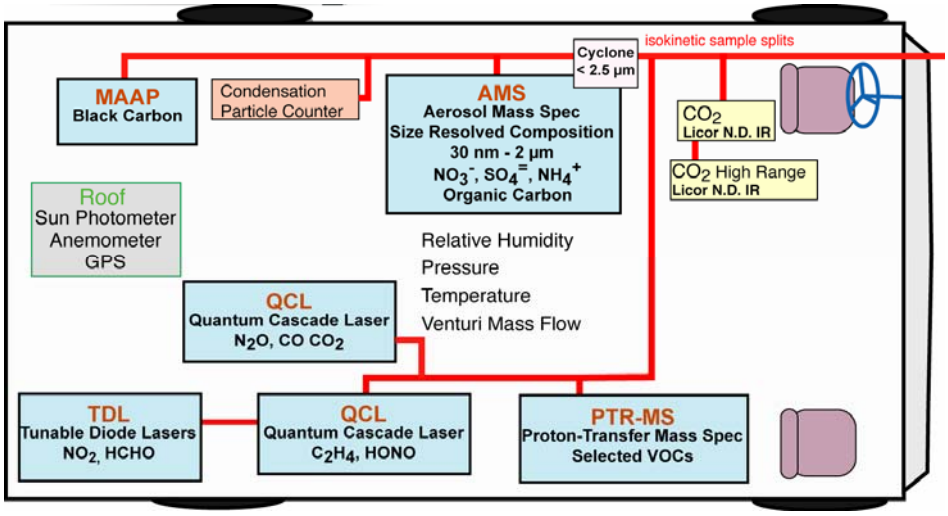


Figure 12: Schematic of the Aerodyne Mobile Laboratory

The sampling lines from the Aerodyne mobile laboratory were connected to a distribution manifold, which distributed sample flow pulled from the several probes located downstream in the aircraft engine exhaust to the various particle-based research groups participating in JETS APEX2. The manifold was operated at sub-ambient pressures and was setup to provide ready access to any particular particle probe for a given engine condition. The manifold pressure was constant at 650 Torr when sampling from the 30 or 50 meter probes, under all engine power settings. The probe dilution flows were monitored and controlled when necessary.

In JETS APEX2, both particle and gas phase chemical species compositions were determined. The primary gas phase emissions, which are also regulated for engine certification, are NO_x, CO, and unburned or partially combusted hydrocarbons. These gaseous species were quantified using chemiluminescence (CL, for NO), tunable infrared laser differential absorption spectroscopy (TILDAS, for NO_2, CO, HCHO, and C_2H_4), and proton transfer reaction mass spectrometric (PTR-MS, for hydrocarbons) techniques. These chosen techniques are different from the regulatory requirements, but allow more detailed exhaust speciation to be determined.

For particle phase speciation, an Aerosol Mass Spectrometer was used (AMS, for size resolved sulfate and organic condensed mass), in conjunction with a Multi-Angle Absorption Photometer (MAAP, for black carbon particle mass) and a Condensation

Particle Counter (CPC, for particle number count). These measurements provided the concentration and size resolved composition of particles ranging from about 30 nm to 1000 nm vacuum aerodynamic diameter.

2.6.1 Gas Phase Instrumentation

2.6.1.1 Tunable Infrared Laser Differential Absorption spectrometers (TILDAS)

Two different types of lasers were used in the TILDAS instruments: tunable lead-salt diode lasers, which operate in a continuous mode and at near liquid nitrogen temperatures, and quantum cascade lasers, which operate in a pulsed mode and at temperatures allowing thermoelectric cooling rather than cryogenic cooling (Nelson et al. 2004). Quantum Cascade -TILDAS systems were used to measure NO_2 in the spectral region of 1606 cm^{-1}, C_2H_4 in the spectral region of 968 cm^{-1}, CO in the spectral region of 2183 cm^{-1}, and acrolein in the spectral region of 959 cm^{-1}. A lead-salt TILDAS system was used to measure HCHO in the spectral region of 1725 cm^{-1}.

2.6.1.2 Chemiluminescent NO sensor

A Thermo-Electron model 42c chemiluminescent detector was used for the NO measurements. The detection method is based on the detection of chemiluminescence stemming from electronically excited NO_2 molecules produced by the reaction of NO with a small flow of ozone added to the sample flow (Heard, 2006).

2.6.1.3 Proton transfer reaction - mass spectrometer (PTR-MS)

Hydrocarbons were measured using a PTR-MS operated by Berk Knighton, Montana State University. The PTR-MS (Ionicon Analytic GMBH) is a chemical ionization based mass spectrometry method that utilizes H_3O^+ as a reagent ion. This instrument has been described elsewhere (de Gouw et al. 2003), so that only a brief description of the relevant details is provided here. The instrument consists of an ion source, a drift tube reaction region and a quadrupole mass spectrometer. H_3O^+ reagent ions formed in the hollow cathode discharge ion source are electrostatically injected into the drift tube through which the sampled air stream is continuously passed at reduced pressure, 1.9 mbar. These H_3O^+ reagent ions are pulled through the air sample by an electric field where they can react via proton transfer reactions with those components in the sample having proton affinities greater than that of water. The reagent ions and the resulting proton transfer reaction products are mass selected and detected using the mass spectrometer.

The PTR-MS sampled the exhaust stream from the main sample inlet through a short length of 1/8” O.D. Teflon tubing. A fraction of the sampled exhaust enters the drift tube reaction region where those components of the sample having proton affinities greater than that of water undergo proton transfer reactions with H_3O^+ reagent ions. The mass spectrometer monitored a selected set of 32 ions at 0.2 seconds per mass, along with the drift tube pressure and temperature, which yielded a cycle measurement time of approximately 8 seconds. The ions monitored included the reagent ions H_3O^+ (m/z 21 O-

18 isotope) and $H_3O^+(H_2O)$ (m/z 39 O-18 isotope), the diagnostic ions NO^+ (m/z 31) and O_2^+ (m/z 32) and the sample ions as presented below.

The sampled exhaust flow stream was periodically diverted through a heated Pt catalyst (400°C) to provide a VOC free gas stream for determining the instrumental background. In many cases the Pt catalyst did not efficiently remove the VOCs from the exhaust sample stream, and this reduced efficiency has been attributed to poisoning of the catalyst due to the sulfur content of the fuel. Under circumstances where the catalyst appeared to be compromised, instrumental background measurements were determined when the main inlet was purged with N_2 blow off from a liquid N_2 dewar. The instrumental background is non-zero for most masses and the reported concentrations reflect the difference between the sample and background signals. The concentration of a HC emission component (R) can be deduced from the measured ion signals using relationships derived either from simple reaction kinetics or from calibrated response factors (Knighton et al., 2007). For compounds where calibration gas standards were not available, the concentrations were calculated by assuming that simple reaction kinetics were applicable (Knighton et al., 2007).

Trace gas levels are reported as emission indices, expressed in units of grams of trace gas emitted per kg of fuel consumed. The fuel consumption and CO_2 emission are proportional, so trace gas emission indices can be derived from the trace gas concentration and CO_2 concentration observed in the exhaust sample. The CO_2 concentration used must have the contribution due to ambient CO_2 subtracted out, and if the sample has been diluted, that dilution factor must be known before the subtraction of the ambient CO_2 can be carried out. The formula used to convert trace gas concentrations in parts per million by volume (ppmv) is

$$\text{EI (trace gas)} = \frac{3160\ MW_t\ (\text{trace gas concentration, ppm})}{44.01((CO_2\ \text{concentration, ppm}_v) - (\text{ambient } CO_2, \text{ppm}_v)/\text{dilution})} \qquad \text{(Eq. 1)}$$

where 3160 is the CO_2 emission index, g CO_2 per kg of fuel, MW is the molecular weight (g/mole) of the trace gas, and 44.01 is the molecular weight of CO_2. For the emission index of nitrogen oxides, NO and NO_2, MW is taken to be 46.01, that is, the NO emission indices are reported as equivalent g NO_2 per kg of fuel. In cases where the sample was not diluted we subtracted an ambient CO_2 concentration of 380 ppmv, while for samples that were diluted by a factor of 2 we subtracted 190 ppmv, and so on. For the 30 m and 50 m sampling data, where fluctuations in observed concentrations were large, a different procedure was used, in which a regression of trace gas concentration against CO_2 concentration was used to simultaneously derive the emission index (from the slope) and the term "(ambient CO_2, ppmv)/dilution" (from the intercept). For time histories in which the relative variance of the trace gas concentration is large this is the preferred method, while when the relative variance is small it is preferable to average the records of trace gas and CO_2 concentrations over the time for a given engine condition and use the averages in the above formula.

2.6.2 Particle measurements

The particle measurements were conducted using the Aerodyne Aerosol Mass Spectrometer (AMS) to characterize the volatile chemical compositions and chemically-speciated size distributions, a Condensation Particle Counter to measure the total particle concentration, and a modified Multiangle Aerosol Photometer (MAAP; Thermo Electron) to measure the aerosol absorption and derive black carbon mass concentrations. The particle instruments were operated downstream of a PM2.5 (UGI) cyclone to remove large particles.

2.6.2.1 Aerosol Mass Spectrometer

The Aerodyne Aerosol Mass Spectrometer (AMS) has been described in detail in the literature (Jayne et al. 2000). The AMS sampled aerosols into a high vacuum and focused the particles into a tight beam using an aerodynamic lens. The focused particle beam exiting the lens was directed through a particle-sizing chamber and impacted on a 3.8 mm circular vaporizer held at 600°C. By mechanically modulating the particle beam with a chopper and using the time-of-flight (TOF) of particles between the chopper and the detector, the particle velocity and the vacuum aerodynamic diameter were obtained. The particle detection scheme consisted of a vaporizer that was coupled into the ionizing cage of a time-of flight mass spectrometer (MS). When the particles struck the vaporizer surface, the nonrefractory (volatile and semi-volatile) components of particles flash vaporized. The vaporization plume was ionized using standard 70 eV electron impact ionization techniques and extracted into the mass spectrometer, spanning a range of 1-300 atomic mass units. The AMS was operated during this study with a time-resolution of 30 seconds, alternating every 15 seconds between a TOF mode (particle mass distributions as a function of size) and a MS mode (particle chemical speciation and quantitative mass loadings) (Jimenez et al. 2003).

Quantitative mass calibration of the instrument was performed by using a pure ammonium nitrate aerosol source. Particles were generated with an atomizer (TSI, model 3076, USA), dried using silica gel, size-selected using a differential mobility analyzer (TSI, model DMA 3071) and sampled simultaneously by the AMS and a CPC (TSI, model 3022a). Multiply charged particles were eliminated using an impactor upstream of the DMA and the AMS isokinetically sampled from the CPC aerosol flow to ensure identical size distributions. The well-characterized aerosol sample calibrated the electron multiplier signals at m/z 30 and 46 for nitrate (NO_3^+) and 15, 16, and 17 for ammonium (NH_4^+). The AMS analysis uses relative ionization efficiencies measured in previous laboratory studies to calibrate for the chemical species present in aircraft exhaust (sulfates and organics). During this experiment, the AMS had a nitrate ionization efficiency of 6.9×10^{-6} ions/molecule and detection limits (three times the standard deviation) of 0.024 and 0.26 $\mu g/m^3$, respectively for sulfates and organics.

2.6.2.2 Multi-Angle Aerosol Photometer

Aerosol black carbon concentrations were derived with a Thermo Electron Multi-Angle Aerosol Photometer (MAAP). A detailed description is provided in the literature

(Petzold et al. 2002; Petzold and Schonlinner 2004). The MAAP is a filter-based photometer that deposits aerosol onto a 2 cm^2 spot on a quartz fiber filter tape. A 630 nm wavelength LED shines on the spot and multiple photodetectors measure the transmission and scattering/reflection of the light from the depositing aerosol layer and the underlying filter. A two stream radiation transfer calculation is used to separate the absorption of the light by the aerosol layer from the scattering of light by the particles and filter matrix (Petzold and Schonlinner 2004). A narrow range of values of σ_{abs} (~6.4-6.6 m^2 g^{-1}) is reported to provide a decent fit for commercially-produced black carbon particles and urban particles containing black carbon collected at several sites (Petzold and Schonlinner 2004). A value of σ_{abs} = 6.6 m^2 g^{-1} is currently used to calculate the instantaneous black carbon mass loading on the filter at a rate of 1 Hz. The MAAP was operated with a flow rate of 8 lpm using custom plumbing. The precision of the MAAP for deriving black carbon mass loadings under these operating conditions is ± 2.4 $\mu g/m^3$.

2.6.2.3 Particle Counting Instrument

The total aerosol concentration was measured with several Condensation Particle Counters (CPC; TSI model 3022a and 7061). The CPC supersaturates a sample flow with butanol vapor, causing submicron particles to grow in size into the supermicron size range where the particles are detected via individual light scattering pulses at low concentrations and via ensemble particle scattering at high concentrations. The 3022a CPC has a 50% cut size of 7 nm at atmospheric pressure, a response time of < 10 seconds for 90% step change, and can sample particle concentrations up to 10^7 cm^{-3}.

2.6.3 Emission Indices

LiCor infrared absorption instruments were used to measure the gas phase CO_2 concentration in the sampled plume. The gas phase CO_2 concentration was used to relate the measured particulate mass loading to fuel-based particulate mass emission indices (EI's), with units of milligrams of PM per kilogram of fuel burned (mg per kg fuel). Following the methodology described in Herndon et al. (Herndon et al. 2005), for a given exhaust component concentration, X, the EI(X) is calculated by

$$\mathrm{EI(x)} = (\Delta X/\Delta CO_2) \times \mathrm{EI}(CO_2) \times M_{air}/M_{CO_2} \times (1/\rho_{air}) \qquad \text{(Eq. 2)}$$

where $\Delta X/\Delta CO_2$ is the emission ratio for the exhaust component, M_{air} is the molar mass of air, M_{CO_2} is the molar mass of CO_2, and ρ_{air} is the density of air at ambient conditions. This expression is based on 100% conversion of the carbon in the fuel to CO_2. Corrections for incomplete combustion can be made, based on measurements of CO and hydrocarbon emissions, but these corrections are within experimental uncertainties for the measurements reported here. EI (CO_2) equals 3160 g CO_2 (kg fuel)$^{-1}$ for most available Jet A fuel, within a few percent. This value can be replaced with that appropriate for a given fuel where the mass fraction of hydrogen in the fuel is known (or equivalently if the C/H ratio is known). EI's are also calculated for particle number concentrations (number per kg fuel) using a slightly modified version of this formula.

2.7 UMR Methodology

UMR has developed a mobile diagnostic facility and a sampling methodology which are optimized for jet engine exhaust characterization using extractive sampling techniques. These have been developed and refined over the last 26 years. Our earliest ground based engine tests were conducted during NASA's project FIRE (Hagen et al., 1994; Hagen et al., 1995; Sassen et al., 1995 ; Podzimek et al., 1995) using a hand held sampling probe behind gas turbine engines at low power with aerosol characterization instrumentation mounted in one of NCAR's (National Center for Atmospheric Research) aircraft for airborne work. This ground sampling was done as an opportunistic addition to project FIRE, which was an airborne sampling program. In subsequent work, (Hagen et al., 1997; Hagen et al., 2003; Hagen et al., 2005; Whitefield et al., 1995; Whitefield et al., 1997; Whitefield et al., 2001; Lilenfeld et al., 1995) ground based sampling became a dominant issue, and the aerosol instrumentation was installed in mobile trailers, which increased in size as time progressed, and the sampling probes and stands became evermore sophisticated. Over this time the mobile sampling facilities have been used in numerous test campaigns at airports with parked aircraft, NASA and industrial facilities having combustor and engine test stands, and at venues having altitude chambers. An overall review of the UMR facility and methodology has been reported elsewhere (Schmid et al., 2004). A schematic of the UMR mobile diagnostic facility is presented in Figure 13.

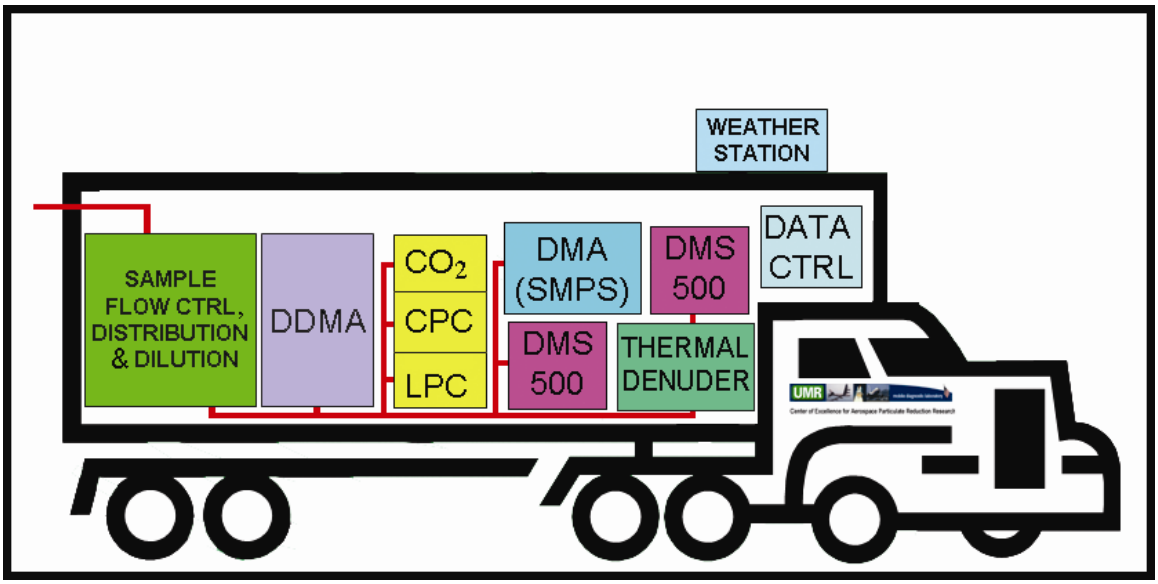


Figure 13: Schematic of the UMR Mobile Diagnostic Facility

Extractive sampling is employed, i.e. the exhaust sample is pulled into a probe, near isokinetically if possible, and diluted with a clean and dry gas, e.g. air or nitrogen. The diluent sheaths the sample near probe tip to minimize thermophoresis, turbulence, diffusion, and impaction. It is then transported to the instrument trailer(s) in a sampling train that is well calibrated for line loss. The UMR system includes flow control systems to support diluent to two active probes simultaneously.

The instrumentation suite in the UMR trailer is flexible and varies from test to test. The following instrumentation is usually included in most test campaigns. A pressure reduction system consisting of a selection of calibrated orifices is available to reduce the sample line pressure to near ambient where most of instrumentation needs to work. This is designed to handle only the small ram pressures associated with sampling at high power conditions, not those expected from sampling directly from combustors. Normally the sample line flow is allowed to increase so that the pressure can be dropped across the probe tip orifice. In cases where this is not practical, our pressure reduction system can be employed.

Condensation Particle Counters (CPC) (TSI 3022 and 3025) are used to measure total particle concentration. Particle size distributions are measured with Differential Mobility Spectrometers (DMS) (Cambustion DMS500) and Differential Mobility Analyzers (DMA) (TSI 3071). The DMA uses a single channel which is swept through different sizes over time, and the newer multi-channel electrometer-based instrument, DMS500, measures a full set of sizes simultaneously. We employ two of the new and fast instruments which run in parallel, one being downstream of a thermal denuder. This allows both the total and non-volatile components of the aerosol to be measured simultaneously. This combination of information can be used to characterize the aerosol's volatility, assess the sampling train for anomalous particle generation and to characterize plume processing of the emission aerosol size distribution. The new fast response instruments allow for much shorter engine run times in order to complete the measurements, and the characterization of transients in the emissions, e.g. those during throttle changes. The older, slower sizing instrument is normally run in parallel with the faster ones in order to accomplish a quality check on the data, and to allow measurements to be made in the case of very clean engines where the signal (particle concentration) is insufficient for the newer instruments. These fast mobility instruments also yield total particle concentration measurements which complements those from the CPC. The DMS500 instruments cover a broad size range, from 5 nm up to 1 μm. A laser particle counter (LPC) is used for size distribution measurements in the large size regime, diameter > 0.5 μm. Hence there is a region of overlap between the DMS500 and LPC. Typically gas turbine engines produce little emissions in the LPC's size range.

The exhaust aerosol's hydration behavior is characterized using the deliquescence technique with a Deliquescence DMA (DDMA). The aerosol is subjected to a high relative humidity, below but near 100%, and its size distribution is re-measured using the DMA technique. Their change in size due to humidity change can be used to determine their critical supersaturation and their soluble mass fraction, i.e. their response to water vapor. This is an important parameter which strongly influences their behavior in the atmosphere. Normally if their soluble mass fraction is zero at engine exit, it is too hot for soluble material to form. However at only 30 to 50m of plume processing, soluble material can be detected. An electrostatic precipitator is used to collect aerosol samples on an electron microscope grid for subsequent off-line single particle analysis. This can be used for morphological information using TEM (Transmission Electronic Microscopy). CO_2 concentration is measured in an undiluted sample line and also in the

diluted sample line, which is used for particle characterization. CO_2 is chemically inert and its emission index for jet fuel is well known. The CO_2 measurement allows an accurate measure of the dilution of the sample, which is necessary for corrections of the data to probe tip concentration values, and can be used to evaluate emission index values for the particle data. A weather station is used to get ambient wind, temperature, and pressure data near the test site. These parameters can influence engine performance and the probability that the exhaust plume reaches downstream sampling probes.

Two other features of the UMR mobile laboratory greatly facilitate successfully accomplishing emissions testing at the diverse range of available venues. A diesel powered electrical generator (60 kW) is available to provide electricity for instruments, lights, air conditioning, etc. In many situations ground supplied electric power is not available, or would be prohibitively expensive. An elaborate communications system is available to handle voice communications between instrument operators within our trailer, test directors in our trailer or external, and colleagues in other instrumented trailers and vans from other institutions. Data acquisition and running the test engine must be coordinated, and this is actually a complicated problem requiring a sophisticated communications system. The trailers and instrumentation need to be relatively close to the engine under test, and engines are very noisy. The communications system must handle both voice communications and noise suppression. Hardware was acquired and software developed to allow digital communications between the large number of computers involved the test campaign. This includes UMR computers and those of colleagues and test managers collaborating in a test campaign. In many cases a few real-time plots can communicate more than many minutes of voice information.

2.7.1 DMS500

The DMS500 instrument is a new device which depends on electrical mobility for particle sizing (Biskos et al. 2005), and has been used primarily for investigation of fast changing spectra such as diesel engine emissions, drug delivery systems such as inhalers, and roadside ambient aerosol sampling. In this instrument the aerosol sample is passed through a cyclone separator to remove particles larger than 1 μm. It is then given a known charge distribution using a corona charger. The aerosol is then charged, inserted into a clean laminar flow air stream, and subjected to an electric field which deflects (in a size dependent manner) the particles' trajectories toward electrometer rings. The currents resulting from the charge transported to the electrometer rings by the particles are measured and the current-electrometer data matrix is converted into particle number and size classification. Since the various electrometer currents are measured simultaneously rather than sequentially, the measurement is fast, up to 10 Hz.

2.7.2 PM parameters

The characterization of the exhaust aerosol is accomplished using the following parameter set.

(1) The size distribution is described by a differential concentration function $N(D_p)$, dependent on particle diameter (D_p), which specifies the concentration of particles, dn, having the logarithm of their diameters between $\log D_p$ and $\log D_p + d\log D_p$ to be $N*d\log D_p$. The logarithmic scale is used since aerosol diameter covers such a large size range.

$$dn = N * d\log D_p \qquad \text{(Eq. 3)}$$

(2) Number-based geometric mean diameter (Dgeom), defined by the equation

$$\log Dgeom = \frac{1}{n_0}\int_0^\infty \log Dp * dn = \frac{1}{n_0}\int_0^\infty \log D_p * N * d\log D_p \qquad \text{(Eq. 4)}$$

where $\mathbf{n_o}$ denotes the total particle concentration,

$$n_0 = \int_0^\infty N * d\log D_p \qquad \text{(Eq.5)}$$

(3) Geometric standard deviation (Sigma), defined by

$$\log \sigma_g = \left(\frac{\int_0^\infty \left(\log\left(Dp / Dgeom \right) \right)^2 Nd\log D_p}{n_0 - 1} \right)^{1/2} \qquad \text{(Eq. 6)}$$

(4) Mass-based geometric mean diameter (DgeomM), defined by

$$\log DgeomM = \frac{1}{\int_0^\infty D_p^{\,3} * N * d\log D_p} \int_0^\infty \log D_p * D_p^{\,3} * N * d\log D_p \qquad \text{(Eq. 7)}$$

(5) Number based emission index (EIn), the number of particles per kilogram fuel burned can be calculated by

$$EIn = EI_{CO_2} \frac{N_0}{M(CO_2)} \qquad \text{(Eq. 8)}$$

where EI_{CO_2} denotes the mass emission index of CO_2 (for aircraft engines EI_{CO_2} = 3160 g/kg; (Schulte and Schlager (1996)). $M(CO_2)$, the mass of CO_2 per volume exhaust sample, is calculated by multiplying measured CO_2 mixing ratios with $(44/29)\rho_{air}$, where ρ_{air} is the air density and 44/29 is the molar mass ratio of CO_2 and air. Strictly speaking, in Eq. 8 both N_0 and $M(CO_2)$ have to be values above ambient, i.e. enhancements over the background signal. However, for measurements close to the engine exit plane of gas turbine engines, the background signals are negligibly small.

(6) Mass-based emission index (EIm) is the mass of particles per kilogram fuel burned and its calculation is analogous to that for EIn and is given by

$$E\,\mathrm{Im} = EI_{CO_2}\frac{M(N_0)}{M(CO_2)} \qquad \text{(Eq. 9)}$$

where $M(N_0)$ is the mass of aerosol per unit volume of exhaust sample.

2.7.3 Line loss characterization

Modification of the aerosol size spectrum due to line loss is an artifact associated with extractive sampling which must be accounted for with calibration experiments. Inertial, thermophoretic, and diffusional effects contribute to the loss of particles in the sampling train. The penetration of particles through a sampling system is size dependent. While it is harder to experimentally quantify losses due to thermophoretic effects, inertial and diffusional losses can be handled by calibration and accounted for in the data reduction. The source aerosol used in line calibration studies must be stable and free of any volatile compounds and moisture as these have a tendency to induce nucleation and interact with soot particles hence altering the size distribution within the sample lines. It is preferable for it to be a combustion source since the sampling train is used to transport combustion aerosols. The source aerosol must also have a sufficient population in the size regime of interest for gas turbine emissions (~ 8-200nm). The sampling system design should minimize line length and aerosol transit time. Bends, flow meters, and valves in the sampling train should be avoided where possible, as these typically involve substantial loss.

UMR has performed a number of such line loss calibration experiments to characterize the loss of particles in the sampling train for previous field campaigns. In these experiments, a poly-dispersed combustion aerosol generated from diesel truck exhaust – a surrogate for a gas turbine engine is used as the calibration source. Lack of availability of a gas turbine engine and the costs associated with running such an engine make it impractical to use in this type of calibration experiment. The DMS500 is used to obtain the penetration as a function of size. It provided distinct advantages for such calibration measurements. With the DMS500, a poly-dispersed source could be employed to provide fast simultaneous size dependent losses for particle diameters ranging from 5 to 1000 nm.

The concentration of the poly-dispersed aerosol is measured with the DMS500 at two locations for the sampling train: the probe tip and the end of the sampling train. The ratio of the concentration of aerosol at the end of the sampling train to the concentration at the probe tip provided the penetration factor (Pen) for the selected aerosol size. This experiment is repeated a number of times for different aerosol sizes (20-300nm). A function is fitted to the experimentally obtained data and this function is then used to correct all particulate data for line loss.

2.7.4 Soluble Mass Fraction

The evolution of combustion particles in the atmosphere is strongly influenced by their ability to interact with water vapor. This characteristic was investigated with a deliquescence technique (Alofs, 1978; Alofs and Trueblood, 1981; Li et al., 1992), where a tandem DMA with an intermediate saturator was used to measure the particles' dry and wet diameters.

The UMR Deliquescence apparatus (DDMA) is designed to determine the fraction of soluble mass in the average aerosol particle of a given, predetermined dry size. It utilizes two differential mobility analyzers (DMA) with a humidifier in between them. The first DMA selects a narrow band of diameters and passes these particles on to a region of precisely controlled, high relative humidity or water saturation ratio (typically SR=0.93). If these aerosol particles contain any soluble mass, then they will take on liquid water, i.e., they will deliquesce or grow to some new equilibrium diameter. This new equilibrium diameter is a function of the dry diameter, the saturation ratio in the humidifier, and the fraction of soluble mass in the particle. The deliquesced aerosol then passes through the second DMA (the sheath air for this DMA is also brought to SR = 0.93). Here a computer controlled size sweep is performed and the wet diameter is obtained. As stated earlier, knowledge of the dry diameter, the saturation ratio, and the wet diameter is sufficient to determine the Soluble Mass Fraction (SMF) for that aerosol.

SMF increases with distance from engine exit plane as the time allowed for the aerosol particle to scavenge soluble species like H_2SO_4 increases. The average aerosol particle contains essentially no soluble material if captured by the probe at the engine exit plane, since the sample is diluted while it is still very hot, i.e., chemical reactions are quenched.

2.8 UCR Methodology

UCR's role in the JETS APEX2 project was to sample and dissect the jet exhaust, measuring all hydrocarbon species from C_1 to C_{30}+ and speciating the particulate matter (PM) into important constituents like elemental and organic carbon, ions, elements, etc. A further requirement was that UCR had to make these measurements for each of the modes while the aircraft engine followed the modified EPA LTO sequence that was used for the testing in JETS APEX2 (Figure 14). UMR and ARI had successfully used this test sequence in earlier tests.

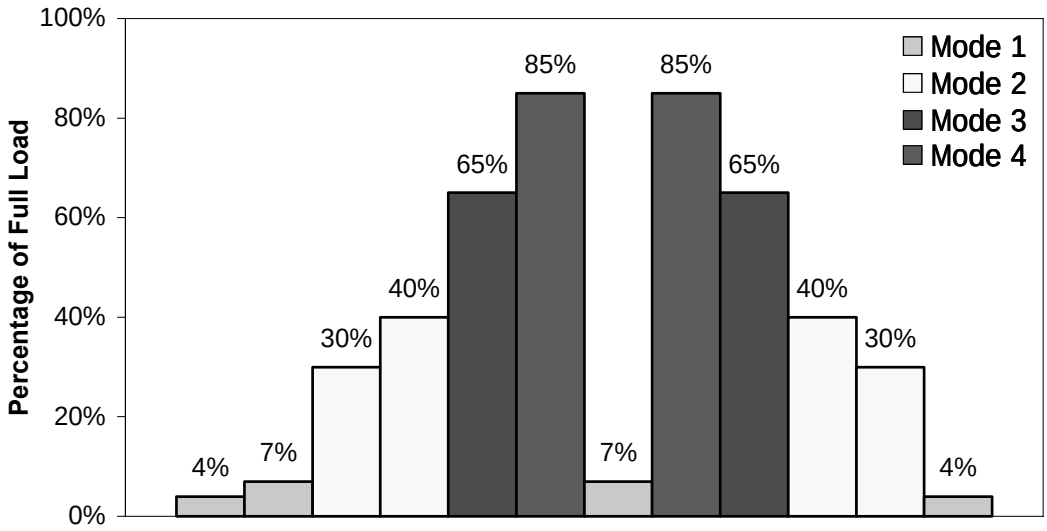


Figure 14: Modified EPA Landing Take-Off (LTO) Sequence Used for Testing.

2.8.1 UCR Design and Fabrication of Sampler for JETS APEX2

UCR participated in APEX1 with the goal of learning about the sampling requirements for measuring speciated emissions in jet exhaust. The schematic of the UCR sampler is shown in Figure 15 and the design basically followed the principles used to measure speciated hydrocarbon and PM emissions in diesel exhaust (Cocker, 2004). UCR was limited to a total flow of 20 liters per minute and to capture the maximum molecules we opted for an undiluted stream.

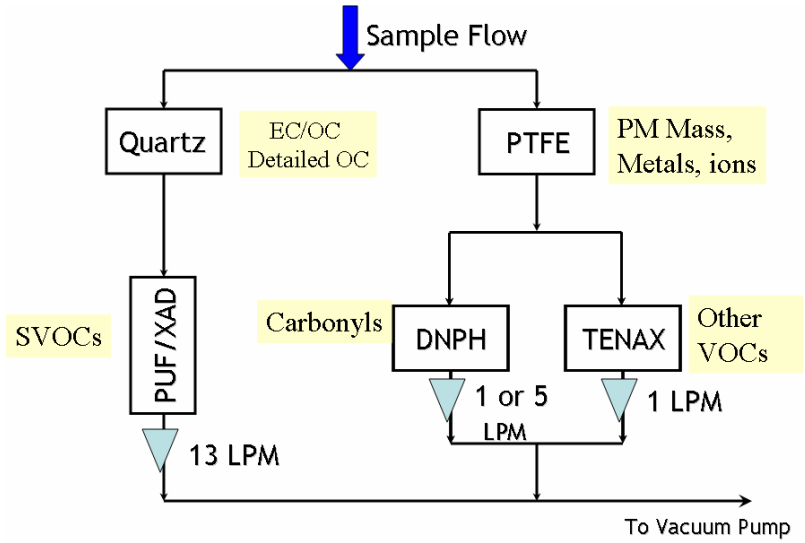


Figure 15: Schematic of UCR's Sampling System for APEX1

Based on UCR participation in APEX1, a number of lessons were learned that were germane to the sampler which UCR needed for JETS APEX2. Specifically:

- Sampling/analysis methods worked but were too slow for the modal switching required in JETS APEX2
- Need many more molecules than were collected in APEX1 for analyses to stay above the analytical minimum detection limit
  - Sample volume should be increased by 10-200 times
  - Need undiluted lines
  - Need sample classifier to keep debris from reaching filters
- Needed accurate flow measurements

UCR's sampler in APEX1 worked well but clearly was not suited for the JETS APEX2 project. The first challenge for UCR was to design, build and verify a sampler that would extract sufficient number of molecules to allow analysis above the instrument analytical limits while following the modal operating cycle specified for JETS APEX2 (Figure 14). UCR decided the highest probability of collecting enough molecules, especially at the lowest power, was if the sampler design combined the samples from the 4% and 7% power and the 30% and 40% power. Modes 3 and 4 were at a single power, 65% and 85% respectively where the PM loading was expected to be the highest. In addition to these changes, UCR wanted to avoid the transitions between loads so sampling commenced 15 seconds at each engine mode after stable operation was announced and stopped 15 seconds prior to switching to the next load. Sampling was not conducted during transitions between modes. Other than the 2 minutes at the 85% load, each mode lasted about 10 minutes with the exact time being recorded in the log books as well as electronically. Thus the UCR sampler design was designed for four modes of operation.

Table 7: Design of the Modal Cycles for the UCR Sampler for JETS APEX2

Mode 1	Roughly 40 minutes at the 4 and 7% power levels
Mode 2	Roughly 40 minutes at the 30 and 40% power levels
Mode 3	Roughly 20 minutes at the 65% power level
Mode 4	Roughly 4 minutes at the 85% power level

In addition to collecting samples at four modes, UCR's sampler needed to be a high volume extractive system with rapid and automatic switching between the specified engine operating modes and the flow rates needed to be monitored, an improvement over the APEX1 sampler. The final design called for critical flow orifices to control flow rates through all systems. Thermocouples and absolute pressure gauges were added so flow rates could be corrected. With the exception of the Summa Canisters, all flows were operated under choked conditions (outlet pressure << 0.52 * inlet pressure). On the C_4-C_{12} line (TDS tube line) and DNPH line, flows were also metered as differential pressure through a laminar flow element. Summa canisters were filled through a small orifice to lower the sampling rate, but absolute flow was not controlled since concentrations were measured on a volume concentration basis.

The final design followed the schematic shown in Figure 16, included numerous mechanical elements and a computer system to operate the switching valves, monitor the

temperature and pressure of the critical flow elements and log the real time flow data. Flow from the sampling probes at the aircraft engine was carried by four 3/8-inch heated lines so the raw exhaust flow could be as high as 200 liters per minute. The final flow determination depended on the diameter, length and geometry of the setup in the field.

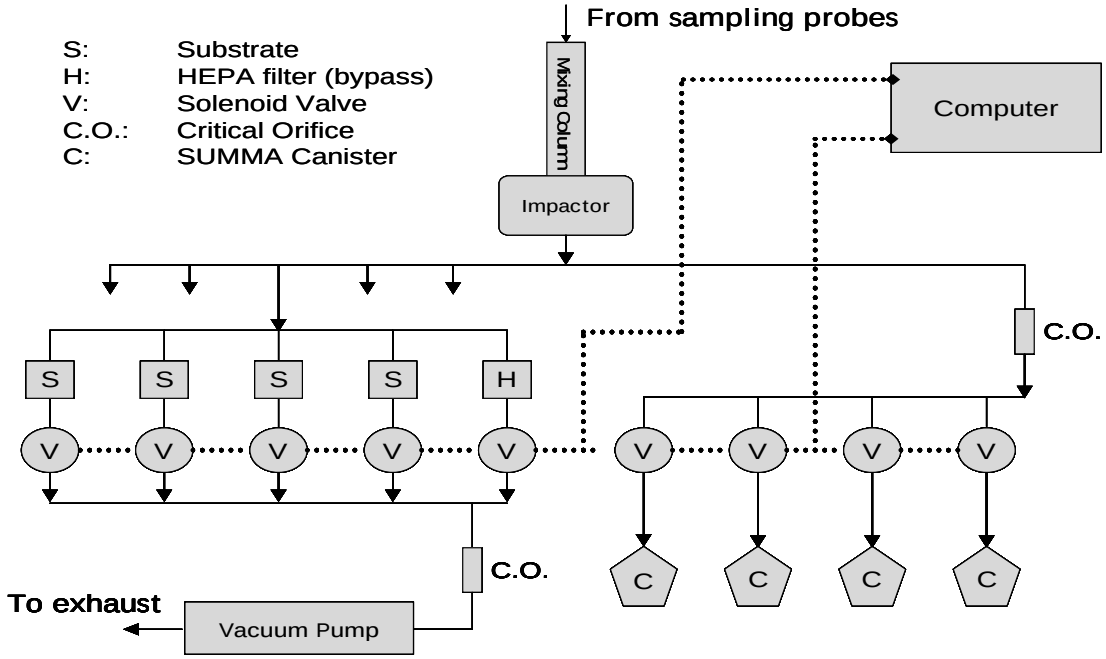


Figure 16: Schematic of sampling setup. "S" setup represents DNPH, TDS, quartz, PUF/quartz, and PTFE (see below for details). Solid lines represent physical flow; dotted lines represent logical control.

Further quality assurance was built into the flow design as each critical flow element (CFO) had both temperature and pressure continuously monitored and displayed on the computer screen to indicate if any CFO failed to meet the desired specifications during the field testing. In addition, the design included laminar flow elements on the low flow lines that continuously monitored flow rates into the sampling manifolds of the carbonyls and thermal desorption tubes. Taken in total, we believed adequate redundancies were designed into the system to ensure accurate flow rates were maintained during the sampling.

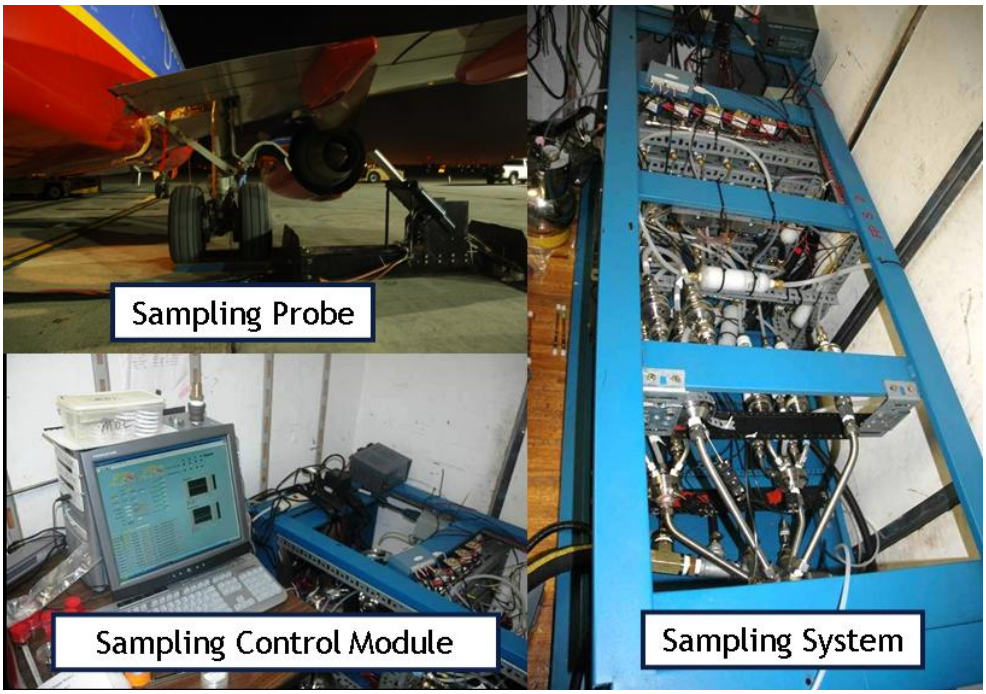


Figure 17: Figure Showing UCR Sampler Constructed for JETS APEX2

2.8.2 Measurement of Mass, Metals and Ions

Teflo filters were used to acquire PM mass, metals and ions concentrations. The filter weighting procedure follows the guidelines of the Code of Federal Regulations (CFR) (40 CFR 86). Briefly, total PM were collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, T = 25°C) and weighed daily until two consecutive weight measurements were within 3 µg. The Teflo filters were subsequently analyzed for metals using XRF method as per EPA IO-3 at the SCAQMD. Finally, the filters were extracted with HPLC water and alcohol and analyzed for ions (ammonium, sulfate, chloride and nitrate) using a Dionex DX-120 ion chromatograph.

2.8.3 Measurement of Elemental and Organic Carbon (EC-OC)

PM samples were collected on 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that were preconditioned at 600°C for 5 h. A 1.5 cm^2 punch is cut out from the quartz filter and analyzed with a Sunset Laboratory (Forest Grove, OR) Thermal/Optical Carbon Aerosol Analyzer according to the NIOSH 5040 reference method (NIOSH 1996).

2.8.4 Speciation of C_1 to C_{30} Hydrocarbons

Because a comprehensive speciation of hydrocarbons was required for this project and there are hundreds of organic species in jet engine exhaust, the sampling system was tailored to match the desired deliverables. Table 8 lists details of the analysis method used. Note an important design feature was the redundancy in measurements. For example, the C_4 to C_6 hydrocarbons were sampled in both the SUMMA canister and the thermal desportiopn tubes. Further heavier molecules like naphthalene were measured in the thermal desorption tubes and the quartz/PUF/XAD channels.

Table 8: Hydrocarbon Speciation: Sampling and Analyses Methods

Chemical Group	Sampling Media	Instrument	Method
C_1-C_8	SUMMA Canister	GC-MS	SCAQMD
C_4-C_{12}	Thermal desorption tubes	GC-FID	SAE 930142HP
Aldehydes and Ketones	DNPH	HPLC/UV-VIS	SAE 930142HP
C_{10}-$C_{30,}$ inc PAHs	Quartz/PUF	GC-MS	EPA TO-13A
Polynuclear Aromatic Hydrocarbons	Quartz	GC-MS	EPA TO-13A

2.8.5 Speciation of C_1 to C_{12} Hydrocarbons, including BTEX & Carbonyls

Traditional air monitoring methods for very-volatile and volatile organic compounds (VVOC/VOC) are not sufficiently sensitive enough to measure the low levels of most compounds found in an exhaust from a lean burn engine, like a turbine. Accordingly, most of the sampling in this work made use of selective adsorbents for concentrating the molecules of interest after the exhaust gas was passed through the Teflon filter. After collection, the columns were returned to the laboratory where the adsorbed molecules were flashed into a concentrator/reservoir at low temperature and then controllably vaporized into a gas chromatograph with either a field ionization detector (GC/FID) or a mass spectrometer detector (GC/MS).

Molecules starting about C_4 (butadiene) through C_{12} were collected and concentrated on an adsorbent column composed with a multi-bed carbon bed including molecular sieve, activated charcoal, and carbotrap resin, each adsorbent with a specific selectivity towards certain boiling ranges or polarity. The absorbent material first contacted in the column adsorbs the most volatile compounds and the remaining compounds will adsorb sequentially in relation to their volatility. The GC sample injection, column, and operating condition are set up according to the specifications of SAE 930142HP Method-2 for C_4-C_{12} hydrocarbons.

Carbonyls were collected on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA) after the Teflon filter. A critical flow orifice was used to

control the 1.0 LPM flow through the cartridge at the JETS APEX2 site to ensure the volume of exhaust sampled through the DNPH cartridge for formaldehyde was within the mass recommended by Waters. Sampled cartridges are extracted using 5 mL of acetonitrile and injected into an Agilent high performance liquid chromatograph (HPLC) equipped with an SPD-10AV UV-vis detector. The HPLC sample injection, column, and operating conditions are set up according to the specifications of the SAE 930142HP protocol (Siegel et al. 1993).

2.8.6 Speciation C_{10} to C_{30} Hydrocarbons, including Naphthalene and PAHs

Jet exhaust flows through a quartz filter and into a column packed with polyurethane foam (PUF)/XAD-4 resin. A portion of the quartz filter was used to analyze for the elemental and organic carbon. Both the PUF/XAD-4 cartridge and the remainder of quartz filter was extracted with methylene chloride and analyzed using a modified method EPA TO13A protocol (GC-MS analysis) to determine total emission rates for naphthalene, PAHs, etc. Details on the analysis method are found elsewhere (Shah et al. 2004).

2.8.7 Detection Limits for the Organic Compounds

2.8.7.1 Calculating the Emissions Index

Typically, aircraft exhaust characterization is reported as Emission Index. The calculation of Emission Index from the mass sampled of a compound is given by:

$$\text{EI (g/kg)} = EI(g/kg) = \frac{Mass_X(\mu g)}{Mass_CO_2(kg)} * 3160(g_CO_2/kg_fuel) * 10^{-6} \qquad \text{(Eq. 10)}$$

where, EI = Emission Index, and X = Compound being analyzed

2.8.7.2 Lower Detection Limits

Each of the analytical methods has lower detection limits specific to the method and equipment used. For this work, the lower detection limits per sample are listed in Table 9 below.

Table 9: Lower Detection limits for Organic Compounds analyzed

Organic Compounds	Instrument	Method	Lower Detection Limit
PAH and Alkanes	Agilent 6890N GC-5973N MS	EPA TO-13A	0.01 ng
C4 – C12	Agilent 5890 GC - FID	SAE 930142HP	2 pico moles C
Carbonyls	Agilent HPLC	SAE 930142HP	0.02 µg
EC OC	Sunset Labs Thermo/Optical Carbon Analyzer	NIOSH Method 5040	20 µgC
PM	Cahn Microbalance	40 CFR 86	20 µg

The Lower Detection Limits (LDL) in terms of EI units, (g/kg), would be different for each compound and each mode of each plane. For example, the lower detection limit for particulate matter or elemental carbon and naphthalene for each mode in terms of EI is presented in following table.

Table 10 : Lower Detection Limit for PM, EC, OC and Naphthalene

		LDL (g/kg fuel)	
Aircraft	**Mode**	**PM/EC**	**Naphthalene**
N435WN	Mode1	0.00223	3.68E-08
	Mode2	0.00151	2.69E-08
	Mode3	0.00206	3.26E-08
	Mode4	0.00849	1.44E-08
N353SW	Mode1	0.00070	1.39E-08
	Mode2	0.00070	1.49E-08
	Mode3	0.00127	2.27E-08
	Mode4	0.00476	9.09E-08
N695SW	Mode1	0.00108	2.17E-08
	Mode2	0.00118	2.39E-08
	Mode3	0.00209	3.52E-08
	Mode4	0.00613	1.21E-07
N429WN	Mode1	0.00051	1.05E-08
	Mode2	0.00072	1.55E-08
	Mode3	0.00114	2.02E-08
	Mode4	0.00406	8.30E-08

2.8.8 Exploratory Measurements for hexavalent chromium and dioxin

As a last minute inclusion in the final test matrix, we added the sampling of exhaust onto appropriate media for the measurement of hexavalent chromium and dioxin. The rationale was there were no known measurements reported in the literature. Further, the alloys used for the combustor section in the turbine often have high amounts of nickel and chromium contents. For example, GE reported that some of the materials used for the combustor section in the turbine might include: HastelloyX, MAR-M-509, HS188 and Rene' N5.

- HastelloyX is about 47% Ni, 22% Cr, 19% Fe, 9% Mo and ~1% Co, C, Mn, Si, and W.
- HS188 is about 22% Ni, 22% Cr, and 39% Co and 3% Fe.
- MarM509 is mostly Co with about 20% Cr, and N5 is mostly Ni with about 7% Cr

As noted above, these alloys are high in chromium and nickel. In any case, these measurements were regarded as exploratory in nature and designed to provide insight as to whether further investigations were warranted for these compounds.

A sample of raw exhaust was extracted from the portside of the subject aircraft and conveyed through a 75 foot by 3/8-inch stainless line to the filter heated to 300ºF. Once the extracted sample reached the measurement bench, it was divided into two streams with a “tee.” The sample portion that flowed directly through the “tee” was dedicated for the analysis of the hexavalent chromium and the sample portion at right angles to this flow was for the dioxin analysis. Each leg had a vacuum pump and critical flow orifice rated at 30 liters per minute. In addition, we included a condensing section before the pump so condensing water would not reach the operating pump.

The measurement for hexavalent chromium in the jet exhaust followed a method in which exhaust gases flowed through a pretreated cellulose fiber filter that was subsequently analyzed using an ion chromatography method of the South Coast Air Quality Management District Method for chrome-VI.

The 47mm treated filters were mounted in Gelman holders and the times recorded for the period of sampling at the 30 liters per minute. A number of preliminary trials were undertaken of the hexavalent chromium system in addition to the sampling of the aircraft exhaust. The test matrix included collecting two samples of ambient air drawn throught he sampling system for one and eight hours. These samples served as verification that the system could measure values normally found for ambient air. Collection of samples with jet engine exhaust were started before the aircraft was in place and continued until the engines were shut down and we could go outside and turn the power off the pumps. The filter was removed and returned to the Petri dish, sealed with Teflon tape and stored with the quartz filters in a refrigerator until sent for analysis.

Dioxin sampling followed a modified EPA Method 23. This method is applicable to the determination of emissions of polychlorinated dibenzo-p-dioxins (PCDD's) and polychlorinated dibenzofurans (PCDF's) from stationary sources. In principle, a sample is

withdrawn from the gas stream, transferred in a heated line, cooled and collected on a packed column of adsorbent material. The sample cannot be separated into a particle and vapor fraction. The PCDD's and PCDF's are extracted from the sample, separated by high resolution gas chromatography (HRGC), and measured by high resolution mass spectrometry (HRMS).

Glassware with the spiked XAD resin was prepared and analyzed by Frontier Analytical Laboratory and Alta Analytical Laboratory, Inc. (Sacramento). Each firm provided two sample trains in appropriate sealed and chilled containers for a total of four sampling trains. Since the plan called for two different aircraft engines to be tested twice, the sample trains were split so that each firm tested one different engine rather than run duplicate samples. With only four sample trains, we decided to check each engine rather than be concerned with the repeatability of the measurements.

3.0 Results

It is a basic premise of this study and other similar studies to argue that if the engine gas phase combustion emissions and performance parameters were representative, then it would be assumed that likewise, the PM emissions were also representative. To address this issue, the engine manufacturer, GEAE, provided on-site and post-test analyses of the gas phase combustion emissions and performance parameters for all engines studied. The details of these analyses are summarized in Appendix F. Based on the results presented in Appendix F, the following conclusion pertaining to representativeness was provided by GEAE: "Trends in engine core speed, EGT and fuel flow data are generally consistent with expectations. The only apparent indication of performance deterioration was on the left engine of N695SW."

3.1 Real-time Chemical Speciation (ARI)

3.1.1 Gas Phase Speciation

The gas phase pollutant species produced by aircraft gas turbine engines fall into two classes: oxides of nitrogen and products of incomplete combustion. The oxides of nitrogen are produced, not by reactions central to fuel hydrocarbon combustion, but primarily through interaction of combustion radical species with nitrogen in the combustion air. These nitrogen oxides are dominated by NO and NO_2, although small amounts of HONO have been quantified and bounds determined in previous aviation emission campaigns (Wormhoudt et al., 2007).

The products of incomplete combustion include carbon monoxide (CO) and unburned/partially combusted hydrocarbons (UHCs). While the regulatory requirement specifies that a flame ionization detector (FID) be used to quantify the total UHCs in sum, a more detailed measurement approach was taken in JETS APEX2. Based on prior measurements of hydrocarbon speciation of aviation gas turbine exhausts (Spicer et al. 1994), individual hydrocarbon species were selected for measurement with the TILDAS and PTR-MS instruments. This allowed for a more detailed determination of the emitted hydrocarbons, but direct comparison to the regulatory FID is complicated by both 1) potentially significant contributions from individual species omitted from the selected TILDAS and PTR-MS species and 2) for the non-uniform response of the FID to individual hydrocarbon species. However, based on previous measurements and intercomparisons (Yelvington et al. 2007), a majority of the gaseous hydrocarbons emitted are accounted for by the combination of TILDAS and PTR-MS measurements reported here.

Carbon monoxide emissions are presented in Figure 18. The emissions data are presented as emission index (EI) in grams of CO emitted per kilogram of fuel burned. As discussed above, the analysis procedure uses the measured CO_2 and the known fuel composition to calculate the CO EI. The CO EIs are highest at the lowest power settings, and decrease

rapidly as the power is increased above idle and taxi powers. The EIs decrease to a lower limit at the highest powers, which is a few percent of the high levels seen at idle (note that the abscissa is plotted logarithmically in this figure). All seven engines tested follow the same trend. The regulatory data for the three engine types are also included in the figure (diamond symbols, ICAO database). The -3B1 and -7B22 the JETS APEX2 data fall below the regulatory data.

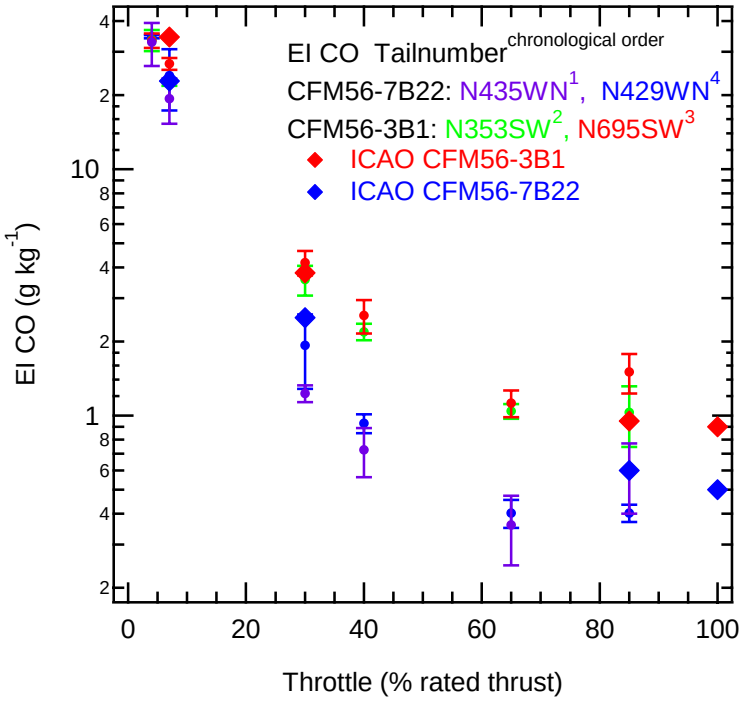


Figure 18: The logarithm of carbon monoxide (CO) emission index (EI) is plotted against the nominal thrust setting for the seven engines measured. The ICAO data points for the three engine types are plotted as diamond symbols.

While there is significant variability in the CO data when plotting against nominal engine power condition, much of that variability can be reduced by accounting for changing ambient conditions and plotting versus engine fuel flow rate (Wey et al. 2006; Yelvington et al. 2007). Even if fuel flow data and ambient temperatures were available to collapse this scatter, it is clear that the –3B1 and, especially, the –7B22 JETS APEX2 data fall significantly below the ICAO data points for CO emissions.

Nitrogen oxide emissions data are presented in Figure 19. Here the sum of NO and NO_2 EIs are plotted, both using a mass basis of NO_2 for calculating the EI so that these two emissions can be summed directly. NOx has the opposite trend as CO, increasing with increasing powers from low numbers at idle to high EIs at take-off thrust.

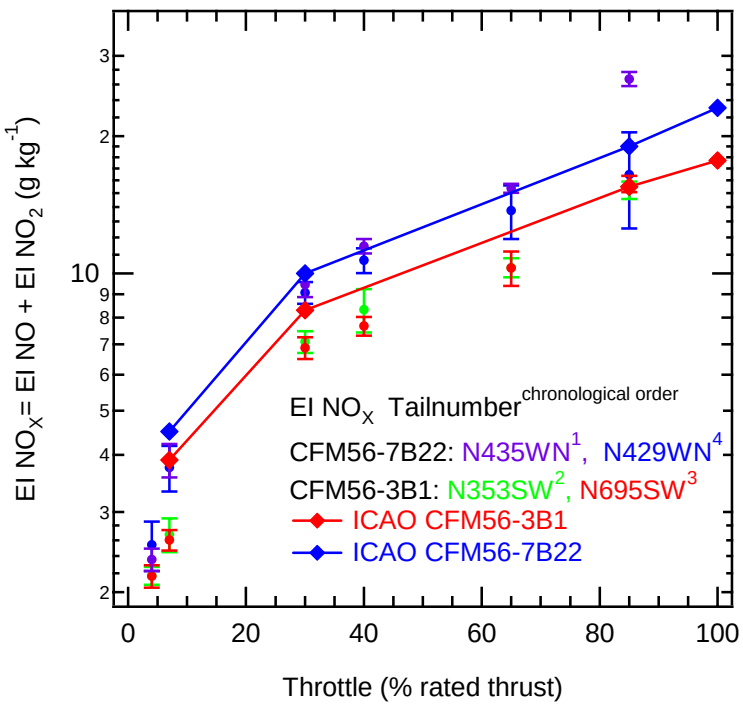


Figure 19: NO_x EIs in g NO_2/kg fuel, plotted versus nominal engine trust setting for the three engine types (seven engines total) that were tested.

Also plotted in the figure are the ICAO NO_x EI data points. Like the CO data, there is good agreement between the ICAO and JETS APEX2 NO_x measurements. In contradistinction to the CO data, the NO_x emissions are greatest for the –7B22, and lowest for the 3B1. This order is replicated in both the ICAO data and in the JETS APEX2 measured data. As for the CO data, some reduction in scatter might be achieved if the engine fuel flow data were used, in combination with the ambient temperature, to collapse those variations.

Formaldehyde (HCHO) EIs are plotted versus the logarithm of engine power setting in Figure 20. The panel on the left is labeled according to engine type, while the right panel is labeled by measurement location. For both plotting schemes, the decreasing trend in HCHO emissions with increasing engine power dominates the emissions behavior. The significant scatter in the data, especially at idle engine powers (< 10% of rated thrust) is understood to be dependent on variations in engine operating condition due to changes in ambient conditions (Wey et al. 2006; Yelvington et al. 2007), and may be collapsed using fuel flow data. The differences between the engine types are modest, and even agree well with the CFM56-2C1 measured in the APEX1 mission (Yelvington et al. 2007).

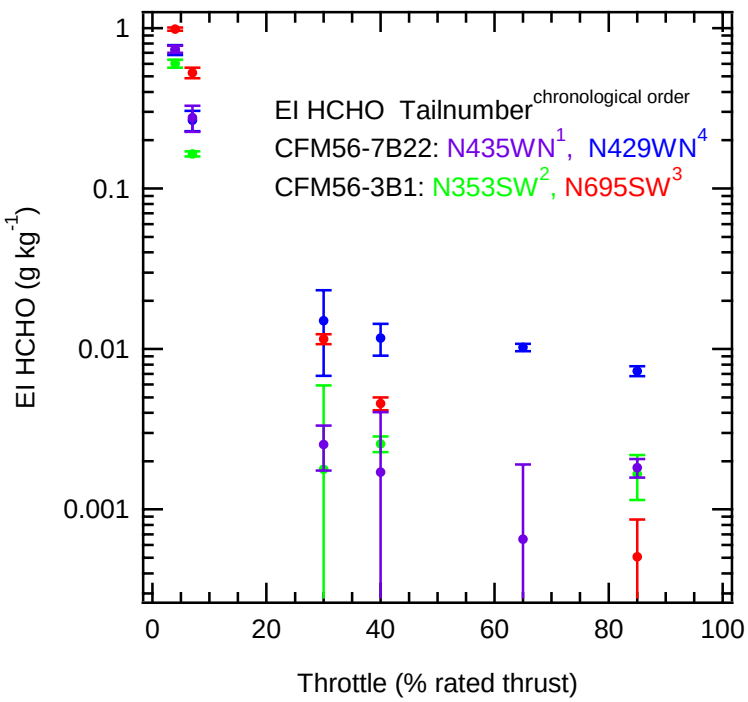


Figure 20: Formaldehyde (HCHO) is plotted versus the logarithm of the nominal engine thrust setting for all engines tested. The engine variability due to fluctuations in ambient conditions is greater than the engine-to-engine differences or to variations due to the downstream measurement locations.

Formaldehyde is one of the highest concentration hydrocarbons in the exhaust and can be measured quite accurately with good time response with the TILDAS system deployed in JETS APEX2. As seen in APEX1 (Knighton et al. 2007; Yelvington et al. 2007), HCHO may be a good indicator for UHC emissions more generally, and this will be further explored with the current set of data. Additional hydrocarbon measurements are presented in the next series of figures, all of which demonstrate the same decreasing trend with increasing engine power. In Table 11, the ratio of HC to HCHO is presented for a number of HC measurements. These ratios were derived from the slope of the graphs of individual hydrocarbons plotted vs. HCHO. This ratio is an appropriate quantity since all of the HC species exhibit the same trend vs. engine power. The PTR-MS technique uses a mass spectrometric analysis of the HC species, and as such species of identical masses may not be individually resolved. Thus, butanes and acrolein are both measured at the mass-to-charge ratio (mz) of 57, and acetone, propanal, and glyoxal are measured as mz59 as presented in Table 11. The C-5 substituted benzenes are measured at mz149.

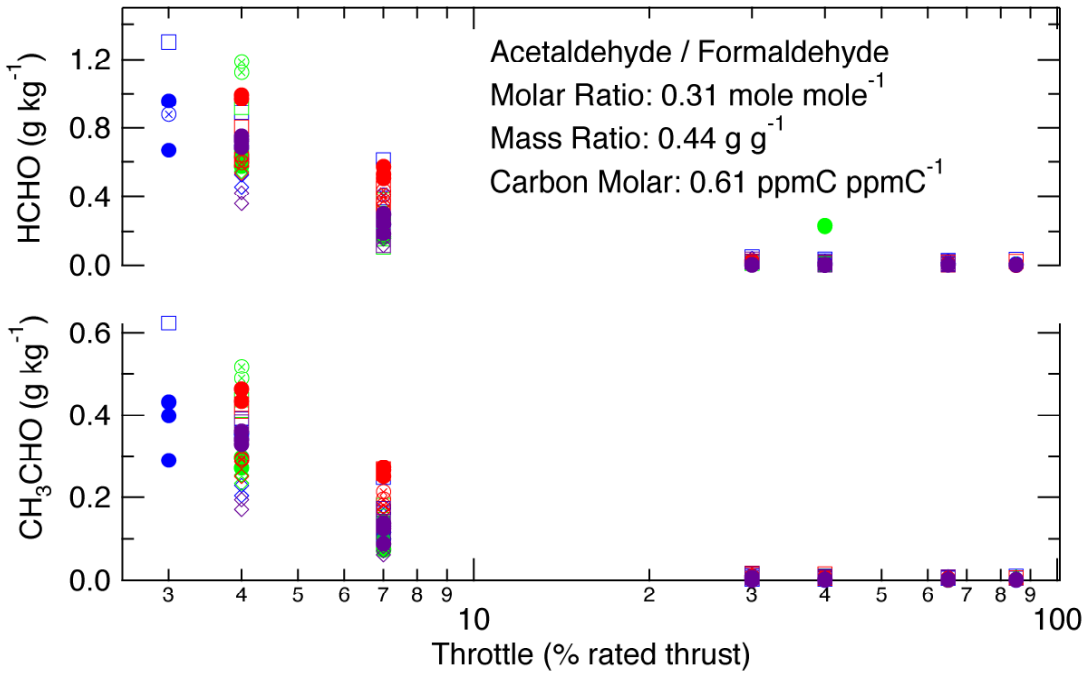


Figure 21: Acetaldehyde (CH_3CHO, lower panel) EI is plotted versus the logarithm of engine power, displaying the same trend as HCHO (upper panel).

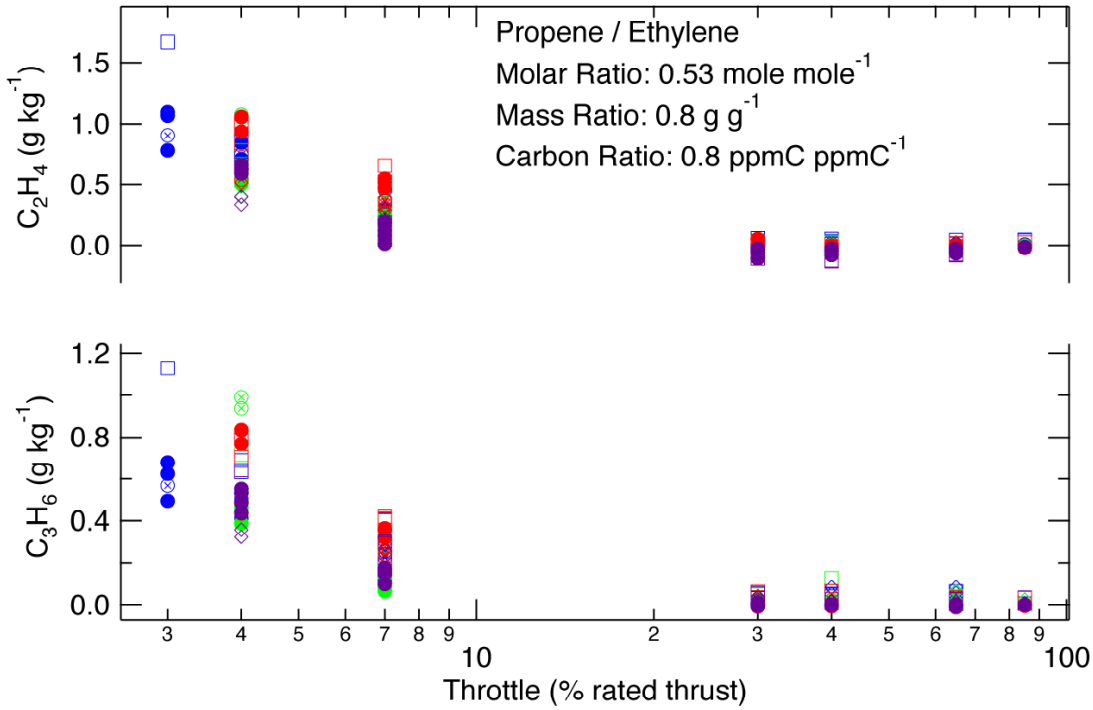


Figure 22: Ethylene (C_2H_2, upper panel) and Propene (C_3H_6, lower panel) are plotted versus the logarithm of engine power, displaying the same trend as HCHO.

Table 11: HCHO Ratios

	Ratio of HC "X" to HCHO					
	N435WN	N353SW	N695SW	N429WN	APEX-1	Spicer et al.
methanol	0.12	0.15	0.13	0.12	0.16	NA
acetic acid	0.020	0.018	0.023	0.038	0.040	NA
mz57	0.88	1.25	0.78	0.83	0.16	0.19
mz59	0.09	0.08	0.08	0.08	0.09	0.13
alkenes						
propylene	0.41	0.47	0.43	0.43	0.38	0.27
pentene	0.27	0.28	0.26	0.26	0.23	0.058
hexene	0.12	0.12	0.11	0.12	0.14	0.022
aromatics						
benzene	0.078	0.080	0.060	0.058	0.058	0.055
toluene	0.033	0.033	0.025	0.023	0.023	0.018
C2-Benzenes	0.043	0.044	0.039	0.037	0.030	0.025
C3-Benzenes	0.032	0.032	0.031	0.031	0.025	NA
C4-Benzenes	0.019	0.018	0.017	0.019	0.013	0.005
Phenol	0.025	0.024	0.022	0.018	0.028	0.005
Styrene	0.011	0.012	0.010	0.009	0.008	0.008
mz149	0.010	0.008	0.008	0.009	0.005	0.005
Naphthalenes						
normal-	0.008	0.008	0.008	0.009	0.006	0.011
methyl-	0.005	0.005	0.005	0.006	0.003	0.008
dimethyl-	0.002	0.002	0.002	0.003	0.001	NA

In addition to the ratios of the individual hydrocarbons to HCHO, the corresponding ratios are presented for the related APEX1 (Knighton et al. 2007) and similar data taken using different measurement techniques by Spicer et al. (Spicer et al. 1994). Generally very good agreement is observed across all of the data sets. Some of the comparisons with the Spicer data are less close (higher alkenes, C4-benzenes, phenols) and the differences in measurement approach may aid in interpreting the differences. Most importantly, the PTR-MS and TILDAS instruments operate in a continuous flow, few-second-residence-time measurement system, which avoids sample capture and storage prior to measurement that was used in the GC-MS system employed by Spicer et al. These measurement discrepancies with the single idle power condition under which most of Spicer et al. measurements were non-zero should be resolved and may result in a better understanding of chemistry that may occur during sample handling or storage. Most notable, however, is that with the multiple power measurements of the APEX1 studies, a very good correlation of most HCs with formaldehyde provides a useful means of better understanding HC emissions performance of aircraft gas turbine engines. Whether the coefficients in Table 11 depend on engine type (beyond the range of CFM56 models

measured here) or on fuel composition (beyond the range explored in APEX1) remains an important open question to be resolved by further measurement programs.

The HC results presented above provide a useful simplifying framework for understanding HC emissions, suggesting that referencing most HCs to a few primary emissions may be a helpful means of representing the wide range of species that are emitted. However, a contrasting perspective is raised both by some of the discrepancies with the Spicer data, as well as the measurements of formic and acetic acid presented in Figure 23. Neither formic acid nor acetic acid are present at the engine exit plane in significant concentrations (small filled circle symbols), yet are present at the downstream measurement locations with significant scatter, more or less independent of engine power setting. The scatter is most significant at the further downstream location (50 m).

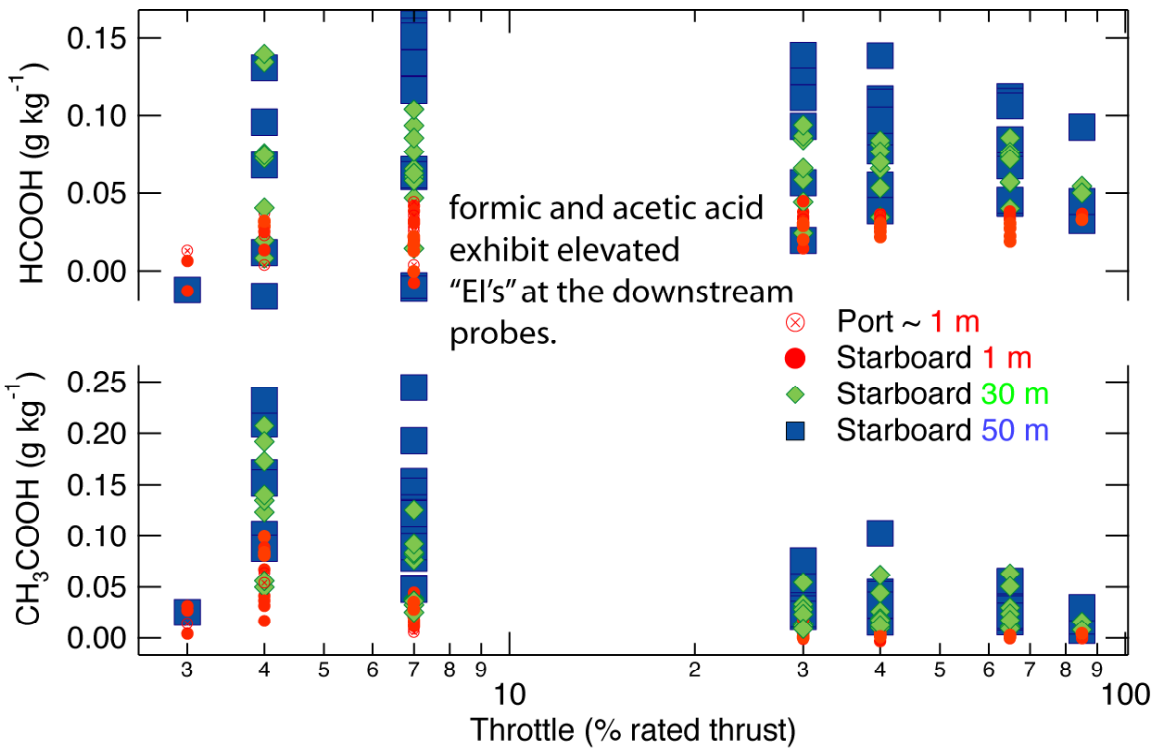


Figure 23: Formic acid (HCOOH, upper panel) and acetic acid (CH_3COOH, lower panel) are plotted versus the logarithm of engine power setting.

Given that the transit time between the engine and the downstream probes is very short (several tenths of seconds), the likelihood is large that these acids are formed in the sampling system. As the measured values are not correlated with engine power, the sampling line history may be determining the measured amount (how long the system had been flowing, temperature of walls, etc.) and contributing to the scatter in the data. These acid data and the discrepancies with the earlier Spicer data for some of the HCs reinforce the concern that sampling and sample handling of reactive HCs must be considered carefully when quantifying the emissions of such species.

3.1.2 Particle Speciation

The composition of the particles emitted by aviation gas turbine engines is a complex issue that involves difficult measurement and data interpretation issues. In fact, the nature and composition of the emitted particles are continually evolving and there is not a single physical situation that can be used to uniquely characterize them. There are several states at which the particles are evolving less quickly that can be used as nominal reference points, but even those depend on the precise definition of those conditions and the measurement of those states requires careful sampling and sample handling so that the physical state of the particles is accurately captured.

The initial particle formation occurs in the engine combustor as a byproduct of the combustion process. The carbonaceous soot particles formed in the high temperatures of the combustor are subject to little change themselves after they leave the combustor, pass out of the engine, and mix with the atmosphere. However, condensable gases also are emitted with the soot particles, and these condensable gases contribute both to condensed material on the soot surfaces and to the formation of new volatile particles composed of the condensed species.

The measurement approach taken in JETS APEX2 was to quantify the composition of the particles centers around the Aerosol Mass Spectrometer (AMS), which measures the size resolved composition of volatile species measured by heating the particles to 600° C on a filament. For aviation gas turbine engines, the volatile components consist of sulfate (sulfuric acid) and organics, as will be discussed and quantified below. Notably, no significant nitrate volatile component is evident, even though this is typically a constituent of background aerosol and nitrogen oxides are emitted in the exhaust. Apparently there is insufficient time or oxidative potential for nitrate to condense into the particle phase under the conditions at JETS APEX2.

The AMS only measures the volatile (600°C) components of the particles, so the AMS is complemented by a MAAP instrument to measure the refractory black carbon mass. While the AMS is size resolved, the MAAP is not, so that coordination with particle size distribution measurements is useful for fully characterizing the non-volatile mass contributions. To aid in making comparisons with the other particle measurements, a CPC is also operated in parallel with the AMS and MAAP instruments in the Aerodyne mobile laboratory. All of these data are presented in the following figures.

The black carbon mass measurement quantified by the MAAP is presented in Figure 24. For all the engine types, the black carbon begins at a low value at low powers and increases at higher powers. While generally increasing with power, there is a modest increase in black carbon at the very lowest idle settings for all engines. After the modest decrease from idle, the black carbon continually increases with engine power, with the most rapid increase between 60 and 80% power. This matches the power dependence of the APEX1 data as well. There is some variation among the various engine types, with the -3B1 > -7B22 even though all engines have the same qualitative trends with engine

power, including the small increase at the lowest powers, and the rapid increase between 60 and 80% power.

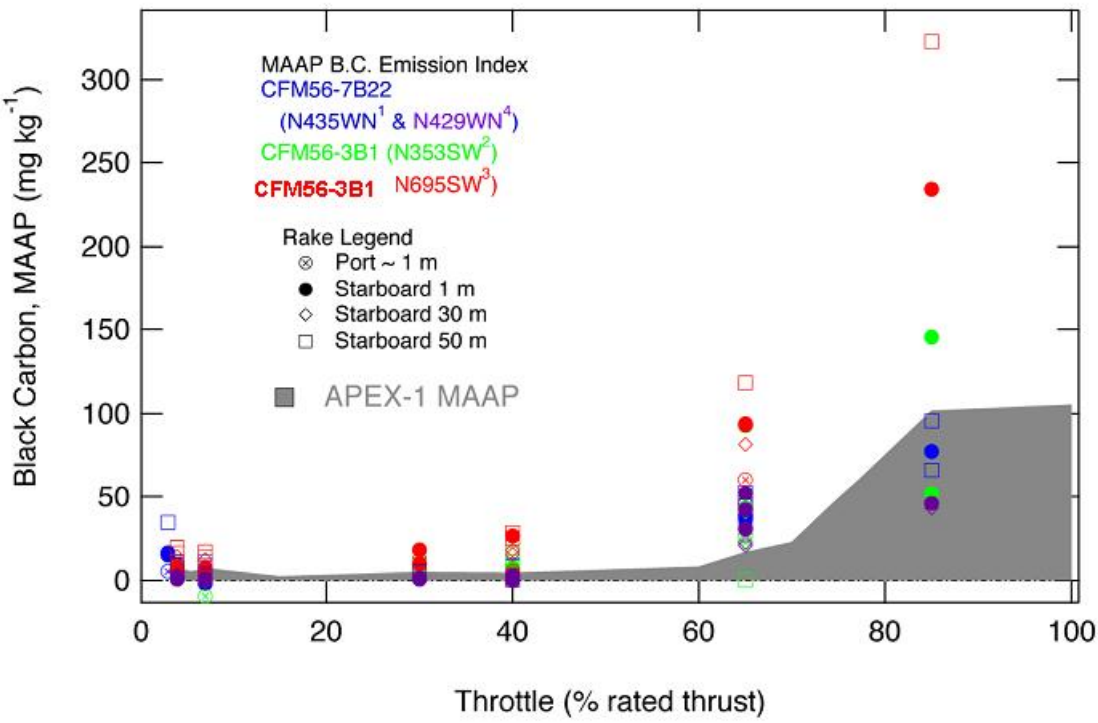


Figure 24: Black Carbon mass EIs measured with the Multi-Angle Absorption Photometer. The mass EIs are reported in mg/ kg fuel (versus g/kg fuel for the gaseous species measurements).

The MAAP black carbon measurements are reported as [mg black carbon]/[kg fuel burned], and emission levels range from a few mg/kg fuel at ~30% rated thrust to several hundred at the highest power conditions for the –3B1. Note that this represents a combustion inefficiency of about 0.0005% to 0.002%, and is thus a modest fraction of even the quite small amounts of incomplete combustion emitted from the highly efficient aviation gas turbine engines. It is worth keeping these small levels in mind when considering the even smaller amounts of volatile condensed mass that is measured by the AMS.

The AMS sulfate and organic measurements are presented in Figure 25. The top panel plots the condensed sulfate as mg/kg fuel for all of the engines as measured at the downstream probe locations versus the engine power setting. These data are compared to the APEX1 sulfate measurements. Note that the variations in fuel sulfur level are reflected directly in the corresponding condensed sulfur amounts since more sulfur is available as condensable sulfate as the fuel sulfur rises (Onasch et al., 2007).

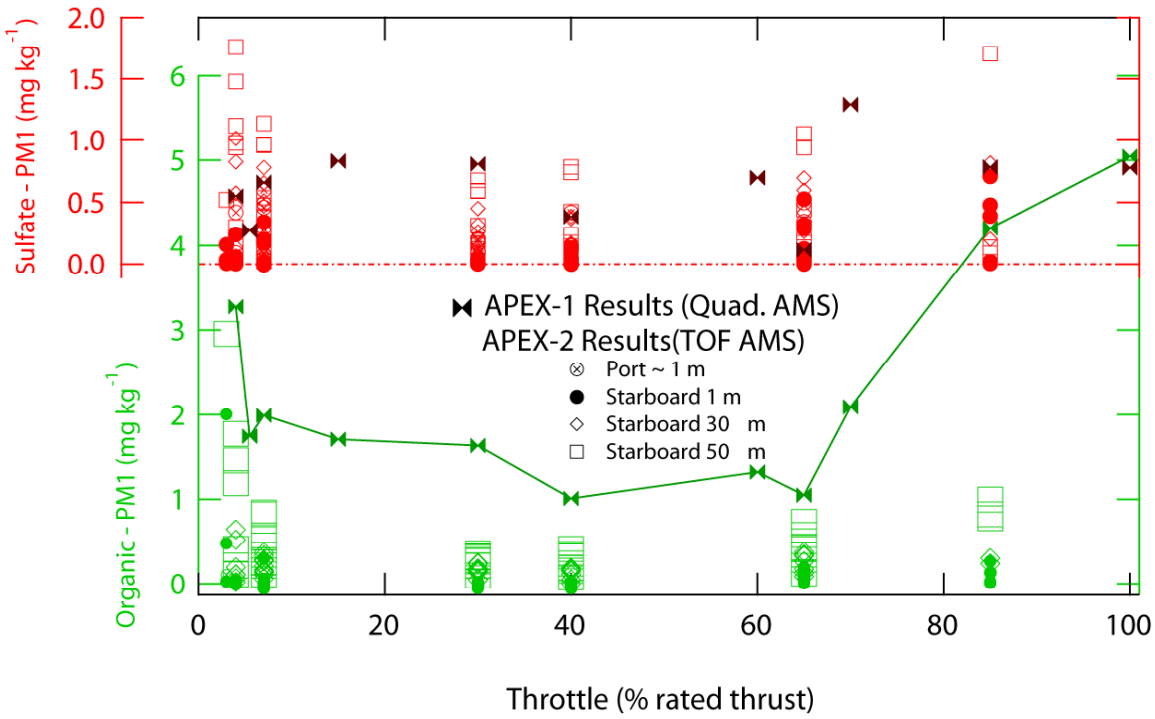


Figure 25: The condensed mass of sulfate (upper panel) and organic (lower panel) are plotted versus engine power setting. APEX1 data is also included with the bowtie symbol.

The sulfate measured in JETS APEX2 is broadly independent of engine power, and varies for the different measurement locations, increasing with down stream distance. The furthest downstream distances agree well with the APEX1 (bowtie symbol) 30 m data, indicating that similar levels of condensed sulfate are observed for all of the CFM56 measurements that have been performed for the APEX1-series of measurements that have been analyzed to date.

The organic data has a maximum at the lowest power conditions, with perhaps a slight increase as the power increases. In the APEX1 data, there was a significant increase at high powers, which is not observed in the JETS APEX2 data. This will require further analysis, and perhaps a reinvestigation of APEX1 data to determine whether the increase in the organic signal at the highest power may have been artifactual in that case.

The mass loadings for both the sulfate and the organic are small compared to that of black carbon, especially at the high engine power conditions. At idle, the locally maximal volatile contributions may approach the black carbon numbers, but otherwise the black carbon dominates the particle mass emitted.

3.2 Physical characterization (UMR)

It is clear from the real-time chemical speciation data (see Figures 18, 19) that the engines in this study were generally operating in a representative manner. The variation in emission characteristics from engine to engine is evident. It is possible these variations could be attributed to the time and number of cycles on the engines at the time of testing. However, no conclusive determination can be made based on the data collected since in this study the sample size per engine technology type was extremely small (3 engines per type). The port engine on aircraft tail number: N695SW did exhibit some non-representative behavior. Analysis by GE indicated performance deterioration on this engine especially at high powers and this was reflected in the PM emissions data recorded for this engine. Data on this engine is included in the engine specific plots presented below, but is excluded in the engine type averages presented in the subsequent discussion. It should also be noted that the sample extracted for real-time chemical speciation was also the sample studied for PM characterization. In other words, all PM measurements were made simultaneously on the same sample flows as those gathered for real-time chemical speciation and thus these results are directly comparable. It is important to note that discussions with Southwest Airlines revealed that both engines on N353SW were modified with a Time on Wing upgrade modification that improves the efficiency of the compressor, combustion and turbine sections of the engine and that N695SW did not have this modification on either engine at the time of testing.

PM parameters are presented in the plots below, for both the -3 and -7 engine types as a function of engine power setting at a stable engine test point that for all data points was no less than 90 seconds. The minimum time needed for a size distribution measurement was dictated by (1) the time smear associated with the difference in streamlines created as the sample was transported from probe to instrumentation and by (2) the need to collect a statistically meaningful sample, i.e. sufficient concentration in each size bin. In the JETS APEX2 study, this time was 3.5 seconds. Therefore, a 90 second stable engine test point allowed for at least 25 size distribution samples. These distributions were then averaged and analyzed for each PM parameter. The error bars in each plot represent the uncertainty in the measurement to1 standard deviation.

3.2.1 PM Emission (Total Aerosol) Parameters at 1m Downstream of Exhaust Nozzle

Number-based geometric mean diameter

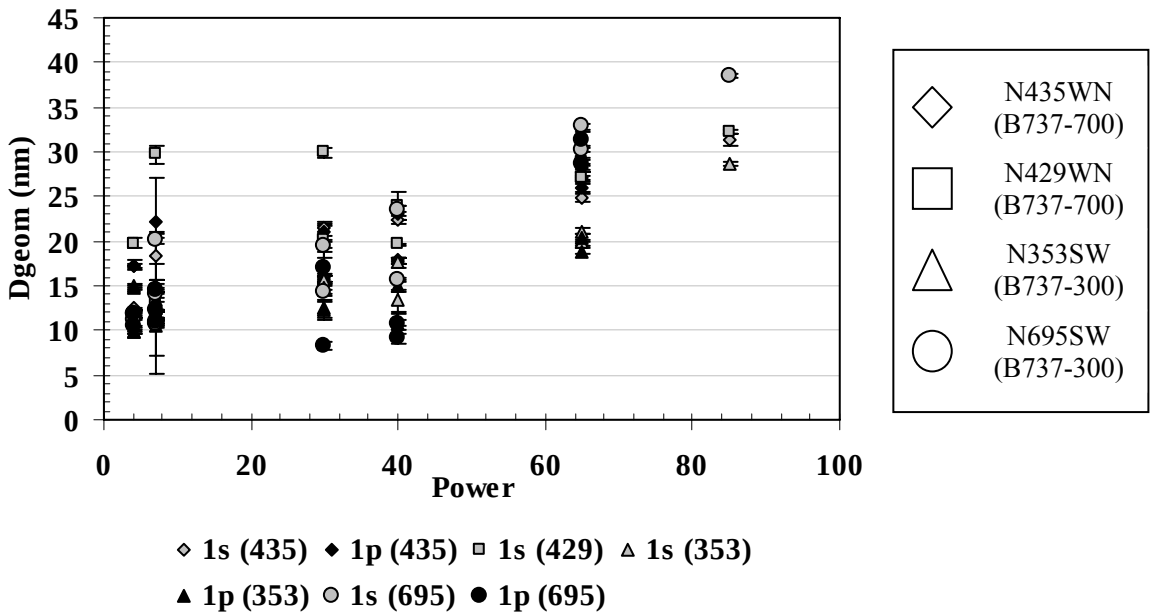


Figure 26: Number-based geometric mean diameter for total aerosol at 1m as a function of power

Number-based geometric mean diameter exhibited a trend to increase with power. This trend was independent of engine type. The scatter amongst engine samples was found to be 20-40% with more scatter at low powers. The relatively large deviation associated with the N429WN at low power conditions can be attributed to engine warmup which will be addressed in the Discussion section.

Geometric standard deviation

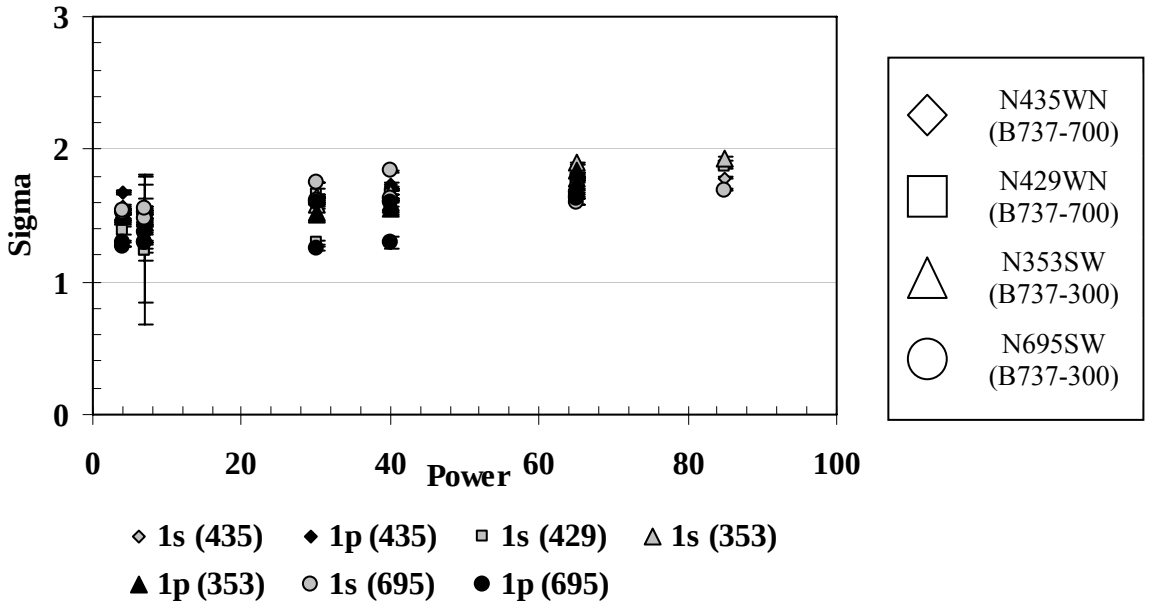


Figure 27: Geometric standard deviation for total aerosol at 1m as a function of power

Geometric standard deviation exhibited a weak positive trend with power. This trend was independent of engine type. The scatter amongst engine samples was found to be 1-10% with more scatter at low powers.

Mass-based geometric mean diameter

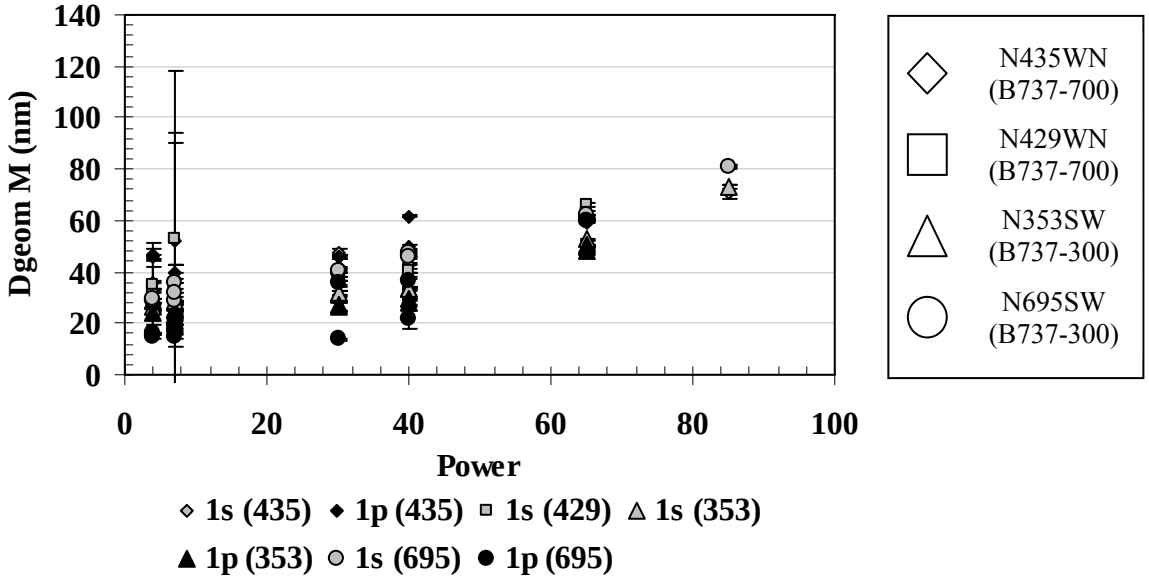


Figure 28: Mass-based geometric mean diameter for total aerosol at 1m as a function of power

Mass-based geometric mean diameter exhibited a trend to increase with power as was the case for the number-based geometric mean diameter. This trend was independent of engine type. The scatter amongst engine samples was found to be 5-30% with more scatter at low powers.

Number-based emission index

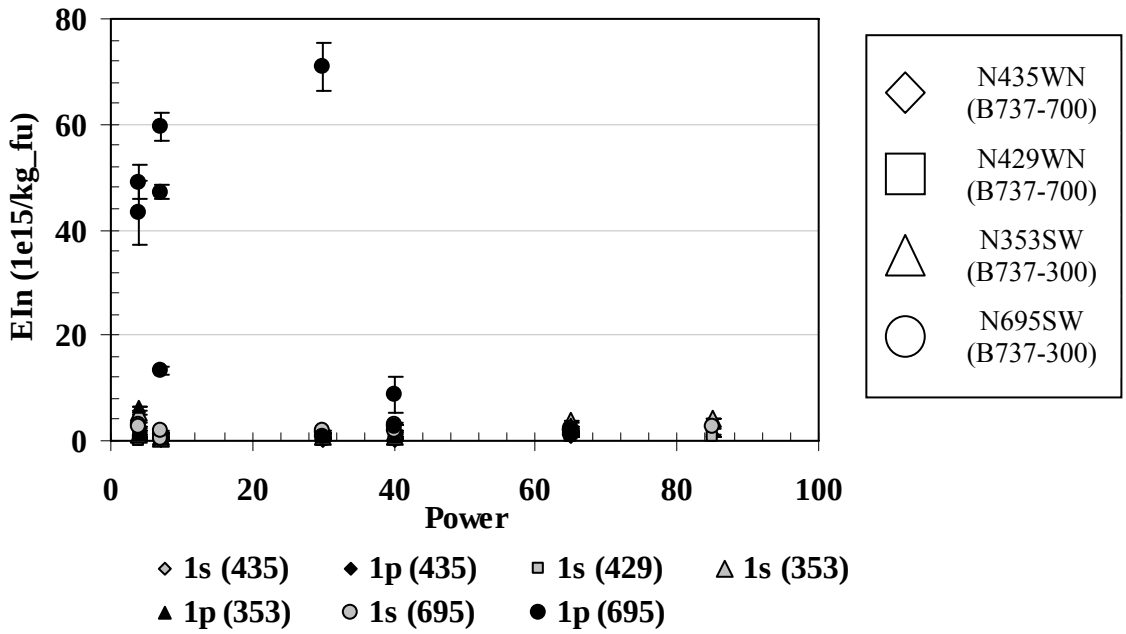


Figure 29: Number-based emission index for total aerosol at 1m as a function of power

For each engine a minimum in number-based emission index was observed in the 30-40% power range. Engine to engine variance exceeded that associated with power change for a given engine.

Mass-based emission index

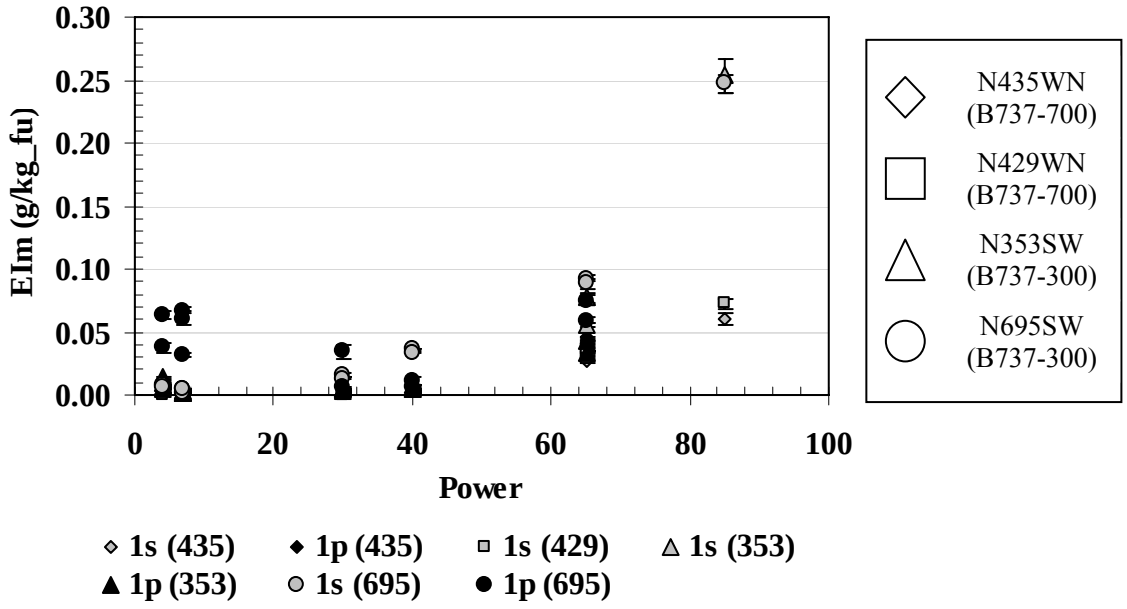


Figure 30: Mass-based emission index for total aerosol at 1m as a function of power

Mass-based emission index exhibited a trend to increase with power. The trend is stronger for the older engine technology (-300 series).

3.2.2 PM Emission (Total Aerosol) Parameters at 50m Downstream of Exhaust Nozzle

Number-based geometric mean diameter

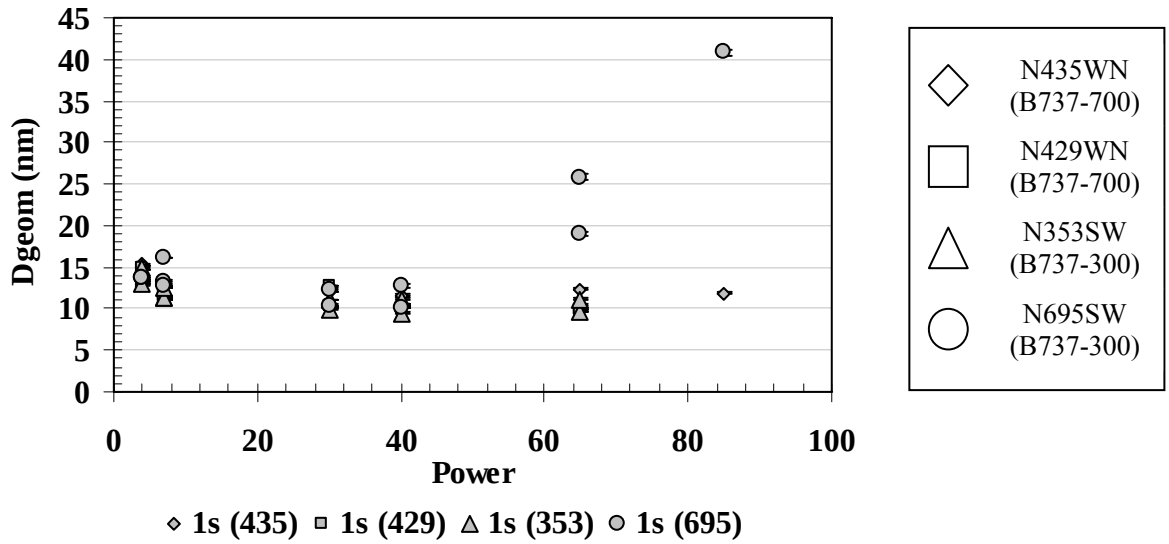


Figure 31: Number-based geometric mean diameter for total aerosol at 50m as a function of power

Number-based geometric mean diameter was found to be independent of power for all but one of the engines studied with a mean value of 12.5nm. In the case of N695SW, a positive trend with power was observed, similar to the trend seen at the 1m sampling location. These Dgeom values are significantly lower than those reported for 1m. This difference can be attributed to gas-to-particle conversion creating a large number of small particles in the 50m sample resulting in a shift to smaller Dgeom.

Geometric standard deviation

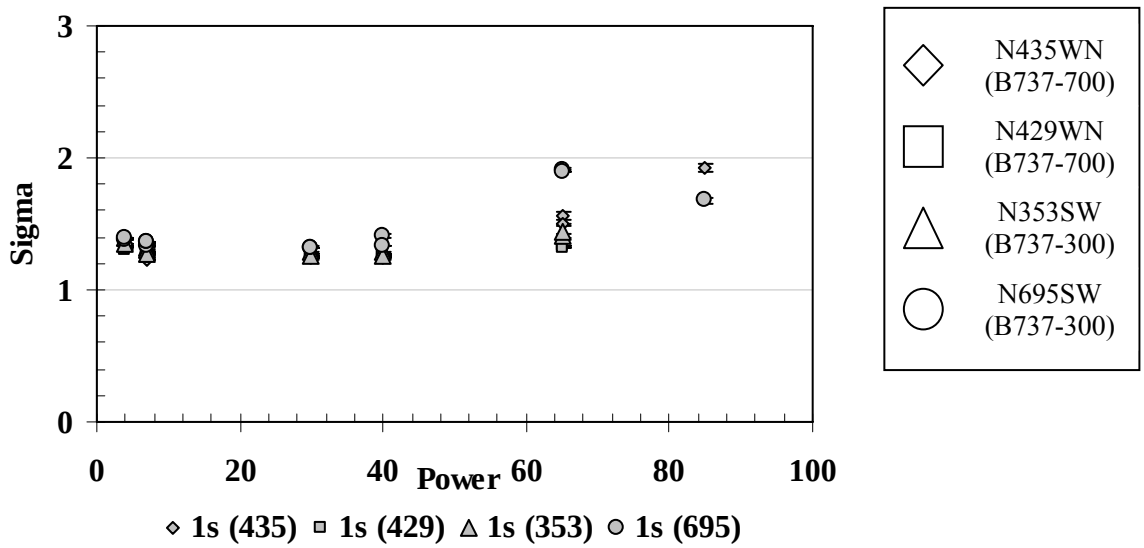


Figure 32: Geometric standard deviation for total aerosol at 50m as a function of power

Geometric standard deviation exhibited a weak positive trend with power as was seen at 1m. This trend was also independent of engine type.

Mass-based geometric mean diameter

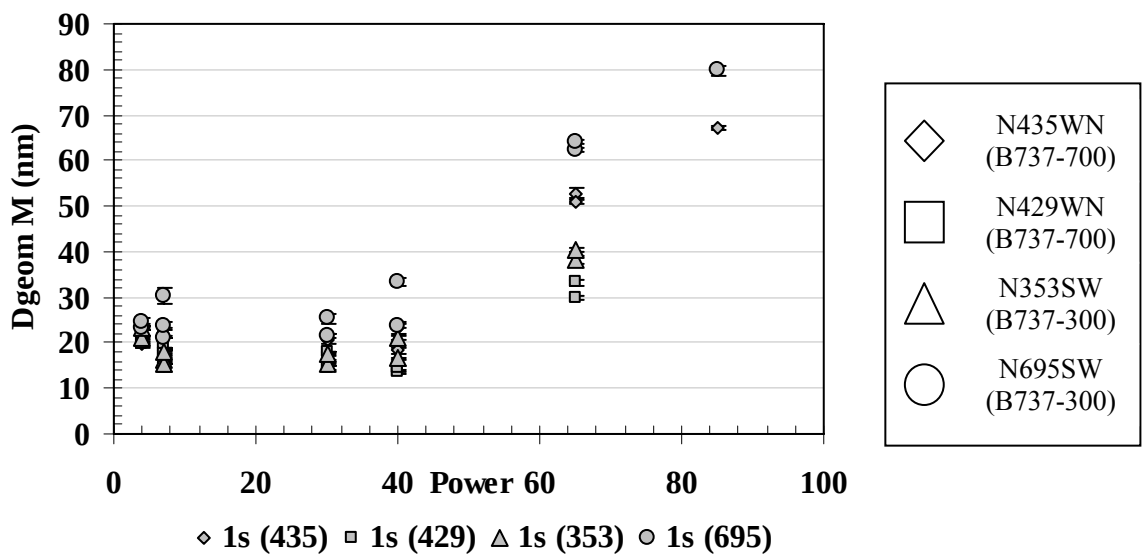


Figure 33: Mass-based geometric mean diameter for total aerosol at 50m as a function of power

Mass-based geometric mean diameter exhibited a trend to increase with power. This trend was independent of engine type. Comparison with the 1m data yields no significant differences.

Number-based emission index

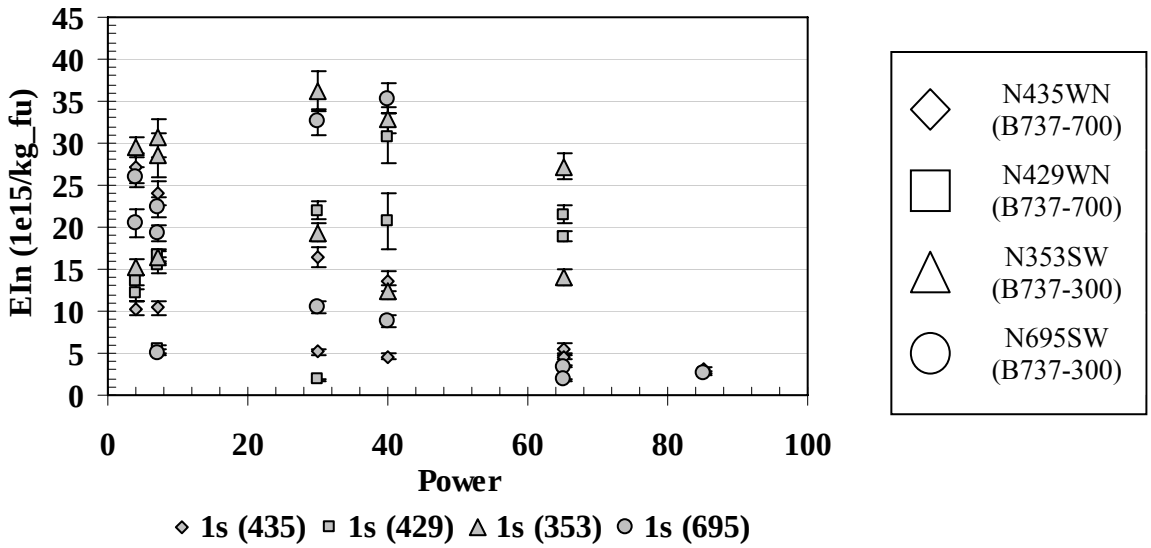


Figure 34: Number-based emission index for total aerosol at 50m as a function of power

No apparent trend with power was observed. It is important to note that this average EIn is an order of magnitude larger at 50m than the equivalent average value at 1m.

Mass-based emission index

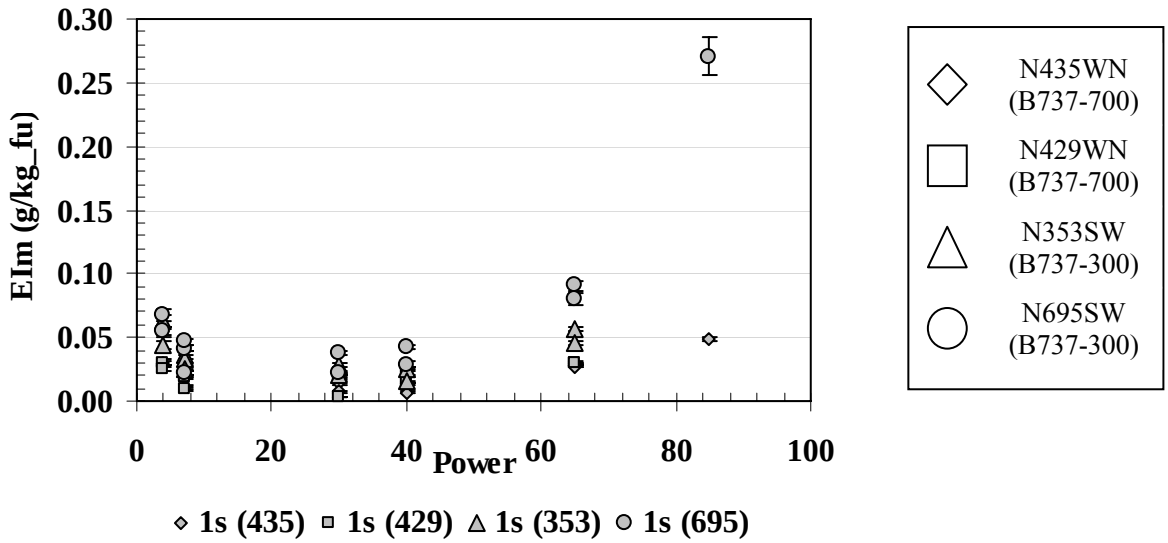


Figure 35: Mass-based emission index for total aerosol at 50m as a function of power

Mass-based emission index exhibited a trend to increase with power passing through a minimum in the 30-40% power range. The trend is stronger for the older engine technology (-300 series). As would be anticipated, no statistically significant difference is observed with respect to the 1m EIm data.

3.2.3 PM Emission (Non-volatile Aerosol) Parameters at 1m Downstream of Exhaust Nozzle

Number-based geometric mean diameter

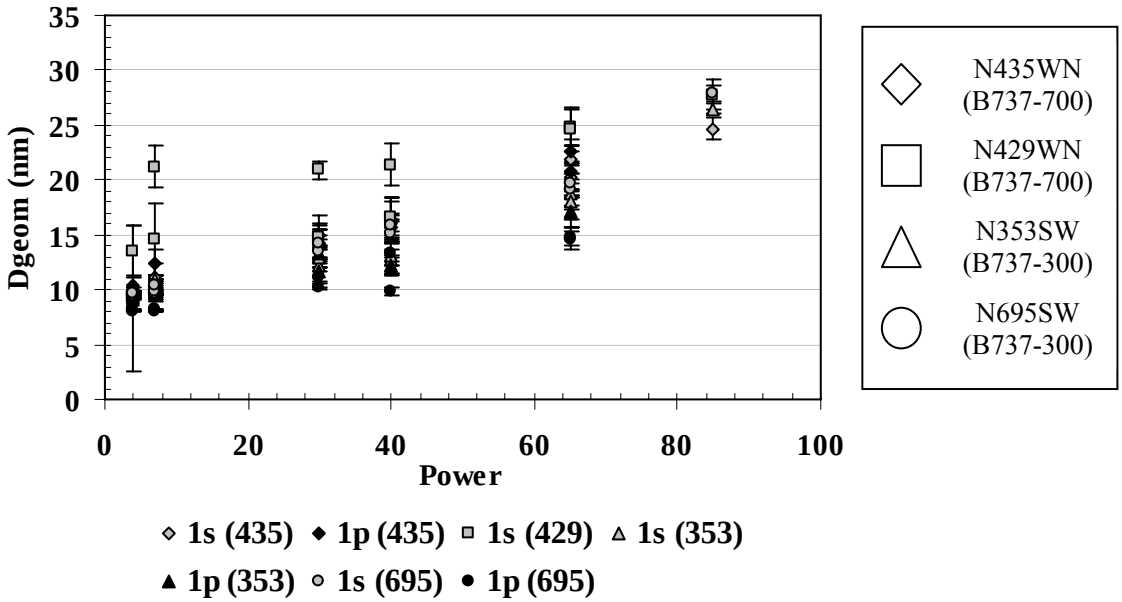


Figure 36: Dgeom for the non-volatile aerosol at 1m as a function of power

Number-based geometric mean diameter exhibited a trend to increase with power. This trend was independent of engine type. The relatively large deviation associated with N429WN at low power conditions can be attributed to engine warmup which will be addressed in the Discussion section.

Geometric standard deviation

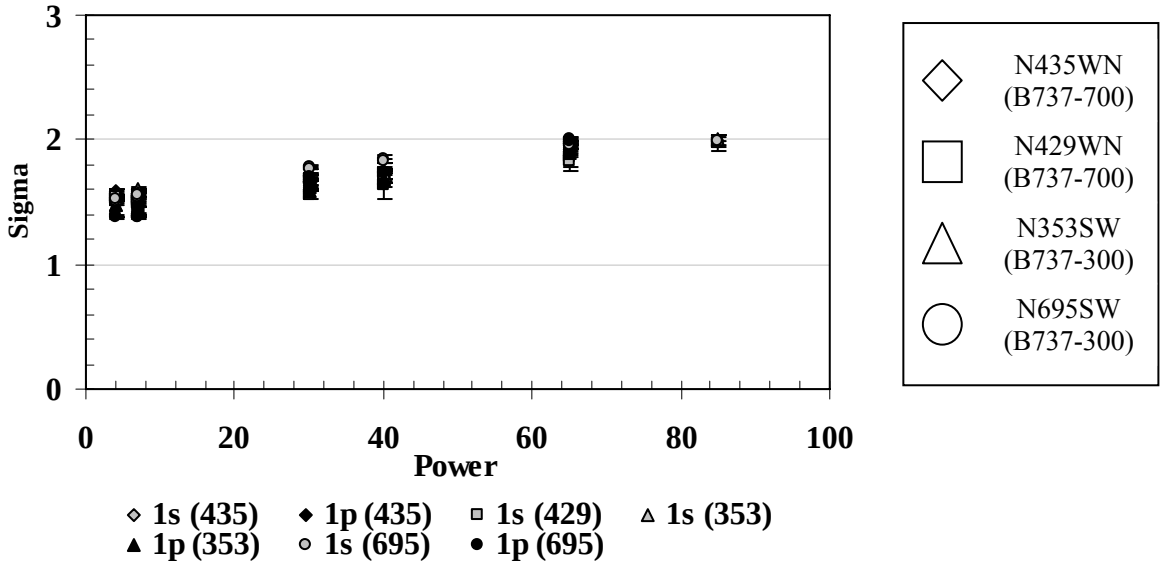


Figure 37: Sigma for the non-volatile aerosol at 1m as a function of power

Geometric standard deviation exhibited a weak positive trend with power. This trend was independent of engine type.

Mass-based geometric mean diameter

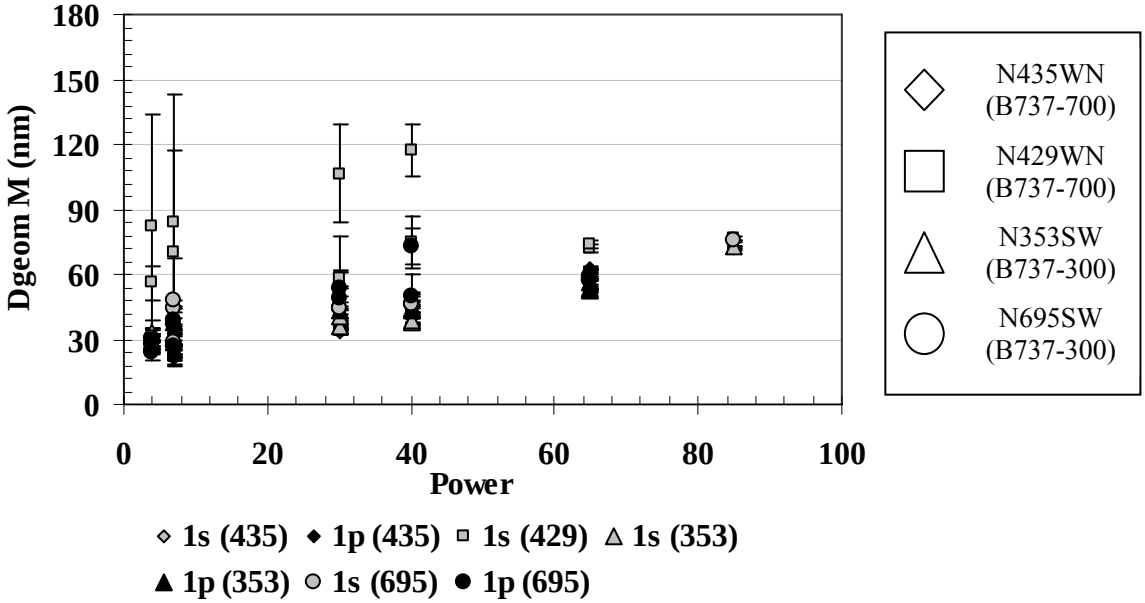


Figure 38: DgeomM for the non-volatile aerosol at 1m as a function of power

Mass-based geometric mean diameter exhibited a trend to increase with power as was the case for the number-based geometric mean diameter. This trend was independent of engine type with the exception of N429WN. The relatively large deviation associated with the N429WN at low power conditions can be attributed to engine warmup which will be addressed in the Discussion section.

Number-based emission index

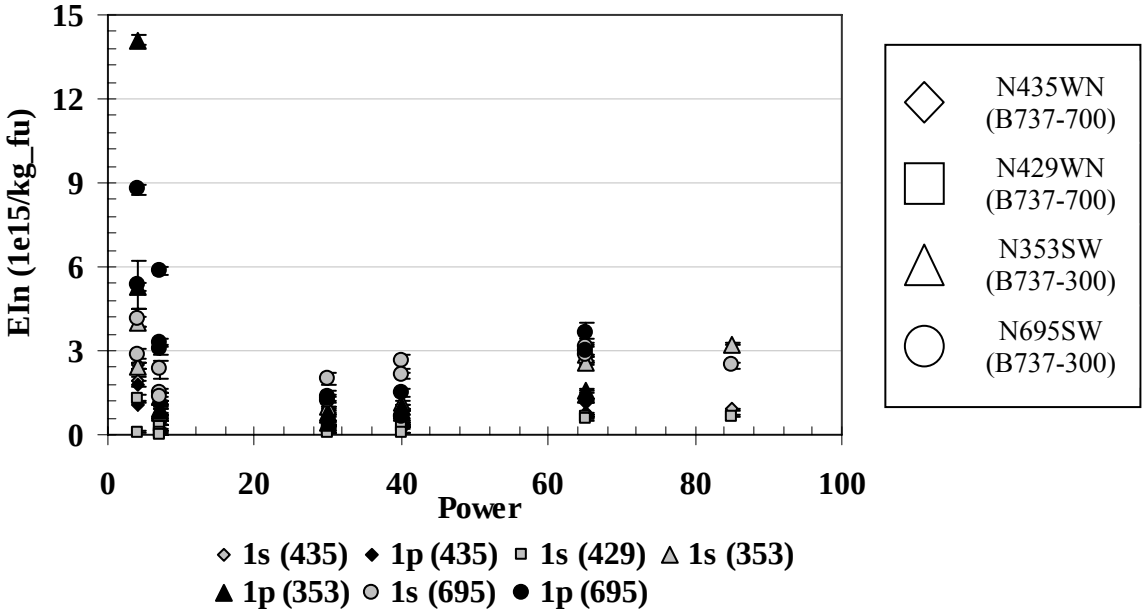


Figure 39: EIn for the non-volatile aerosol at 1m as a function of power

For each engine a minimum in number-based emission index was observed in the 30-40% power range. Engine to engine variance exceeded that associated with power change for a given engine.

Mass-based emission index

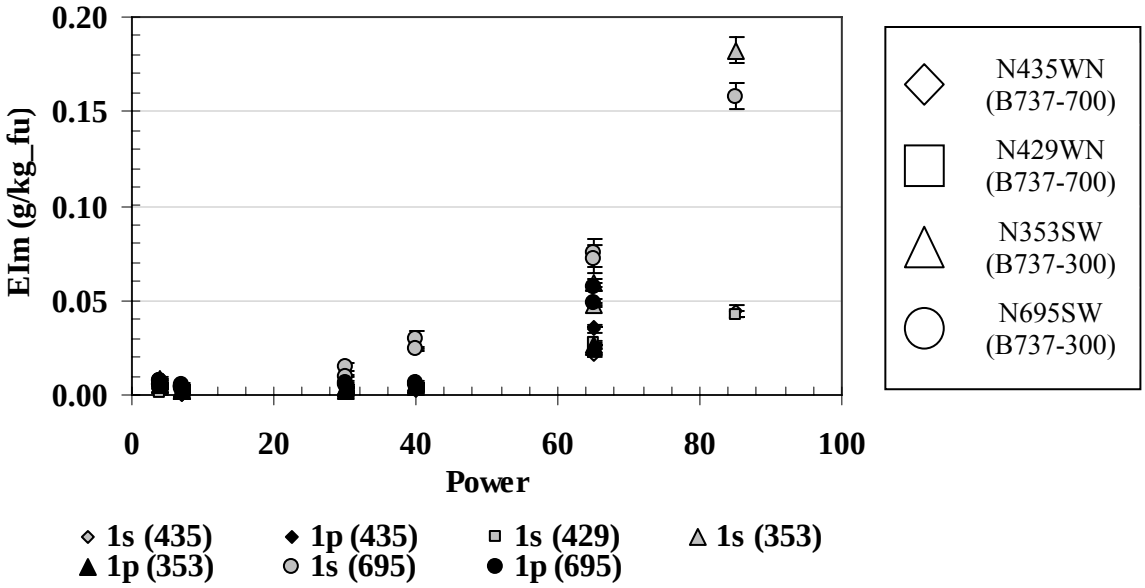


Figure 40: EIm for the non-volatile aerosol at 1m as a function of power

Mass-based emission index exhibited a trend to increase with power. The trend is stronger for the older engine technology (-3 series).

3.2.4 Deliquescence Results

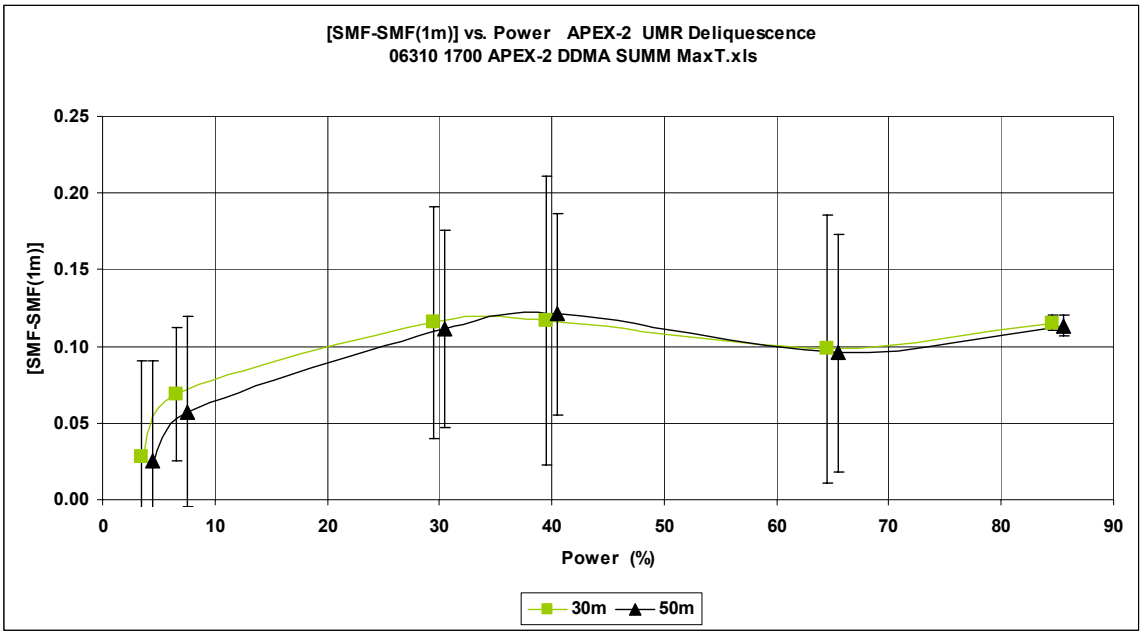


Figure 41: Results of the deliquescence experiment

At the 1m location, the Soluble Mass Fraction (SMF) of the aerosol sample was found to be negligible. This result is expected since the exit plane temperature (at 1m) greatly exceeds that of any anticipated soluble material e.g. sulfuric acid. The SMF was found to increase with distance from the engine exit plane reaching ~10% at 50m. No statistically significant variation is observed with engine power.

3.3 Total organic gases and aerosol chemical speciation (UCR)

3.3.1 UCR Results for Mass Flow

As discussed in the methodology section, UCR's role was to deliver a special sampler and the measurement of speciated hydrocarbons and particulate matter for jet exhaust at each mode. A new sampler was needed for the JETS APEX 2 project since the sampler from APEX1 was not suitable for the test cycle designed for the JETS APEX2 project. Therefore UCR designed, constructed and planned to verify the performance of a custom high volume sampler before the tests at the Oakland Airport. However, ARB funding for the Oakland test was approved on August 9th and because the deployment to the field took place on August 20th, the approximate two week period after funding was spent purchasing parts, assembly, packaging, troubleshooting, and deploying the instrument. As a consequence of the late contracting and a policy of no pre-awards, neither the flow measurements nor the planned verification of the JETS APEX2 sampling unit against another sampling system, as is usually carried out for a new sampler before a field campaign, were carried out.

Much of the programming for the electronic controls and final leak checks and repairs to the sampler were made at the Oakland airport the day before testing started. As discussed earlier, UCR used a number of methods to ensure that the flows rates in the final sampler matched the planned values. The process started in the field by extensive leak checking of the system under pressure. Identifiable leaks were repaired. For example, the large pipe threads near the impactor required epoxy to seal the leak with subsequent vacuum checks indicating the system was leak tight. Finally, flow in the low flow channels (thermal desorption tube and carbonyl trap line) was verified with a primary flow calibration unit. The high flow rates were only verified when the unit was returned to UCR as there was no standard gauge available in the field.

Table 12 summarizes the calibrated flow rates through the sampling media and for the system. Each flow rate was pressure and temperature corrected for sampling conditions encountered for each engine. Critical flow orifices were used to control flow rates through all systems. With the exception of the Summa Canisters, all flows were operated under choked conditions (outlet pressure << 0.52 * inlet pressure). Thermocouples and absolute pressure gauges were used to correct for pressure and temperature fluctuations in the system. On the C_4-C_{12} line (TDS tube line) and DNPH line, flows were also metered as differential pressure through a laminar flow element. Summa canisters were filled

through a small orifice to lower the sampling rate, but absolute flow was not controlled since measurements are made on a volume concentration basis.

Table 12: Flow rate in LPM for Different Lines & Plane as a Function of Mode

Aircraft		Quartz	Teflon	PUF	DNPH*	TDS*	Summa
N435WN	Mode1	69.5	30.2	21.9	0.97	0.17	*
	Mode2	79.2	34.5	23.2	1.16	0.19	*
	Mode3	83.5	36.8	27.9	0.92	0.20	*
	Mode4	92.6	40.9	28.9	1.30	0.20	*
N353SW	Mode1	53.9	36.6	22.0	0.85	0.18	*
	Mode2	59.9	41.2	23.0	0.89	0.19	*
	Mode3	76.0	37.8	25.4	0.98	0.17	*
	Mode4	71.7	47.1	29.6	1.32	0.22	*
N695SW	Mode1	54.7	37.9	22.6	0.98	0.16	*
	Mode2	62.0	41.4	24.4	1.06	0.18	*
	Mode3	67.3	41.3	29.5	1.32	0.21	*
	Mode4	77.4	50.9	30.8	1.48	0.22	*
N429WN	Mode1	53.0	37.5	21.8	0.94	0.17	*
	Mode2	59.5	41.6	23.1	1.15	0.18	*
	Mode3	64.2	40.6	27.5	0.91	0.19	*
	Mode4	76.4	50.9	29.9	1.34	0.19	*

*Flow directly measured through laminar flow element at inlet to sample manifold.

3.3.2 Internal Consistency Checks

The system design included a number of internal consistency checks to verify the integrity of the system and the data set. These included: redundant filter collection for carbon analysis (elemental and organic carbon), redundant flow measurement and sensing devices, and redundant internally measured CO_2 concentrations. Additional redundancy in compound analyses was made in the overlap region between Summa canisters and thermal desorption tube sampling (TDS). All flows were verified at the point of sample collection to be consistent with manufacturer specifications for orifices and pressure drops. The sample was designed to provide mass concentrations in the sample stream so that EI calculations could be performed with CO_2 data provided by others on the research team.

A comparison was therefore made between the total carbon collected on the two branches of the sampling system, which is displayed (µg m-3 basis) in Figure 42 below. Note the outstanding agreement between the parallel samples with a slope (0.98) and regression value obtained (r2=0.994) for this test.

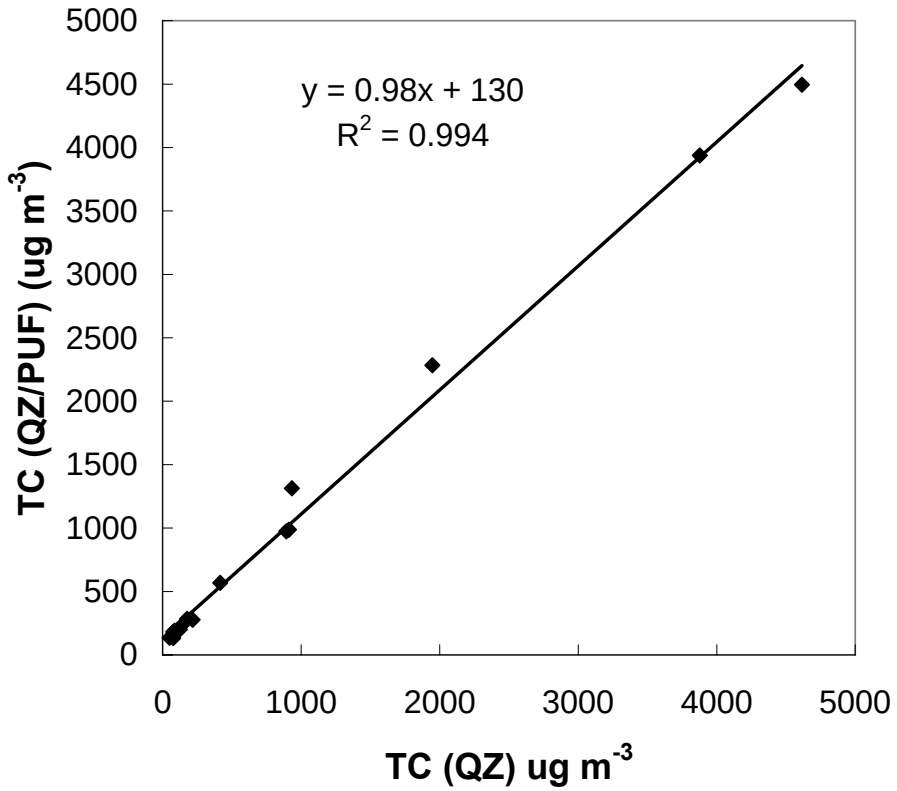


Figure 42: Correlation of total carbon concentration measured between parallel sample trains. One train was designed for high flow through the quartz to ensure sufficient sample for EC-OC analyses while the other train is the quartz-PUF combination for semi-volatile analysis.

Next, the total PM mass concentration measured on the Teflo filters are compared with the total carbon concentration obtained on the high flow quartz leg. This comparison provides another consistency check between measurements of particulate matter. Excellent agreement was noted between these legs (Figure 43) with a slope of 1.02 and an R2 of 0.997 noted for the test. This provided confidence in the measured values on these three legs.

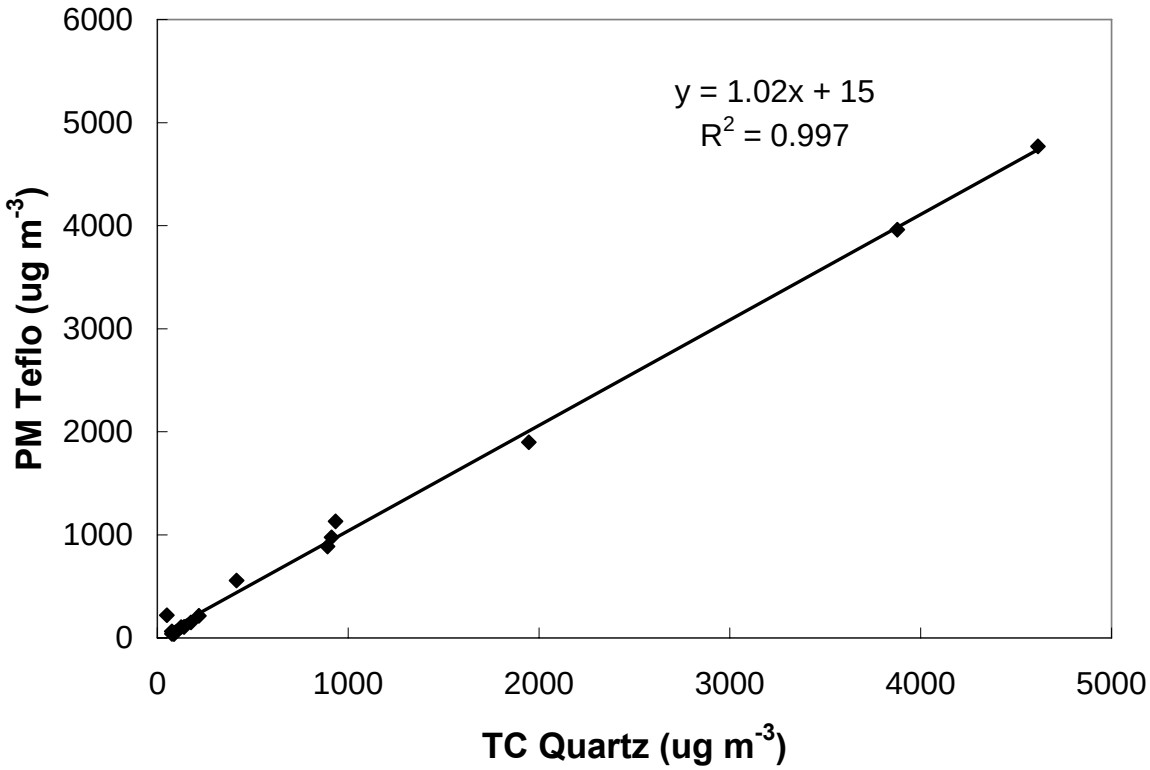


Figure 43: Comparison of PM mass concentration (measured on Teflo) vs. TC mass concentration measured on high flow quartz.

Additional redundancy was built into the system for the gas-phase hydrocarbons to ensure the integrity of the gas-phase speciation. The Summa canisters were intended to provide the C_1 to C_8 speciation with direct comparisons available for the overlap region (C_4-C_8) with the thermal desorption tube system. It was expected that the major species could be directly compared in this range. However, the Summa canisters, as will be discussed below, failed to yield any compounds. The Summa canisters were also intended to verify the dilution ratio (if an ambient air penetrated the sampling system) at the carbonyl sampling point.

Finally, a check of the metals data was available by comparison of the sulfate ion analysis to the sulfur obtained by XRF. Here, the assumption is that all sulfurous species were present as sulfate on the filters. This comparison is limited by the extremely small concentrations of sulfur present on the filter which pushed the sulfate analyses using IC near minimum detection limits. A comparison of the measurements is seen in Figure 44 below.

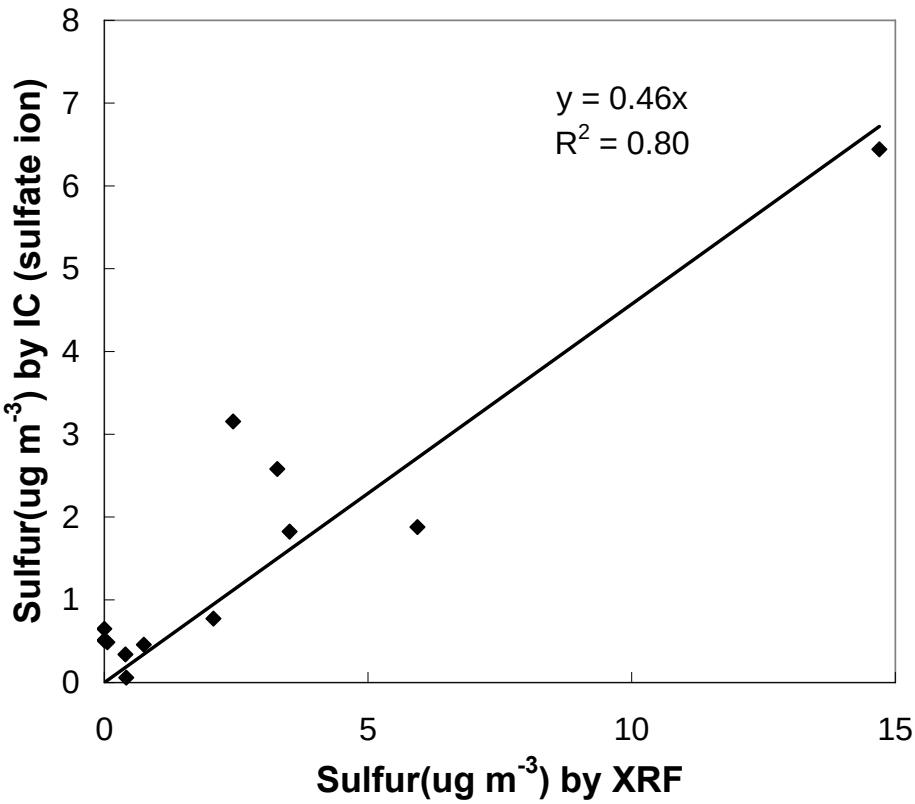


Figure 44: Comparison of sulfur concentration (measured sulfate as sulfur by IC) to sulfur mass concentration measured by XRF.

3.3.3 Particulate matter

Particulate matter mass concentrations were measured on Teflo filters. Dramatic increases in the PM concentrations are noted as the power increased to 85%. Figures 45 and 46 provide the EI and mass concentration measured for the PM for each mode, respectively. It should be noted that N353SW Mode 3 failed internal QA/QC and is not reported.

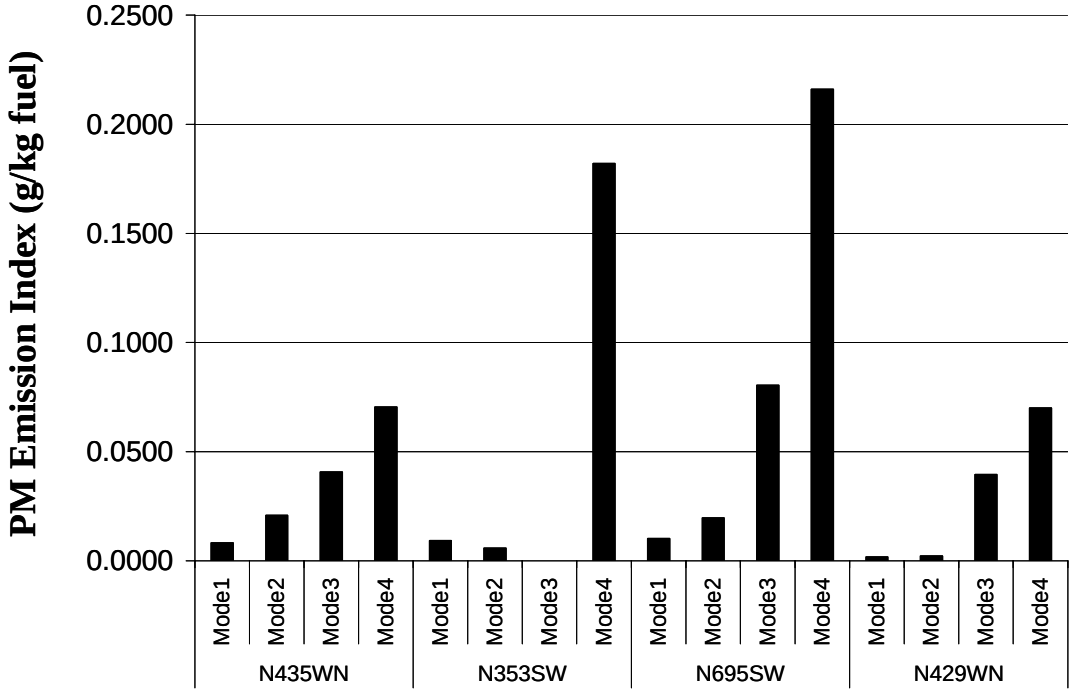


Figure 45: PM emission indices

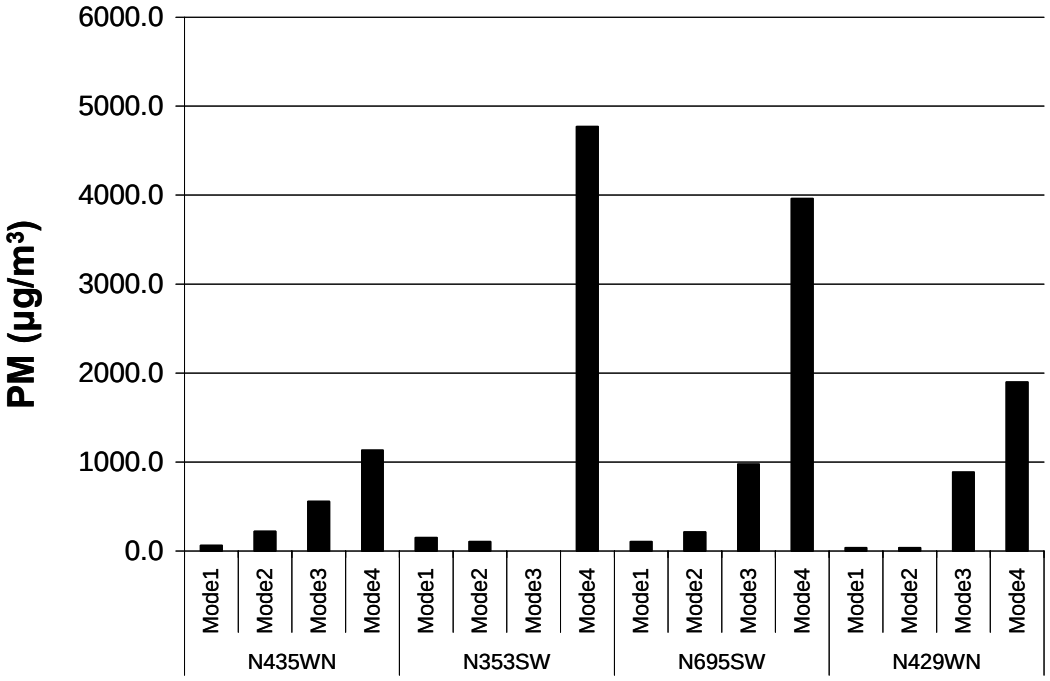


Figure 46: PM mass concentrations

3.3.4 Elemental and organic carbon

As explained in the earlier sections, pre-weighed Teflon and fired quartz filter media were inserted into the Gelman holders prior to the beginning of the aircraft test cycle. At the completion of the test cycle, the media were removed, sealed in Petri dishes and stored cool before their return to the laboratory for measurement of the mass, elemental and organic carbon using the methods described earlier. Tables 13 and 14 summarize the mass concentrations and EIs measured for PM, EC and OC. The relative concentrations of EC to OC are shown in Figure 47. Media for Mode3 for N353SW failed the QC testing and are not reported (the Teflon and quartz masses did not agree).

Table 13: mass concentrations of PM, EC, OC and TC

			Mode1	Mode2	Mode3	Mode4
N435WN	EC	(ug/m3)	19.3	18.0	326	664
	OC	(ug/m3)	56.8	32.1	89.6	270
	TC	(ug/m3)	76.1	50.0	416	934
	PM	(ug/m3)	62.5	220	557	1131
N353SW	EC	(ug/m3)	71.7	62.6	N/A	4036
	OC	(ug/m3)	105	62.6	N/A	579
	TC	(ug/m3)	176	125	N/A	4615
	PM	(ug/m3)	150	104	N/A	4770
N695SW	EC	(ug/m3)	57.4	148	722	3133
	OC	(ug/m3)	82.5	70.1	190	745
	TC	(ug/m3)	140	218	913	3877
	PM	(ug/m3)	105	214	976	3961
N429WN	EC	(ug/m3)	17.3	27.8	759	1288
	OC	(ug/m3)	70.1	49.0	133	659
	TC	(ug/m3)	87.4	76.9	892	1947
	PM	(ug/m3)	37.1	38.5	887	1898

Table 14: EI (g kg^{-1} fuel)

		Mode1	Mode2	Mode3	Mode4
N435WN	PM	0.0082	0.0209	0.041	0.070
	EC	0.0025	0.0017	0.024	0.041
	OC	0.0075	0.0030	0.0065	0.017
N353SW	PM	0.0092	0.0058	N/A	0.182
	EC	0.0044	0.0035	N/A	0.154
	OC	0.0065	0.0035	N/A	0.022
N695SW	PM	0.0102	0.0196	0.080	0.216
	EC	0.0056	0.0135	0.060	0.171
	OC	0.0080	0.0064	0.016	0.041
N429WN	PM	0.0017	0.0022	0.039	0.070
	EC	0.00080	0.0016	0.034	0.047
	OC	0.0032	0.0028	0.0059	0.024

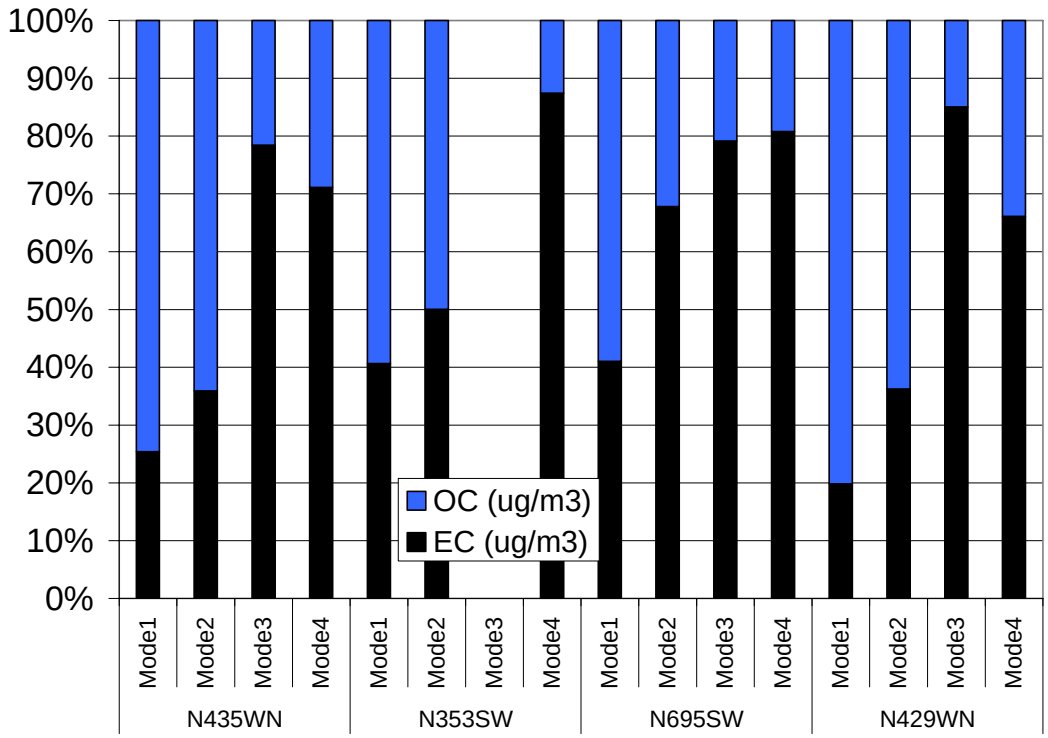


Figure 47: Relative EC and OC emission rates for each aircraft as a function of mode

3.3.5 Polycyclic Aromatic Hydrocarbons (PAHs) and n-alkanes (C_{12}+)

PAHs and n-alkanes (C12+) were collected on quartz followed by a PUF-XAD-PUF sandwich. This sample line was verified by total carbon catch on the quartz filter against both the particle sample line and the high flow quartz line (see consistency check section above). In this work, "naphthalenic" PAHs include naphthalene and its 1-methyl and 2-methyl derivatives; while "non-naphthalenic" PAHs range from acenaphthylene to dibenz[a,h]anthracene in increasing molecular weight. The naphthalenic PAHs are the overwhelmingly dominant PAH species measured. Figures 48 and 49 provide the relative distribution of naphthalenic and non-naphthalenic compounds. Note that the relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer (Spicer et al.1992, 1994). It was also noted that there was a sharp decrease in the relative contribution of substituted naphthalenes at the higher load points. Trends in the non-naphthalenic compounds are also noted with acenaphthylene present significantly only in the idle mode and fluoranthene decreasing with increasing power.

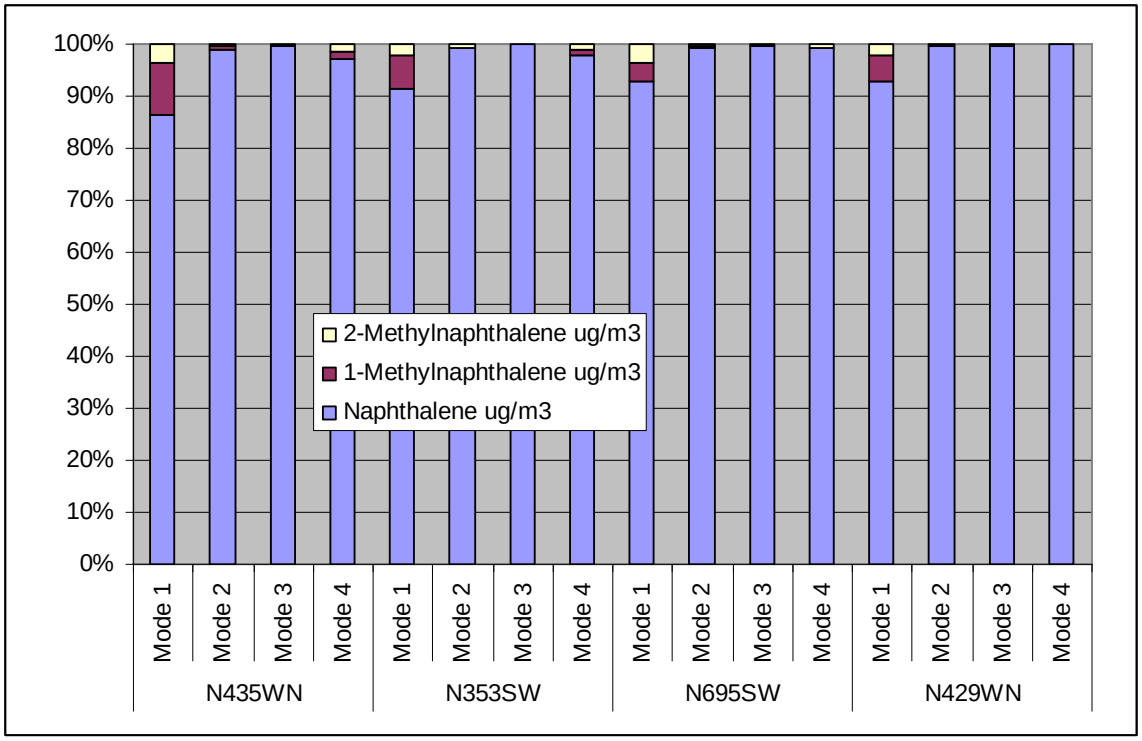


Figure 48: Comparison of the relative contribution of naphthalenic compounds

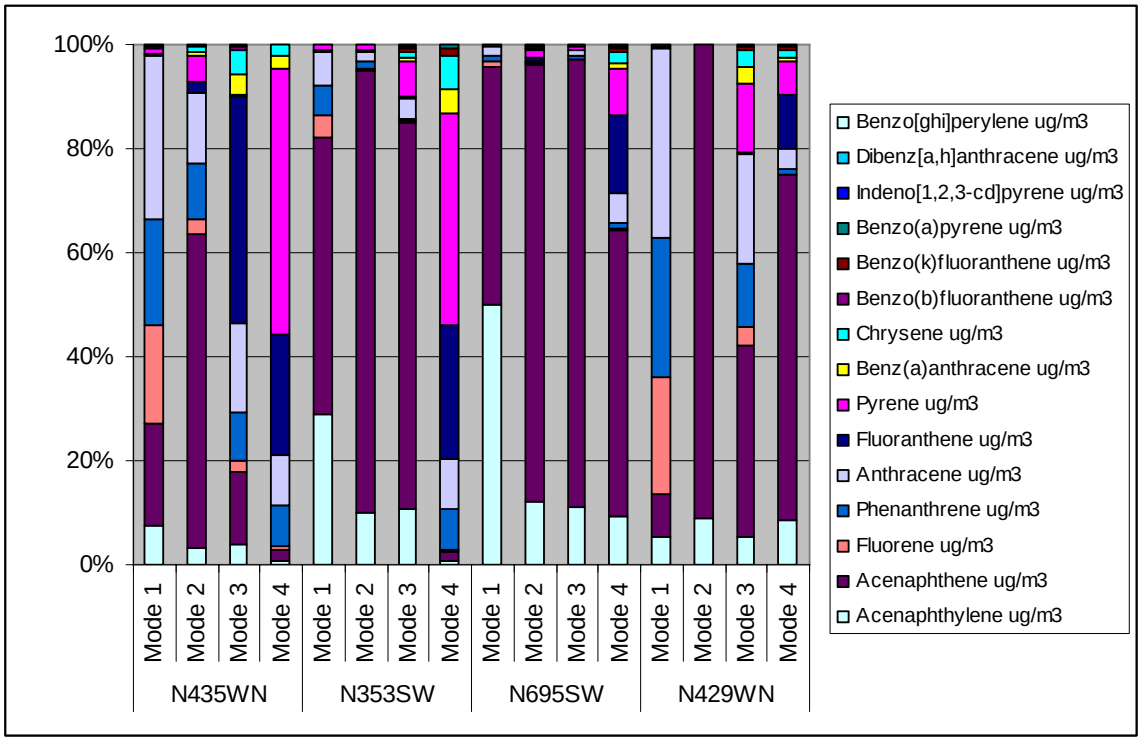


Figure 49: Comparison of relative contributions of non-naphthalenic PAH compounds

The relative distribution of n-alkanes are also charted below (Figure 50).

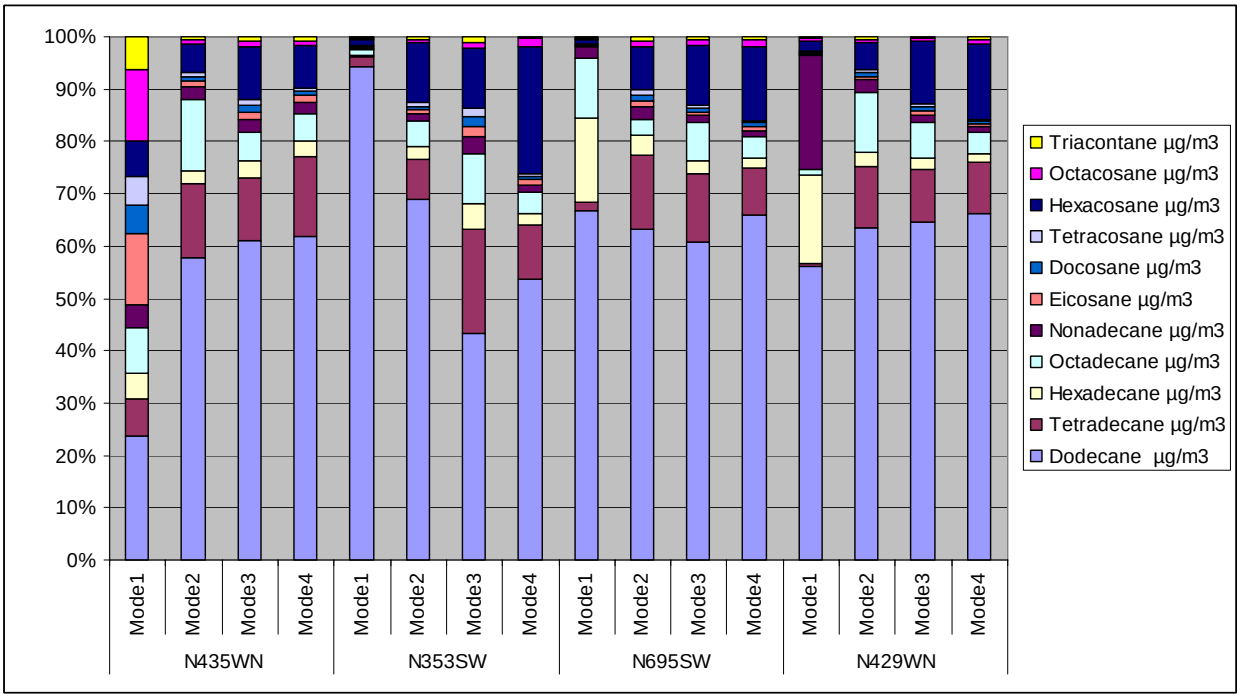


Figure 50: Comparison of n-alkane distribution (C_{12}-C_{30})

Tables 15-17 and 18-22 summarize the mass concentrations and EIs for the PAH and n-alkane compounds, respectively:

Table 15: Mass concentration of PAH and n-alkanes (C_{12}-C_{30}) – N435WN

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	(ug/m3)	8.18E+01	4.93E+03	4.75E+03	8.15E+02
1-Methylnaphthalene	(ug/m3)	9.69E+00	3.63E+01	1.11E+01	1.32E+01
2-Methylnaphthalene	(ug/m3)	3.25E+00	1.00E+01	4.28E+00	1.15E+01
Acenaphthylene	(ug/m3)	1.10E+01	9.73E-01	5.70E-01	2.98E-01
Acenaphthene	(ug/m3)	2.82E+01	1.89E+01	2.05E+00	1.21E+00
Fluorene	(ug/m3)	2.68E+01	9.06E-01	3.14E-01	4.44E-01
Phenanthrene	(ug/m3)	2.95E+01	3.30E+00	1.34E+00	4.34E+00
Anthracene	(ug/m3)	4.50E+01	4.28E+00	2.52E+00	5.16E+00
Fluoranthene	(ug/m3)	7.86E-01	6.68E-01	6.33E+00	1.26E+01
Pyrene	(ug/m3)	1.50E+00	1.58E+00	8.74E-02	2.76E+01
Benz(a)anthracene	(ug/m3)	3.15E-01	2.65E-01	5.46E-01	1.24E+00
Chrysene	(ug/m3)	3.20E-01	2.68E-01	7.09E-01	1.26E+00
Benzo(b)fluoranthene	(ug/m3)	6.77E-02	4.37E-02	7.56E-02	BDL
Benzo(k)fluoranthene	(ug/m3)	1.87E-01	9.46E-02	6.49E-02	BDL
Benzo(a)pyrene	(ug/m3)	4.94E-02	BDL	BDL	BDL
Indeno[1,2,3-cd]pyrene	(ug/m3)	BDL	BDL	BDL	BDL
Dibenz[a,h]anthracene	(ug/m3)	BDL	BDL	BDL	BDL
Benzo[ghi]perylene	(ug/m3)	BDL	BDL	BDL	BDL
n-Alkanes					
Dodecane	(ug/m3)	1.26E+00	5.63E+00	7.18E+00	3.88E+1
Tetradecane	(ug/m3)	3.77E-01	1.38E+00	1.41E+00	9.66E+00
Hexadecane	(ug/m3)	2.54E-01	2.40E-01	3.85E-01	1.76E+00
Octadecane	(ug/m3)	4.58E-01	1.23E+00	6.59E-01	3.39E+00
Nonadecane	(ug/m3)	2.34E-01	2.52E-01	2.67E-01	1.29E+00
Eicosane	(ug/m3)	7.18E-01	9.96E-02	1.58E-01	7.98E-01
Docosane	(ug/m3)	2.86E-01	8.66E-02	1.75E-01	5.91E-01
Tetracosane	(ug/m3)	3.01E-01	7.81E-02	1.22E-01	3.91E-01
Hexacosane	(ug/m3)	3.57E-01	5.30E-01	1.17E+00	5.09E+00
Octacosane	(ug/m3)	7.16E-01	6.90E-02	1.40E-01	4.84E-01
Triacontane	(ug/m3)	3.34E-01	5.72E-02	9.98E-02	5.51E-01

Table 16: Mass concentration of PAH and n-alkanes (C_{12}-C_{30}) – N353SW

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	(ug/m3)	1.03E+02	1.49E+04	8.01E+04	1.15E+03
1-Methylnaphthalene	(ug/m3)	7.18E+00	2.71E+01	1.12E+02	1.33E+01
2-Methylnaphthalene	(ug/m3)	2.33E+00	8.08E+01	3.14E+01	1.35E+01
Acenaphthylene	(ug/m3)	2.27E+02	2.27E+01	9.72E+00	4.69E-01
Acenaphthene	(ug/m3)	4.15E+02	1.91E+02	6.85E+01	1.45E+00
Fluorene	(ug/m3)	3.44E+01	6.58E-01	3.26E-01	2.29E-01
Phenanthrene	(ug/m3)	4.32E+01	3.13E+00	4.43E-01	6.15E+00
Anthracene	(ug/m3)	4.98E+01	3.92E+00	3.74E+00	7.32E+00
Fluoranthene	(ug/m3)	3.35E+00	1.21E+00	4.31E-02	1.95E+01
Pyrene	(ug/m3)	8.00E+00	2.15E+00	6.35E+00	3.13E+01
Benz(a)anthracene	(ug/m3)	2.92E-01	1.19E-01	7.57E-01	3.53E+00
Chrysene	(ug/m3)	2.96E-01	1.21E-01	7.97E-01	4.99E+00
Benzo(b)fluoranthene	(ug/m3)	BDL	BDL	2.45E-01	BDL
Benzo(k)fluoranthene	(ug/m3)	BDL	BDL	5.41E-01	1.09E+00
Benzo(a)pyrene	(ug/m3)	BDL	BDL	2.10E-01	4.10E-01
Indeno[1,2,3-cd]pyrene	(ug/m3)	BDL	BDL	1.68E-01	BDL
Dibenz[a,h]anthracene	(ug/m3)	BDL	BDL	2.80E-01	BDL
Benzo[ghi]perylene	(ug/m3)	BDL	BDL	BDL	BDL
n-Alkanes					
Dodecane	(ug/m3)	4.20E+01	8.41E+00	4.33E+00	5.18E+01
Tetradecane	(ug/m3)	7.77E-01	9.32E-01	2.00E+00	9.78E+00
Hexadecane	(ug/m3)	1.71E-01	3.10E-01	5.08E-01	2.21E+00
Octadecane	(ug/m3)	4.95E-01	5.85E-01	9.40E-01	3.89E+00
Nonadecane	(ug/m3)	1.43E-01	1.84E-01	3.29E-01	1.32E+00
Eicosane	(ug/m3)	7.58E-02	9.80E-02	1.93E-01	9.42E-01
Docosane	(ug/m3)	6.82E-02	7.82E-02	1.93E-01	6.39E-01
Tetracosane	(ug/m3)	1.15E-01	9.37E-02	1.57E-01	4.81E-01
Hexacosane	(ug/m3)	4.42E-01	1.40E+00	1.14E+00	2.34E+01
Octacosane	(ug/m3)	1.83E-01	6.92E-02	1.06E-01	1.43E+00
Triacontane	(ug/m3)	6.17E-02	5.66E-02	1.21E-01	3.81E-01

Table 17: Mass concentration of PAH and n-alkanes (C_{12}-C_{30}) – N695SW

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	(ug/m3)	1.46E+02	1.56E+03	1.79E+04	1.27E+04
1-Methylnaphthalene	(ug/m3)	6.07E+00	5.76E+00	5.24E+01	1.60E+01
2-Methylnaphthalene	(ug/m3)	5.42E+00	4.67E+00	1.27E+01	7.88E+01
Acenaphthylene	(ug/m3)	2.78E+02	8.93E+00	2.06E+01	9.24E+00
Acenaphthene	(ug/m3)	2.52E+02	6.18E+01	1.61E+02	5.42E+01
Fluorene	(ug/m3)	7.46E+00	5.80E-02	3.77E-01	3.86E-01
Phenanthrene	(ug/m3)	5.78E+00	3.99E-01	1.15E+00	1.15E+00
Anthracene	(ug/m3)	8.25E+00	6.51E-02	1.82E+00	5.69E+00
Fluoranthene	(ug/m3)	8.79E-01	5.22E-01	4.06E-02	1.48E+01
Pyrene	(ug/m3)	1.02E+00	1.24E+00	1.30E+00	8.84E+00
Benz(a)anthracene	(ug/m3)	4.16E-02	2.67E-01	3.11E-01	1.12E+00
Chrysene	(ug/m3)	5.31E-01	2.70E-01	3.15E-01	1.96E+00
Benzo(b)fluoranthene	(ug/m3)	6.63E-02	6.19E-02	BDL	BDL
Benzo(k)fluoranthene	(ug/m3)	1.38E-01	1.02E-01	7.84E-02	7.01E-01
Benzo(a)pyrene	(ug/m3)	1.52E-01	2.40E-02	4.25E-02	2.92E-01
Indeno[1,2,3-cd]pyrene	(ug/m3)	3.36E-02	BDL	BDL	2.36E-01
Dibenz[a,h]anthracene	(ug/m3)	BDL	BDL	BDL	1.99E-01
Benzo[ghi]perylene	(ug/m3)	3.53E-02	BDL	BDL	BDL
n-Alkanes					
Dodecane	(ug/m3)	2.58E+01	5.04E+00	1.06E+01	5.41E+01
Tetradecane	(ug/m3)	6.46E-01	1.13E+00	2.25E+00	7.39E+00
Hexadecane	(ug/m3)	6.24E+00	2.85E-01	4.25E-01	1.66E+00
Octadecane	(ug/m3)	4.47E+00	2.48E-01	1.31E+00	3.27E+00
Nonadecane	(ug/m3)	7.71E-01	1.98E-01	2.23E-01	9.43E-01
Eicosane	(ug/m3)	9.32E-02	9.03E-02	1.12E-01	6.61E-01
Docosane	(ug/m3)	6.34E-02	8.56E-02	1.34E-01	5.79E-01
Tetracosane	(ug/m3)	5.14E-02	7.56E-02	7.98E-02	2.91E-01
Hexacosane	(ug/m3)	3.46E-01	6.60E-01	1.99E+00	1.16E+01
Octacosane	(ug/m3)	1.32E-01	7.83E-02	2.25E-01	1.21E+00
Triacontane	(ug/m3)	8.12E-02	7.07E-02	9.09E-02	4.60E-01

Table 18: Mass concentration of PAH and n-alkanes (C_{12}-C_{30}) – N429WN

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	(ug/m3)	1.07E+02	2.20E+04	9.23E+03	1.22E+04
1-Methylnaphthalene	(ug/m3)	5.71E+00	3.73E+01	1.75E+01	1.17E+01
2-Methylnaphthalene	(ug/m3)	2.33E+00	7.52E+00	1.85E+01	6.30E+00
Acenaphthylene	(ug/m3)	2.22E+01	4.42E+02	5.49E-01	1.23E+01
Acenaphthene	(ug/m3)	3.39E+01	4.46E+03	3.89E+00	9.43E+01
Fluorene	(ug/m3)	9.53E+01	7.56E-01	4.09E-01	3.61E-01
Phenanthrene	(ug/m3)	1.11E+02	2.67E+00	1.28E+00	1.13E+00
Anthracene	(ug/m3)	1.53E+02	2.56E+00	2.22E+00	5.72E+00
Fluoranthene	(ug/m3)	9.04E-01	5.42E-01	4.30E-02	1.50E+01
Pyrene	(ug/m3)	1.05E+00	1.29E+00	1.38E+00	8.95E+00
Benz(a)anthracene	(ug/m3)	4.27E-02	2.77E-01	3.30E-01	1.14E+00
Chrysene	(ug/m3)	5.45E-01	2.81E-01	3.34E-01	1.99E+00
Benzo(b)fluoranthene	(ug/m3)	6.82E-02	6.43E-02	BDL	BDL
Benzo(k)fluoranthene	(ug/m3)	1.42E-01	1.06E-01	8.31E-02	7.10E-01
Benzo(a)pyrene	(ug/m3)	1.57E-01	2.50E-02	4.50E-02	2.95E-01
Indeno[1,2,3-cd]pyrene	(ug/m3)	3.45E-02	BDL	BDL	2.39E-01
Dibenz[a,h]anthracene	(ug/m3)	BDL	BDL	BDL	2.01E-01
Benzo[ghi]perylene	(ug/m3)	3.63E-02	BDL	BDL	BDL
n-Alkanes					
Dodecane	(ug/m3)	1.39E+01	5.50E+00	1.17E+01	5.54E+01
Tetradecane	(ug/m3)	1.11E-01	1.03E+00	1.85E+00	8.26E+00
Hexadecane	(ug/m3)	4.19E+00	2.23E-01	3.81E-01	1.40E+00
Octadecane	(ug/m3)	2.54E-01	9.98E-01	1.23E+00	3.54E+00
Nonadecane	(ug/m3)	5.39E+00	2.07E-01	2.73E-01	8.22E-01
Eicosane	(ug/m3)	8.29E-02	5.79E-02	1.52E-01	5.16E-01
Docosane	(ug/m3)	5.35E-02	6.25E-02	1.47E-01	3.41E-01
Tetracosane	(ug/m3)	6.50E-02	5.63E-02	9.31E-02	2.76E-01
Hexacosane	(ug/m3)	4.62E-01	4.39E-01	2.15E+00	1.22E+01
Octacosane	(ug/m3)	1.55E-01	4.80E-02	8.93E-02	4.93E-01
Triacontane	(ug/m3)	7.96E-02	4.44E-02	7.38E-02	5.60E-01

Table 19: Emission Indices for PAH and n-alkanes (C_{12}-C_{30}) – N435WN

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	g/kgfuel	1.64E-02	7.15E-01	5.30E-01	7.74E-02
1-Methylnaphthalene	g/kgfuel	1.94E-03	5.25E-03	1.23E-03	1.25E-03
2-Methylnaphthalene	g/kgfuel	6.50E-04	1.45E-03	4.77E-04	1.10E-03
Acenaphthylene	g/kgfuel	2.20E-03	1.41E-04	6.35E-05	2.83E-05
Acenaphthene	g/kgfuel	5.64E-03	2.74E-03	2.28E-04	1.15E-04
Fluorene	g/kgfuel	5.35E-03	1.31E-04	3.50E-05	4.22E-05
Phenanthrene	g/kgfuel	5.91E-03	4.78E-04	1.49E-04	4.12E-04
Anthracene	g/kgfuel	8.99E-03	6.20E-04	2.80E-04	4.90E-04
Fluoranthene	g/kgfuel	1.57E-04	9.68E-05	7.06E-04	1.20E-03
Pyrene	g/kgfuel	3.01E-04	2.29E-04	9.74E-06	2.63E-03
Benz(a)anthracene	g/kgfuel	6.31E-05	3.83E-05	6.08E-05	1.18E-04
Chrysene	g/kgfuel	6.39E-05	3.88E-05	7.89E-05	1.20E-04
Benzo(b)fluoranthene	g/kgfuel	1.35E-05	6.32E-06	8.42E-06	0.00E+00
Benzo(k)fluoranthene	g/kgfuel	3.75E-05	1.37E-05	7.23E-06	0.00E+00
Benzo(a)pyrene	g/kgfuel	9.88E-06	BDL	BDL	BDL
Indeno[1,2,3-cd]pyrene	g/kgfuel	BDL	BDL	BDL	BDL
Dibenz[a,h]anthracene	g/kgfuel	BDL	BDL	BDL	BDL
Benzo[ghi]perylene	g/kgfuel	BDL	BDL	BDL	BDL
n-Alkanes					
Dodecane	g/kgfuel	7.80E-05	2.35E-04	2.63E-04	1.13E-03
Tetradecane	g/kgfuel	2.34E-05	5.76E-05	5.16E-05	2.82E-04
Hexadecane	g/kgfuel	1.58E-05	1.00E-05	1.41E-05	5.12E-05
Octadecane	g/kgfuel	2.84E-05	5.50E-05	2.42E-05	9.89E-05
Nonadecane	g/kgfuel	1.45E-05	1.05E-05	9.79E-06	3.76E-05
Eicosane	g/kgfuel	4.46E-05	4.41E-06	5.78E-06	2.33E-05
Docosane	g/kgfuel	1.77E-05	3.62E-06	6.43E-06	1.72E-05
Tetracosane	g/kgfuel	1.87E-05	3.26E-06	4.46E-06	1.14E-05
Hexacosane	g/kgfuel	2.22E-05	2.21E-05	4.30E-05	1.48E-04
Octacosane	g/kgfuel	4.44E-05	2.89E-06	5.13E-06	1.41E-05
Triacontane	g/kgfuel	2.07E-05	2.39E-06	3.66E-06	1.61E-05

Table 20: Emission Indices for PAH and n-alkanes (C_{12}-C_{30}) – N353SW

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	g/kgfuel	9.69E-03	1.26E+00	5.52E+00	6.68E-02
1-Methylnaphthalene	g/kgfuel	6.75E-04	2.28E-03	7.69E-03	7.72E-04
2-Methylnaphthalene	g/kgfuel	2.19E-04	6.80E-03	2.17E-03	7.88E-04
Acenaphthylene	g/kgfuel	2.14E-02	1.91E-03	6.70E-04	2.73E-05
Acenaphthene	g/kgfuel	3.90E-02	1.61E-02	4.72E-03	8.41E-05
Fluorene	g/kgfuel	3.24E-03	5.54E-05	2.25E-05	1.33E-05
Phenanthrene	g/kgfuel	4.06E-03	2.63E-04	3.05E-05	3.58E-04
Anthracene	g/kgfuel	4.68E-03	3.31E-04	2.58E-04	4.26E-04
Fluoranthene	g/kgfuel	3.15E-04	1.02E-04	2.97E-06	1.13E-03
Pyrene	g/kgfuel	7.52E-04	1.81E-04	4.38E-04	1.82E-03
Benz(a)anthracene	g/kgfuel	2.75E-05	1.00E-05	5.22E-05	2.05E-04
Chrysene	g/kgfuel	2.78E-05	1.02E-05	5.49E-05	2.91E-04
Benzo(b)fluoranthene	g/kgfuel	BDL	BDL	1.69E-05	0.00E+00
Benzo(k)fluoranthene	g/kgfuel	BDL	BDL	3.73E-05	6.35E-05
Benzo(a)pyrene	g/kgfuel	BDL	BDL	1.45E-05	2.39E-05
Indeno[1,2,3-cd]pyrene	g/kgfuel	BDL	BDL	1.16E-05	BDL
Dibenz[a,h]anthracene	g/kgfuel	BDL	BDL	1.93E-05	BDL
Benzo[ghi]perylene	g/kgfuel	BDL	BDL	BDL	BDL
n-Alkanes					
Dodecane	g/kgfuel	1.59E-03	2.68E-04	9.81E-05	1.23E-03
Tetradecane	g/kgfuel	2.94E-05	2.97E-05	4.52E-05	2.32E-04
Hexadecane	g/kgfuel	6.46E-06	9.87E-06	1.15E-05	5.23E-05
Octadecane	g/kgfuel	1.87E-05	1.86E-05	2.13E-05	9.21E-05
Nonadecane	g/kgfuel	5.39E-06	5.85E-06	7.45E-06	3.13E-05
Eicosane	g/kgfuel	2.87E-06	3.12E-06	4.38E-06	2.23E-05
Docosane	g/kgfuel	2.58E-06	2.49E-06	4.38E-06	1.51E-05
Tetracosane	g/kgfuel	4.34E-06	2.99E-06	3.55E-06	1.14E-05
Hexacosane	g/kgfuel	1.67E-05	4.46E-05	2.59E-05	5.53E-04
Octacosane	g/kgfuel	6.93E-06	2.20E-06	2.39E-06	3.39E-05
Triacontane	g/kgfuel	2.33E-06	1.80E-06	2.73E-06	9.02E-06

Table 21: Emission Indices for PAH and n-alkanes (C_{12}-C_{30}) – N695SW

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	g/kgfuel	2.16E-02	2.18E-01	2.25E+00	1.06E+00
1-Methylnaphthalene	g/kgfuel	9.01E-04	8.03E-04	6.58E-03	1.33E-03
2-Methylnaphthalene	g/kgfuel	8.04E-04	6.50E-04	1.59E-03	6.55E-03
Acenaphthylene	g/kgfuel	4.12E-02	1.24E-03	2.59E-03	7.68E-04
Acenaphthene	g/kgfuel	3.74E-02	8.60E-03	2.02E-02	4.51E-03
Fluorene	g/kgfuel	1.11E-03	8.07E-06	4.74E-05	3.21E-05
Phenanthrene	g/kgfuel	8.58E-04	5.56E-05	1.44E-04	9.57E-05
Anthracene	g/kgfuel	1.22E-03	9.07E-06	2.29E-04	4.73E-04
Fluoranthene	g/kgfuel	1.31E-04	7.27E-05	5.10E-06	1.23E-03
Pyrene	g/kgfuel	1.52E-04	1.73E-04	1.64E-04	7.35E-04
Benz(a)anthracene	g/kgfuel	6.17E-06	3.71E-05	3.91E-05	9.35E-05
Chrysene	g/kgfuel	7.88E-05	3.76E-05	3.96E-05	1.63E-04
Benzo(b)fluoranthene	g/kgfuel	9.85E-06	8.62E-06	BDL	BDL
Benzo(k)fluoranthene	g/kgfuel	2.05E-05	1.42E-05	9.85E-06	5.83E-05
Benzo(a)pyrene	g/kgfuel	2.26E-05	3.35E-06	5.34E-06	2.43E-05
Indeno[1,2,3-cd]pyrene	g/kgfuel	4.99E-06	BDL	BDL	1.96E-05
Dibenz[a,h]anthracene	g/kgfuel	BDL	BDL	BDL	1.65E-05
Benzo[ghi]perylene	g/kgfuel	5.24E-06	BDL	BDL	BDL
n-Alkanes					
Dodecane	g/kgfuel	1.55E-03	2.71E-04	5.71E-04	1.76E-03
Tetradecane	g/kgfuel	3.89E-05	6.07E-05	1.22E-04	2341E-04
Hexadecane	g/kgfuel	3.75E-04	1.54E-05	2.30E-05	5.43E-05
Octadecane	g/kgfuel	2.69E-04	1.34E-05	7.09E-05	1.06E-04
Nonadecane	g/kgfuel	4.64E-05	1.07E-05	1.21E-05	3.07E-05
Eicosane	g/kgfuel	5.61E-06	4.86E-06	6.08E-06	2.16E-05
Docosane	g/kgfuel	3.81E-06	4.60E-06	7.23E-06	1.89E-05
Tetracosane	g/kgfuel	3.09E-06	4.07E-06	4.32E-06	9.49E-06
Hexacosane	g/kgfuel	2.08E-05	3.55E-05	1.07E-04	3.77E-04
Octacosane	g/kgfuel	7.96E-06	4.21E-06	1.11E-05	3.94E-05
Triacontane	g/kgfuel	4.89E-06	3.80E-06	4.92E-06	1.50E-05

Table 22: Emission Indices for PAH and n-alkanes (C_{12}-C_{30}) – N429WN

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
Naphthalene	g/kgfuel	7.53E-03	1.90E+00	6.26E-01	6.85E-01
1-Methylnaphthalene	g/kgfuel	4.01E-04	3.23E-03	1.19E-03	6.56E-04
2-Methylnaphthalene	g/kgfuel	1.63E-04	6.52E-04	1.25E-03	3.54E-04
Acenaphthylene	g/kgfuel	1.56E-03	3.83E-02	3.73E-05	6.90E-04
Acenaphthene	g/kgfuel	2.38E-03	3.87E-01	2.64E-04	5.30E-03
Fluorene	g/kgfuel	6.68E-03	6.55E-05	2.78E-05	2.03E-05
Phenanthrene	g/kgfuel	7.80E-03	2.31E-04	8.68E-05	6.38E-05
Anthracene	g/kgfuel	1.07E-02	2.21E-04	1.51E-04	3.22E-04
Fluoranthene	g/kgfuel	6.34E-05	4.70E-05	2.92E-06	8.43E-04
Pyrene	g/kgfuel	7.37E-05	1.12E-04	9.38E-05	5.03E-04
Benz(a)anthracene	g/kgfuel	3.00E-06	2.40E-05	2.24E-05	6.40E-05
Chrysene	g/kgfuel	3.83E-05	2.43E-05	2.27E-05	1.12E-04
Benzo(b)fluoranthene	g/kgfuel	4.78E-06	5.57E-06	BDL	BDL
Benzo(k)fluoranthene	g/kgfuel	9.97E-06	9.15E-06	5.64E-06	3.99E-05
Benzo(a)pyrene	g/kgfuel	1.10E-05	2.16E-06	3.06E-06	1.66E-05
Indeno[1,2,3-cd]pyrene	g/kgfuel	2.42E-06	BDL	BDL	1.34E-05
Dibenz[a,h]anthracene	g/kgfuel	BDL	BDL	BDL	1.13E-05
Benzo[ghi]perylene	g/kgfuel	2.55E-06	BDL	BDL	BDL
n-Alkanes					
Dodecane	g/kgfuel	3.95E-04	1.82E-04	3.34E-04	1.20E-04
Tetradecane	g/kgfuel	3.14E-06	3.41E-05	5.27E-05	1.78E-04
Hexadecane	g/kgfuel	1.19E-04	7.40E-06	1.09E-05	3.02E-05
Octadecane	g/kgfuel	7.21E-06	3.31E-05	3.50E-05	7.65E-05
Nonadecane	g/kgfuel	1.53E-04	6.87E-06	7.79E-06	1.78E-05
Eicosane	g/kgfuel	2.35E-06	1.92E-06	4.34E-06	1.12E-05
Docosane	g/kgfuel	1.52E-06	2.07E-06	4.20E-06	7.36E-06
Tetracosane	g/kgfuel	1.84E-06	1.86E-06	2.66E-06	5.96E-06
Hexacosane	g/kgfuel	1.31E-05	1.45E-05	6.14E-05	2.64E-04
Octacosane	g/kgfuel	4.36E-06	1.59E-06	2.55E-06	1.07E-05
Triacontane	g/kgfuel	2.26E-06	1.47E-06	2.11E-06	1.21E-05

Figure 51 illustrates the emission indices for significant PAHs as a function of different modes for different aircraft tested.

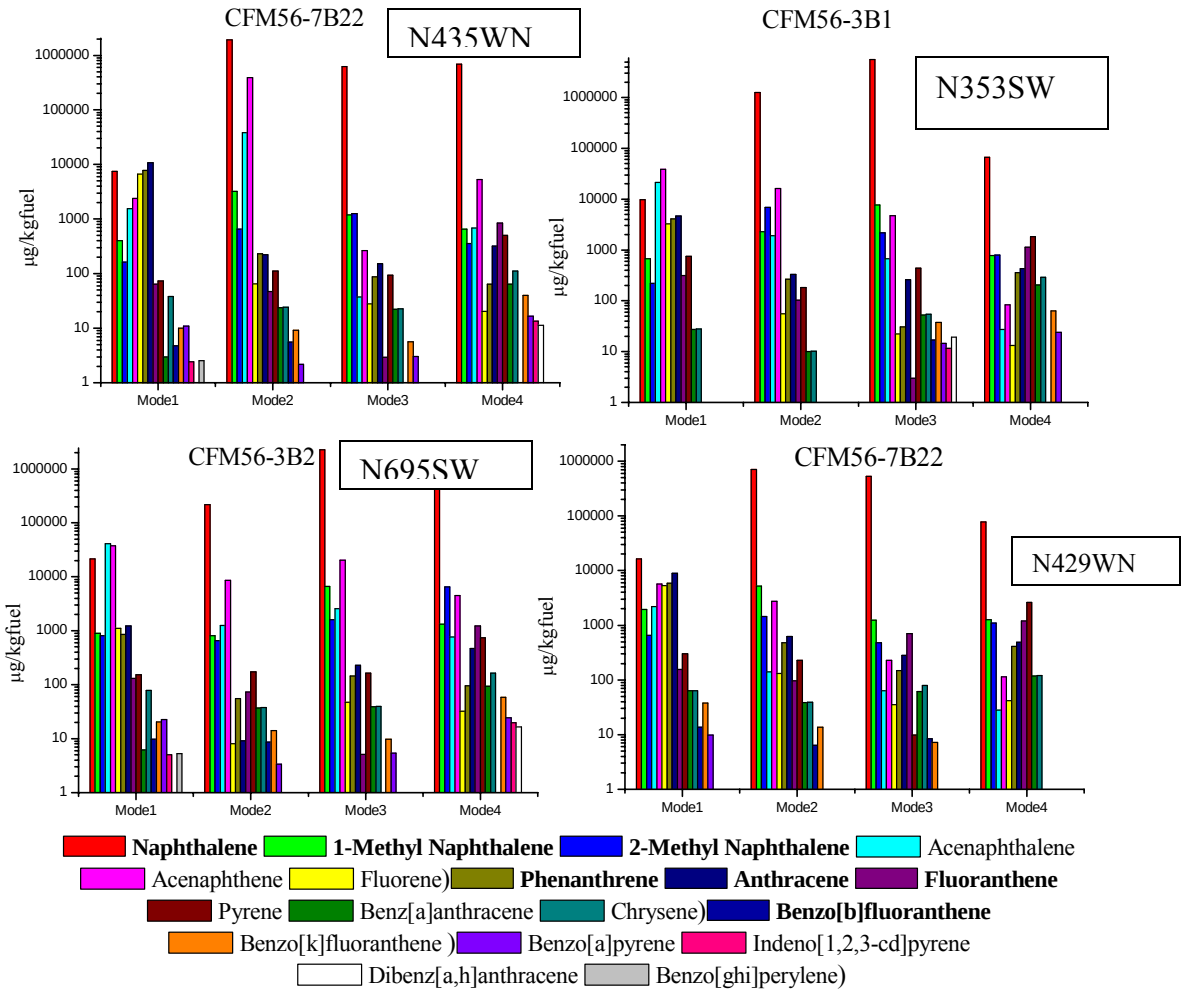


Figure 51: Emission Indices for significant Poly Aromatic Hydrocarbons as a function of different modes for different aircraft

3.3.6 Chromium Analysis

Results of the chromium analysis are shown in Table 23. The values for the ambient air at one hour showed that a measurement below the lower detection limit was possible with the sampling system and the value at eight hours was close to that normally measured for ambient air.

Table 23: Chromium (VI) analyses

Sample ID	sample	time (hrs)	Mean (ppt)	ng/filter	Conc (ng/filter)	LOD (ng/filter)
AE-13	air	1	43	0.65	ND	1.2
AE-14	air	8	81	1.22	1.2	1.2
AE-15	N435WN	4	118	1.77	1.8	1.2
AE-16	N353SW	4	47	0.71	ND	1.2
AE-17	N695SW	4	56	0.84	ND	1.2
AE-18	N429WN	4	7504	112.56	113	1.2
Total Chromium					(n/filter)	
AE 18					829.6	

Samples were obtained from the port engine of each aircraft tested over the whole test cycle and analyzed for Chromium (VI). The results of the analysis were as expected, except for the sample AE-18 (N429WN) which showed a large response for Chromium (VI). It is important to note that AE-18 was the only one of the 6 samples collected by UCR that had high Chromium (VI). In addition to the samples reported here, the EPA also took 6 ambient samples during the testing and their results did not show Chromium VI.

As a result, SCAQMD dissolved filter AE18 and analyzed it for total chromium with ICP-MS. Total chromium for AE-18 is shown in the table and the ratio of Chromium (VI) to total Chromium was about 15% as normally seen for samples collected next to a plating plant. Although AE-18 results appear an outlier, the total chromium amount on the filter by x-ray is similar to the amount measured in this test so the result can not be eliminated based on the chromium test alone. More corroborative results will be needed such as the Cr/Ni ratio or the like.

3.3.7 Dioxin Analysis

One sample was taken from the port engine over the entire test cycle of each aircraft and analyzed for dioxin at either the Alta or Frontier laboratories. Results for all four samples, one from each aircraft, showed the dioxin and congeners levels were below the detection limits of both laboratories. Both laboratories showed excellent recovery of the spiked congeners and no dioxin or additional congeners were found. A question might be asked whether dioxin was lost to the heated sample lines as we did not rinse those out before the analysis. However, given the combustor conditions and lack of chlorine, we did not expect to find measurable levels of dioxin. Further studies might examine losses in the sampling system; however, measurements from this study indicate that the recovered dioxin levels are likely to be less than the values listed in Table 24 below.

Table 24: Detection Limits for Dioxin

Analyte	Alta Lab DL*	Frontier Lab DL*
2,3,7,8-TCDD	2.34	2.35
1,2,3,7,8-PeCDD	3.18	3.85
1,2,3,4,7,8-HxCDD	5.04	4.45
1,2,3,6,7,8-HxCDD	4.44	3.92
1,2,3,7,8,9-HxCDD	4.76	4.2
1,2,3,4,6,7,8-HpCDD	3.13	2.69
OCDD	7.3	15.7
2,3,7,8-TCDF	2.34	2.36
1,2,3,7,8-PeCDF	3.49	3.85
2,3,4,7,8-PeCDF	3.28	3.62
1,2,3,4,7,8-HxCDF	1.15	1.07
1,2,3,6,7,8-HxCDF	0.9578	0.89
2,3,4,6,7,8-HxCDF	1.07	0.992
1,2,3,7,8,9-HxCDF	1.35	1.25
1,2,3,4,6,7,8-HpCDF	2.09	1.84
1,2,3,4,7,8,9-HpCDF	2.71	2.38
OCDF	5.84	9.83

*Detection Limit for Alta and Frontier labs in picograms per sample

3.3.8 Metals

Metals were collected on the Teflon filter and analyzed by XRF. The distributions of metals are provided in Figure 52.

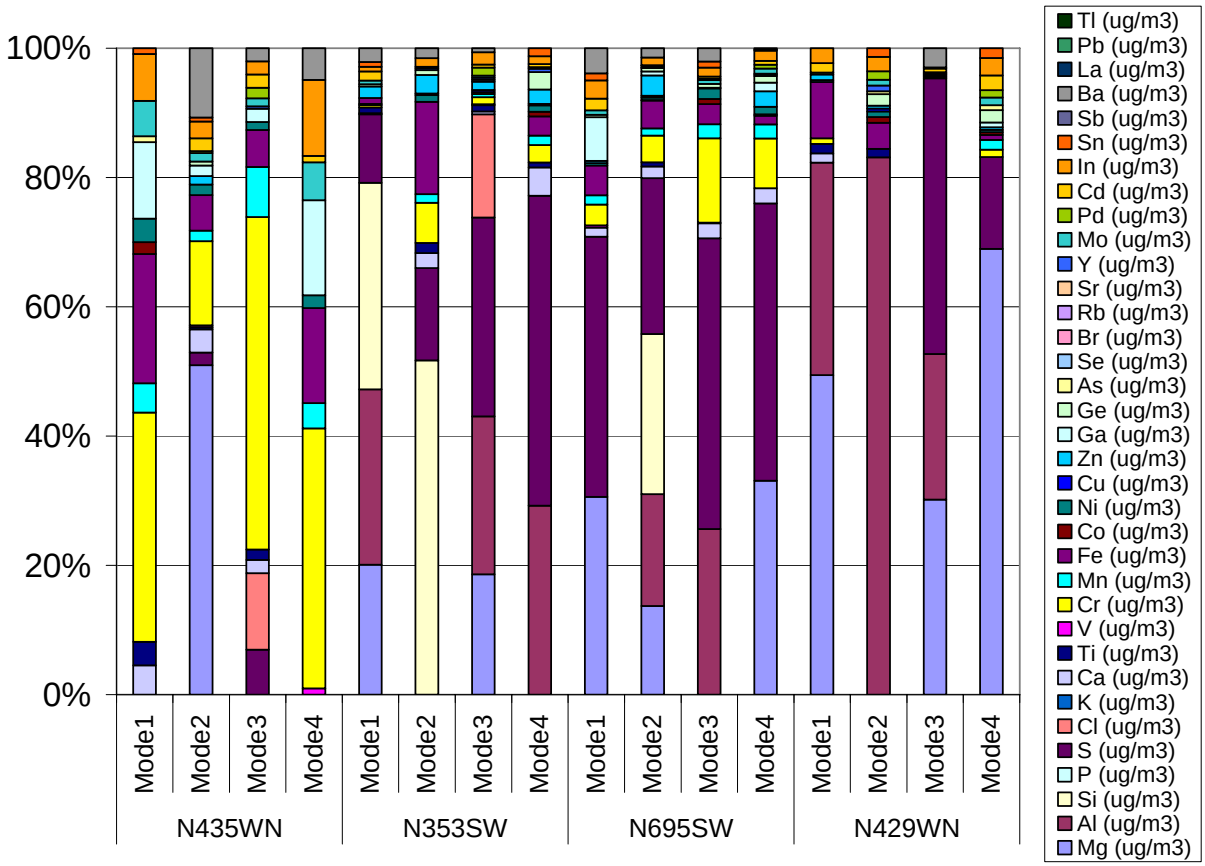


Figure 52: Distribution of Metals

It should be noted that the starboard engine on N435WN had a significantly higher total Cr levels than other engines, including the N429WN engine. The latter port engine was the filter with significant Cr+6 so it adds further question to the Cr+6 finding. In general, the variability in the metal distribution was greater between engines than between engine loads. Mass concentrations and EIs for the metals are summarized in Tables 25-28 and 29-32, respectively.

Table 25: Metal mass concentrations – N435WN

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
Mg	(ug/m3)	BDL	1.50	BDL	BDL
Al	(ug/m3)	BDL	BDL	BDL	BDL
Si	(ug/m3)	BDL	BDL	BDL	BDL
P	(ug/m3)	BDL	BDL	BDL	BDL
S	(ug/m3)	BDL	0.057	0.288	BDL
Cl	(ug/m3)	BDL	BDL	0.490	BDL
K	(ug/m3)	BDL	BDL	BDL	BDL
Ca	(ug/m3)	0.051	0.105	0.085	BDL
Ti	(ug/m3)	0.041	0.010	0.068	BDL
V	(ug/m3)	BDL	0.010	BDL	0.082
Cr	(ug/m3)	0.398	0.381	2.13	3.35
Mn	(ug/m3)	0.051	0.048	0.321	0.327
Fe	(ug/m3)	0.224	0.162	0.237	1.23
Co	(ug/m3)	0.020	BDL	BDL	BDL
Ni	(ug/m3)	0.041	0.048	0.051	0.163
Cu	(ug/m3)	BDL	BDL	BDL	BDL
Zn	(ug/m3)	BDL	0.038	BDL	BDL
Ga	(ug/m3)	0.133	0.048	0.085	1.23
Ge	(ug/m3)	BDL	0.019	BDL	BDL
As	(ug/m3)	0.010	BDL	BDL	BDL
Se	(ug/m3)	BDL	BDL	BDL	BDL
Br	(ug/m3)	BDL	BDL	BDL	BDL
Rb	(ug/m3)	BDL	BDL	BDL	BDL
Sr	(ug/m3)	BDL	BDL	BDL	BDL
Y	(ug/m3)	BDL	BDL	0.017	BDL
Mo	(ug/m3)	0.061	0.038	0.051	0.490
Pd	(ug/m3)	BDL	0.010	0.068	BDL
Cd	(ug/m3)	BDL	0.057	0.085	0.082
In	(ug/m3)	0.082	0.076	0.085	0.981
Sn	(ug/m3)	0.010	0.019	BDL	BDL
Sb	(ug/m3)	BDL	BDL	BDL	BDL
Ba	(ug/m3)	BDL	0.314	0.085	0.409
La	(ug/m3)	BDL	BDL	BDL	BDL
Pb	(ug/m3)	BDL	BDL	BDL	BDL
Tl	(ug/m3)	BDL	BDL	BDL	BDL

Table 26: Metal mass concentrations – N353SW

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
Mg	(ug/m3)	0.760	BDL	1.99	BDL
Al	(ug/m3)	1.03	BDL	2.608	8.92
Si	(ug/m3)	1.21	1.50	BDL	BDL
P	(ug/m3)	BDL	BDL	BDL	BDL
S	(ug/m3)	0.401	0.415	3.28	14.6
Cl	(ug/m3)	BDL	BDL	1.70	BDL
K	(ug/m3)	BDL	BDL	BDL	BDL
Ca	(ug/m3)	0.006789	0.068	0.050	1.35
Ti	(ug/m3)	0.034	0.045	0.101	0.225
V	(ug/m3)	BDL	BDL	0.017	BDL
Cr	(ug/m3)	0.014	0.181	0.118	0.824
Mn	(ug/m3)	0.006789	0.038	0.050	0.450
Fe	(ug/m3)	0.034	0.415	BDL	0.899
Co	(ug/m3)	BDL	BDL	0.034	0.225
Ni	(ug/m3)	BDL	0.030	BDL	0.300
Cu	(ug/m3)	BDL	0.008	0.034	0.075
Zn	(ug/m3)	0.068	0.083	0.135	0.674
Ga	(ug/m3)	BDL	BDL	0.034	BDL
Ge	(ug/m3)	0.014	0.023	BDL	0.824
As	(ug/m3)	BDL	BDL	BDL	BDL
Se	(ug/m3)	BDL	BDL	BDL	BDL
Br	(ug/m3)	BDL	BDL	BDL	BDL
Rb	(ug/m3)	BDL	BDL	BDL	BDL
Sr	(ug/m3)	BDL	BDL	BDL	BDL
Y	(ug/m3)	BDL	0.008	0.034	0.150
Mo	(ug/m3)	0.020	0.008	0.034	0.075
Pd	(ug/m3)	BDL	BDL	0.135	BDL
Cd	(ug/m3)	0.054	BDL	0.050	0.150
In	(ug/m3)	0.027	0.038	0.202	0.375
Sn	(ug/m3)	0.027	BDL	BDL	0.375
Sb	(ug/m3)	BDL	BDL	BDL	BDL
Ba	(ug/m3)	0.081	0.045	0.067	BDL
La	(ug/m3)	BDL	BDL	BDL	BDL
Pb	(ug/m3)	BDL	BDL	BDL	BDL
Tl	(ug/m3)	BDL	BDL	BDL	BDL

Table 27: Metal mass concentrations – N695SW

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
Mg	(ug/m3)	0.571	1.17	BDL	11.3
Al	(ug/m3)	BDL	1.48	3.38	BDL
Si	(ug/m3)	BDL	2.12	BDL	BDL
P	(ug/m3)	BDL	BDL	BDL	BDL
S	(ug/m3)	0.750	2.07	5.94	14.7
Cl	(ug/m3)	BDL	BDL	BDL	BDL
K	(ug/m3)	BDL	BDL	BDL	BDL
Ca	(ug/m3)	0.027	0.154	0.305	0.809
Ti	(ug/m3)	BDL	0.054	BDL	BDL
V	(ug/m3)	0.007	BDL	0.015	BDL
Cr	(ug/m3)	0.060	0.355	1.72	2.63
Mn	(ug/m3)	0.027	0.093	0.289	0.742
Fe	(ug/m3)	0.086	0.371	0.411	0.472
Co	(ug/m3)	BDL	0.008	0.107	0.067
Ni	(ug/m3)	0.007	0.031	0.213	0.405
Cu	(ug/m3)	BDL	0.023	BDL	BDL
Zn	(ug/m3)	0.007	0.270	0.015	0.809
Ga	(ug/m3)	0.126	0.054	BDL	0.472
Ge	(ug/m3)	0.007	0.046	0.076	0.337
As	(ug/m3)	BDL	BDL	BDL	0.067
Se	(ug/m3)	BDL	BDL	BDL	BDL
Br	(ug/m3)	BDL	BDL	BDL	BDL
Rb	(ug/m3)	BDL	0.008	BDL	BDL
Sr	(ug/m3)	BDL	BDL	BDL	BDL
Y	(ug/m3)	BDL	BDL	BDL	0.067
Mo	(ug/m3)	0.013	0.023	0.076	0.270
Pd	(ug/m3)	BDL	0.008	0.030	0.202
Cd	(ug/m3)	0.033	BDL	0.046	0.202
In	(ug/m3)	0.053	0.100	0.183	0.539
Sn	(ug/m3)	0.020	BDL	0.122	0.067
Sb	(ug/m3)	BDL	BDL	BDL	BDL
Ba	(ug/m3)	0.073	0.124	0.274	0.067
La	(ug/m3)	BDL	BDL	BDL	BDL
Pb	(ug/m3)	BDL	BDL	BDL	BDL
Tl	(ug/m3)	BDL	BDL	BDL	BDL

Table 28: Metal mass concentrations – N429WN

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
Mg	(ug/m3)	1.13	BDL	2.49	11.9
Al	(ug/m3)	0.751	1.42	1.86	BDL
Si	(ug/m3)	BDL	BDL	BDL	BDL
P	(ug/m3)	BDL	BDL	BDL	BDL
S	(ug/m3)	BDL	BDL	3.51	2.44
Cl	(ug/m3)	BDL	BDL	BDL	BDL
K	(ug/m3)	BDL	BDL	BDL	BDL
Ca	(ug/m3)	0.033	BDL	BDL	BDL
Ti	(ug/m3)	0.033	0.023	BDL	BDL
V	(ug/m3)	BDL	BDL	BDL	BDL
Cr	(ug/m3)	0.020	BDL	BDL	0.198
Mn	(ug/m3)	BDL	BDL	BDL	0.264
Fe	(ug/m3)	0.199	0.068	BDL	0.132
Co	(ug/m3)	BDL	0.015	0.015	0.066
Ni	(ug/m3)	0.007	0.015	BDL	0.066
Cu	(ug/m3)	BDL	0.008	BDL	BDL
Zn	(ug/m3)	0.020	0.008	0.015	0.066
Ga	(ug/m3)	BDL	BDL	BDL	0.132
Ge	(ug/m3)	BDL	0.030	BDL	0.330
As	(ug/m3)	BDL	0.008	0.015	0.132
Se	(ug/m3)	BDL	BDL	BDL	BDL
Br	(ug/m3)	BDL	BDL	BDL	BDL
Rb	(ug/m3)	BDL	BDL	BDL	BDL
Sr	(ug/m3)	BDL	BDL	BDL	BDL
Y	(ug/m3)	BDL	0.015	0.015	BDL
Mo	(ug/m3)	BDL	0.015	0.015	0.198
Pd	(ug/m3)	0.007	0.023	BDL	0.198
Cd	(ug/m3)	0.033	BDL	0.046	0.396
In	(ug/m3)	0.053	0.038	0.015	0.462
Sn	(ug/m3)	BDL	0.023	BDL	0.264
Sb	(ug/m3)	BDL	BDL	BDL	BDL
Ba	(ug/m3)	BDL	BDL	0.245	BDL
La	(ug/m3)	BDL	BDL	BDL	BDL
Pb	(ug/m3)	BDL	BDL	BDL	BDL
Tl	(ug/m3)	BDL	BDL	BDL	BDL

Table 29: Metal Emission Indices – N435WN

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
Mg	g/kgfuel	BDL	1.42E-04	BDL	BDL
Al	g/kgfuel	BDL	BDL	BDL	BDL
Si	g/kgfuel	BDL	BDL	BDL	BDL
P	g/kgfuel	BDL	BDL	BDL	BDL
S	g/kgfuel	BDL	5.43E-06	2.10E-05	BDL
Cl	g/kgfuel	BDL	BDL	3.58E-05	BDL
K	g/kgfuel	BDL	BDL	BDL	BDL
Ca	g/kgfuel	6.69E-06	9.96E-06	6.18E-06	BDL
Ti	g/kgfuel	5.35E-06	9.05E-07	4.94E-06	BDL
V	g/kgfuel	BDL	9.05E-07	BDL	5.09E-06
Cr	g/kgfuel	5.22E-05	3.62E-05	1.56E-04	2.09E-04
Mn	g/kgfuel	6.69E-06	4.53E-06	2.35E-05	2.04E-05
Fe	g/kgfuel	2.94E-05	1.54E-05	1.73E-05	7.64E-05
Co	g/kgfuel	2.68E-06	BDL	BDL	BDL
Ni	g/kgfuel	5.35E-06	4.53E-06	3.71E-06	1.02E-05
Cu	g/kgfuel	BDL	BDL	BDL	BDL
Zn	g/kgfuel	BDL	3.62E-06	BDL	BDL
Ga	g/kgfuel	1.74E-05	4.53E-06	6.18E-06	7.64E-05
Ge	g/kgfuel	BDL	1.81E-06	BDL	BDL
As	g/kgfuel	1.34E-06	BDL	BDL	BDL
Se	g/kgfuel	BDL	BDL	BDL	BDL
Br	g/kgfuel	BDL	BDL	BDL	BDL
Rb	g/kgfuel	BDL	BDL	BDL	BDL
Sr	g/kgfuel	BDL	BDL	BDL	BDL
Y	g/kgfuel	BDL	BDL	1.24E-06	BDL
Mo	g/kgfuel	8.03E-06	3.62E-06	3.71E-06	3.05E-05
Pd	g/kgfuel	BDL	9.05E-07	4.94E-06	BDL
Cd	g/kgfuel	BDL	5.43E-06	6.18E-06	5.09E-06
In	g/kgfuel	1.07E-05	7.24E-06	6.18E-06	6.11E-05
Sn	g/kgfuel	1.34E-06	1.81E-06	BDL	BDL
Sb	g/kgfuel	BDL	BDL	BDL	BDL
Ba	g/kgfuel	BDL	2.99E-05	6.18E-06	2.55E-05
La	g/kgfuel	BDL	BDL	BDL	BDL
Pb	g/kgfuel	BDL	BDL	BDL	BDL
Tl	g/kgfuel	BDL	BDL	BDL	BDL

Table 30: Metal Emission Indices – N353SW

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
Mg	g/kgfuel	4.69E-05	BDL	8.97E-05	BDL
Al	g/kgfuel	6.32E-05	BDL	1.18E-04	3.40E-04
Si	g/kgfuel	7.45E-05	8.30E-05	BDL	BDL
P	g/kgfuel	BDL	BDL	BDL	BDL
S	g/kgfuel	2.47E-05	2.29E-05	1.48E-04	5.58E-04
Cl	g/kgfuel	BDL	BDL	7.68E-05	BDL
K	g/kgfuel	BDL	BDL	BDL	BDL
Ca	g/kgfuel	4.19E-07	3.75E-06	2.28E-06	5.15E-05
Ti	g/kgfuel	2.09E-06	2.50E-06	4.56E-06	8.58E-06
V	g/kgfuel	BDL	BDL	7.61E-07	BDL
Cr	g/kgfuel	8.37E-07	1.00E-05	5.32E-06	3.14E-05
Mn	g/kgfuel	4.19E-07	2.09E-06	2.28E-06	1.72E-05
Fe	g/kgfuel	2.09E-06	2.29E-05	BDL	3.43E-05
Co	g/kgfuel	BDL	BDL	1.52E-06	8.58E-06
Ni	g/kgfuel	BDL	1.67E-06	BDL	1.14E-05
Cu	g/kgfuel	BDL	4.17E-07	1.52E-06	2.86E-06
Zn	g/kgfuel	4.19E-06	4.59E-06	6.08E-06	2.57E-05
Ga	g/kgfuel	BDL	0.00E+00	1.52E-06	0.00E+00
Ge	g/kgfuel	8.37E-07	1.25E-06	0.00E+00	3.14E-05
As	g/kgfuel	BDL	BDL	BDL	BDL
Se	g/kgfuel	BDL	BDL	BDL	BDL
Br	g/kgfuel	BDL	BDL	BDL	BDL
Rb	g/kgfuel	BDL	BDL	BDL	BDL
Sr	g/kgfuel	BDL	BDL	BDL	BDL
Y	g/kgfuel	BDL	4.17E-07	1.52E-06	5.72E-06
Mo	g/kgfuel	1.26E-06	4.17E-07	1.52E-06	2.86E-06
Pd	g/kgfuel	BDL	BDL	6.08E-06	BDL
Cd	g/kgfuel	3.35E-06	BDL	2.28E-06	5.72E-06
In	g/kgfuel	1.67E-06	2.09E-06	9.13E-06	1.43E-05
Sn	g/kgfuel	1.67E-06	BDL	BDL	1.43E-05
Sb	g/kgfuel	BDL	BDL	BDL	BDL
Ba	g/kgfuel	5.02E-06	2.50E-06	3.04E-06	BDL
La	g/kgfuel	BDL	BDL	BDL	BDL
Pb	g/kgfuel	BDL	BDL	BDL	BDL
Tl	g/kgfuel	BDL	BDL	BDL	BDL

Table 31: Metal Emission Indices – N695SW

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
Mg	g/kgfuel	5.56E-05	1.07E-04	BDL	6.18E-04
Al	g/kgfuel	BDL	1.35E-04	2.79E-04	BDL
Si	g/kgfuel	BDL	1.94E-04	BDL	BDL
P	g/kgfuel	BDL	BDL	BDL	BDL
S	g/kgfuel	7.30E-05	1.89E-04	4.89E-04	8.01E-04
Cl	g/kgfuel	BDL	BDL	BDL	BDL
K	g/kgfuel	BDL	BDL	BDL	BDL
Ca	g/kgfuel	2.58E-06	1.41E-05	2.51E-05	4.41E-05
Ti	g/kgfuel	BDL	4.94E-06	BDL	BDL
V	g/kgfuel	6.46E-07	BDL	1.25E-06	BDL
Cr	g/kgfuel	5.81E-06	3.24E-05	1.42E-04	1.43E-04
Mn	g/kgfuel	2.58E-06	8.46E-06	2.38E-05	4.04E-05
Fe	g/kgfuel	8.40E-06	3.39E-05	3.39E-05	2.57E-05
Co	g/kgfuel	BDL	7.05E-07	8.78E-06	3.68E-06
Ni	g/kgfuel	6.46E-07	2.82E-06	1.76E-05	2.21E-05
Cu	g/kgfuel	BDL	2.12E-06	BDL	BDL
Zn	g/kgfuel	6.46E-07	2.47E-05	1.25E-06	4.41E-05
Ga	g/kgfuel	1.23E-05	4.94E-06	0.00E+00	2.57E-05
Ge	g/kgfuel	6.46E-07	4.23E-06	6.27E-06	1.84E-05
As	g/kgfuel	BDL	BDL	BDL	3.68E-06
Se	g/kgfuel	BDL	BDL	BDL	BDL
Br	g/kgfuel	BDL	BDL	BDL	BDL
Rb	g/kgfuel	BDL	7.05E-07	BDL	BDL
Sr	g/kgfuel	BDL	BDL	BDL	BDL
Y	g/kgfuel	BDL	BDL	BDL	3.68E-06
Mo	g/kgfuel	1.29E-06	2.12E-06	6.27E-06	1.47E-05
Pd	g/kgfuel	BDL	7.05E-07	2.51E-06	1.10E-05
Cd	g/kgfuel	3.23E-06	BDL	3.76E-06	1.10E-05
In	g/kgfuel	5.17E-06	9.17E-06	1.51E-05	2.94E-05
Sn	g/kgfuel	1.94E-06	BDL	1.00E-05	3.68E-06
Sb	g/kgfuel	BDL	BDL	BDL	BDL
Ba	g/kgfuel	7.11E-06	1.13E-05	2.26E-05	3.68E-06
La	g/kgfuel	BDL	BDL	BDL	BDL
Pb	g/kgfuel	BDL	BDL	BDL	BDL
Tl	g/kgfuel	BDL	BDL	BDL	BDL

Table 32: Metal Emission Indices – N429WN

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
Mg	g/kgfuel	5.20E-05	BDL	1.11E-04	4.38E-04
Al	g/kgfuel	3.45E-05	8.05E-05	8.26E-05	BDL
Si	g/kgfuel	BDL	BDL	BDL	BDL
P	g/kgfuel	BDL	BDL	BDL	BDL
S	g/kgfuel	BDL	BDL	1.56E-04	9.01E-05
Cl	g/kgfuel	BDL	BDL	BDL	BDL
K	g/kgfuel	BDL	BDL	BDL	BDL
Ca	g/kgfuel	1.53E-06	BDL	BDL	BDL
Ti	g/kgfuel	1.53E-06	1.29E-06	BDL	BDL
V	g/kgfuel	BDL	BDL	BDL	BDL
Cr	g/kgfuel	9.17E-07	BDL	BDL	7.30E-06
Mn	g/kgfuel	BDL	BDL	BDL	9.74E-06
Fe	g/kgfuel	9.17E-06	3.87E-06	BDL	4.87E-06
Co	g/kgfuel	BDL	8.61E-07	6.83E-07	2.43E-06
Ni	g/kgfuel	3.06E-07	8.61E-07	BDL	2.43E-06
Cu	g/kgfuel	BDL	4.31E-07	BDL	BDL
Zn	g/kgfuel	9.17E-07	4.31E-07	6.83E-07	2.43E-06
Ga	g/kgfuel	BDL	BDL	BDL	4.87E-06
Ge	g/kgfuel	BDL	1.72E-06	BDL	1.22E-05
As	g/kgfuel	BDL	4.31E-07	6.83E-07	4.87E-06
Se	g/kgfuel	BDL	BDL	BDL	BDL
Br	g/kgfuel	BDL	BDL	BDL	BDL
Rb	g/kgfuel	BDL	BDL	BDL	BDL
Sr	g/kgfuel	BDL	BDL	BDL	BDL
Y	g/kgfuel	BDL	8.61E-07	6.83E-07	BDL
Mo	g/kgfuel	BDL	8.61E-07	6.83E-07	7.30E-06
Pd	g/kgfuel	3.06E-07	1.29E-06	BDL	7.30E-06
Cd	g/kgfuel	1.53E-06	BDL	2.05E-06	1.46E-05
In	g/kgfuel	2.44E-06	2.15E-06	6.83E-07	1.70E-05
Sn	g/kgfuel	BDL	1.29E-06	BDL	9.74E-06
Sb	g/kgfuel	BDL	BDL	BDL	BDL
Ba	g/kgfuel	BDL	BDL	1.09E-05	BDL
La	g/kgfuel	BDL	BDL	BDL	BDL
Pb	g/kgfuel	BDL	BDL	BDL	BDL
Tl	g/kgfuel	BDL	BDL	BDL	BDL

The metals were determined by the South Coast AQMD who provided the following detection limits for their analysis.

Table 33: Limits of Detection for Metals by X-ray Fluorescence

Element (µg/filter)			
Mg	1.200	**Ga**	0.425
Al	1.000	**Ge**	0.017
Si	1.200	**As**	0.003
P	0.204	**Se**	0.017
S	0.204	**Rb**	0.007
Cl	0.068	**Sr**	0.017
K	0.017	**Y**	0.003
Ca	0.017	**Mo**	0.017
Ti	0.051	**Pd**	0.026
V	0.020	**Cd**	0.017
Cr	0.017	**In**	0.017
Mn	0.009	**Sn**	0.026
Fe	0.007	**Sb**	0.024
Co	0.007	**Ba**	0.170
Ni	0.003	**La**	0.425
Cu	0.003	**Pb**	0.051
Zn	0.003	**Tl**	0.850

The lower detection limit for sulfur in terms of EI units (g/kg) is given in the Table 34.

Table 34: Lower Detection Limit for Sulfur

Aircraft	LDL Units	Mode1	Mode2	Mode3	Mode4
N435WN	(g/kg fuel)	2.27E-05	1.54E-05	2.10E-05	8.66E-05
N353SW	(g/kg fuel)	7.12E-06	7.09E-06	1.29E-05	4.86E-05
N695SW	(g/kg fuel)	1.10E-05	1.20E-05	2.13E-05	6.25E-05
N429WN	(g/kg fuel)	5.20E-06	7.32E-06	1.16E-05	4.14E-05

3.3.9 Ions

The Teflo filter samples from the starboard engine were analyzed for elements by x-ray and ions by ion chromatography. Using the x-ray values, we calculated that the water used for extraction needed to a minimum to obtain measurable values. It is noted that only sulfate ions were above the detection limits of the instrument and the extracted ions (<1 ppm in water) were very close to the lower detection limit of the instrument. Tables 35 and 36 summarize the sulfate (as Sulfur) mass concentrations and EIs measured, respectively.

Table 35: Sulfate mass concentration (µg/m^3)

Aircraft	Units	Mode1	Mode2	Mode3	Mode4
N435WN	µg/m^3	3.104133	2.399801	3.869629	15.44179
N353SW	µg/m^3	1.140132	1.506883	5.723966	28.61581
N695SW	µg/m^3	1.544406	2.640123	5.346368	22.32409
N429WN	µg/m^3	1.3945	1.216621	2.25667	42.22484

Table 36: Sulfate (as Sulfur) Emission Indices

Aircraft	Units	Mode 1	Mode 2	Mode 3	Mode 4
N435WN	EI(g/kg)	0.000346	0.000181	0.000398	0.006552
N353SW	EI(g/kg)	3.98E-05	5.24E-05	0.000363	0.006818
N695SW	EI(g/kg)	8.31E-05	0.000155	0.000559	0.006839
N429WN	EI(g/kg)	3.55E-05	4.36E-05	0.000128	0.008566

3.3.10 Mass Concentration Data

3.3.10.1 Gas-phase Carbonyls

Based on APEX1, the formaldehyde concentration would be within a range of 5 to 15% of the total hydrocarbon concentrations at the lowest engine power conditions. Formaldehyde emissions were as expected and EI values were calculated using the CO_2 values from adjacent probes. The relative carbonyl EI values are shown in Figure 53.

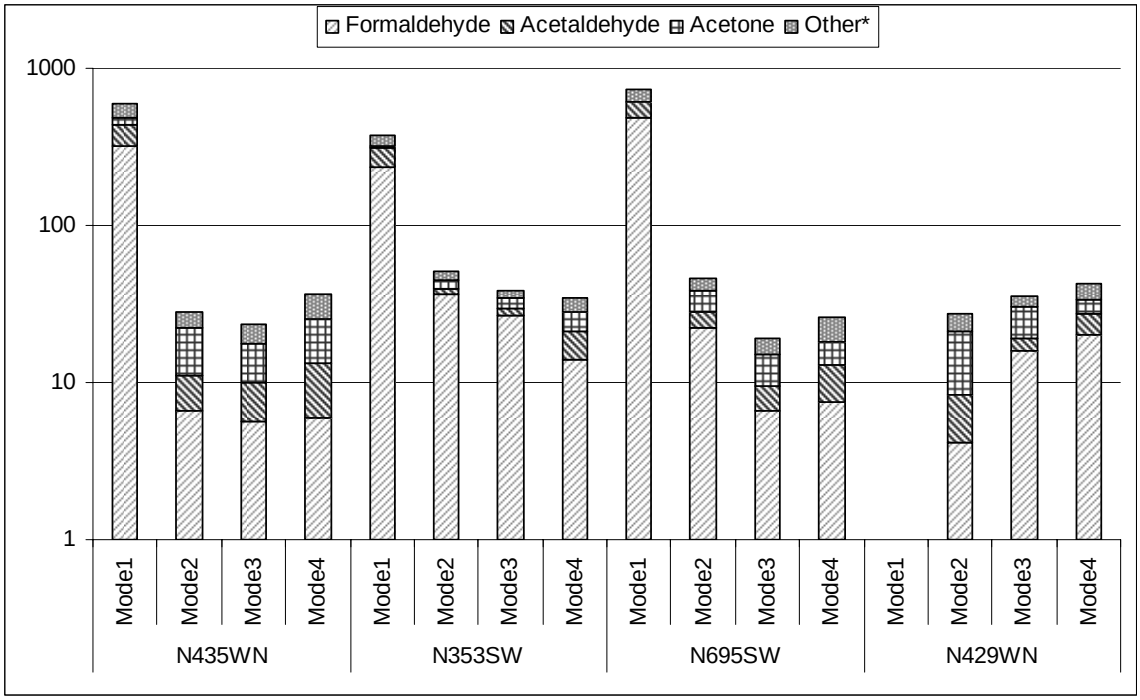


Figure 53: Relative Carbonyl Emission Indices (mg/kg-fuel)

other refers to the sum of the EI's of Propionaldehyde, Crotonaldehyde, MethylAcrolein, Methyl Ethyl Ketone, Butyraldehyde, Benzaldehyde, Valeraldehyde, Tolualdehyde and Hexanaldehyde*

The major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone. The analytical chromatogram showed an unknown compound co-eluding with acrolein, which bottled up the quantification of acrolein for the present study. The compound disappeared on refrigeration for extended periods of time. Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions.

Table 37 summarizes the mass concentration of carbonyls measured at the DNPH. The values are not corrected for ambient dilution.

Table 37: Mass concentration of carbonyl species measured in sampler

			Mode 1	Mode 2	Mode 3	Mode 4
N435WN	Formaldehyde	(ug/m3)	603	18.1	21.5	30.7
	Acetaldehyde	(ug/m3)	207	12.4	16.8	38.2
	Acetone	(ug/m3)	89.5	30.5	28.8	62.8
	Acrolein	(ug/m3)	N/A	N/A	N/A	N/A
	Propionaldehyde	(ug/m3)	55.6	BDL	BDL	BDL
	Crotonaldehyde	(ug/m3)	27.6	1.42	2.94	9.52
	Methylacrolein	(ug/m3)	12.7	6.27	6.21	14.2
	Methyl Ethyl Ketone	(ug/m3)	10.4	0.369	BDL	0.446
	Butyraldehyde	(ug/m3)	31.4	2.34	2.96	2.47
	Benzaldehyde	(ug/m3)	31.0	1.15	3.80	10.4
	Valeraldehyde	(ug/m3)	6.87	0.895	2.09	4.73
	Tolualdehyde	(ug/m3)	14.0	0.376	BDL	4.32
	Hexanaldehyde	(ug/m3)	24.2	3.39	4.17	12.4
N353SW	Formaldehyde	(ug/m3)	798	144	156	128
	Acetaldehyde	(ug/m3)	276	10.7	16.8	65.9
	Acetone	(ug/m3)	24.7	23.1	29.9	59.8
	Acrolein	(ug/m3)	N/A	N/A	N/A	N/A
	Propionaldehyde	(ug/m3)	5.53	1.74	BDL	BDL
	Crotonaldehyde	(ug/m3)	36.0	1.41	3.01	8.78
	Methylacrolein	(ug/m3)	0.947	3.88	5.44	16.7
	Methyl Ethyl Ketone	(ug/m3)	0.683	BDL	BDL	BDL
	Butyraldehyde	(ug/m3)	18.6	1.63	2.96	5.20
	Benzaldehyde	(ug/m3)	84.2	3.82	1.41	11.8
	Valeraldehyde	(ug/m3)	11.3	1.58	2.26	5.49
	Tolualdehyde	(ug/m3)	11.7	1.73	BDL	BDL
	Hexanaldehyde	(ug/m3)	14.6	7.39	7.00	13.4
N695SW	Formaldehyde	(ug/m3)	1171	60.6	28.3	50.3
	Acetaldehyde	(ug/m3)	312	16.9	12.0	36.7
	Acetone	(ug/m3)	16.2	27.5	24.9	35.6
	Acrolein	(ug/m3)	N/A	N/A	N/A	N/A
	Propionaldehyde	(ug/m3)	65.5	1.89	BDL	BDL
	Crotonaldehyde	(ug/m3)	42.0	0.985	1.74	7.53
	Methylacrolein	(ug/m3)	1.40	3.95	3.12	11.0
	Methyl Ethyl Ketone	(ug/m3)	15.3	0.202	BDL	BDL
	Butyraldehyde	(ug/m3)	26.9	1.12	1.26	6.97
	Benzaldehyde	(ug/m3)	49.3	0.459	2.48	12.1
	Valeraldehyde	(ug/m3)	14.0	0.787	0.975	3.32
	Tolualdehyde	(ug/m3)	24.4	0.942	0.697	BDL
	Hexanaldehyde	(ug/m3)	29.0	10.8	5.94	10.8
N429WN	Formaldehyde	(ug/m3)	16.8	17.6	99.7	185
	Acetaldehyde	(ug/m3)	17.5	17.0	20.4	65.4
	Acetone	(ug/m3)	56.5	53.4	71.7	59.4
	Acrolein	(ug/m3)	N/A	N/A	N/A	N/A
	Propionaldehyde	(ug/m3)	2.42	2.24	6.11	30.9
	Crotonaldehyde	(ug/m3)	1.54	1.11	2.84	8.93
	Methylacrolein	(ug/m3)	12.4	10.3	9.89	11.6
	Methyl Ethyl Ketone	(ug/m3)	1.42	0.991	0.186	BDL
	Butyraldehyde	(ug/m3)	3.49	1.68	2.27	3.88
	Benzaldehyde	(ug/m3)	3.11	2.98	3.00	11.1
	Valeraldehyde	(ug/m3)	1.19	1.13	2.76	7.40
	Tolualdehyde	(ug/m3)	3.58	2.35	2.47	BDL
	Hexanaldehyde	(ug/m3)	3.23	3.31	5.42	10.1

3.3.10.2 Light Hydrocarbons from Thermal Desorption Tubes

C_4-C_{12} hydrocarbon values were explored based on the concentrations measured from the Thermal Desorption Tubes (TDS) but the values were much lower than expected from APEX1 and other research. Tables 38-41, 42-45, and 46-49, summarize the mass concentration of alkenes, alkanes and aromatics, respectively, in the C_4-C_{12} range measured from the thermal desorption tubes. The mass concentrations in these tables were not corrected for ambient dilution since we could not determine the dilution ratio. Based on the measured concentrations being near typical ambient values, there is no appropriate method to scale these values to develop suitable emission factors.

C_4-C_{12} hydrocarbon mass concentrations were measured using TDS (Tables 38 – 49) which were located on the low flow side of the sampling system. The data presented are not reliable as the mass concentrations do not significantly exceed ambient levels. In the absence of a leak these concentrations would be expected to be higher and may have significantly exceeded ambient levels thereby enhancing their reliability.

3.3.10.3 C_1-C_8 SUMMA Canister Analyses

SUMMA canisters were collected at the light hydrocarbon manifold to provide the sole measurement of the C_1-C_4 analyses, redundancy for measuring the C_4-C_8 analyses including 1, 3-Butadiene and BTEX, and provide CO_2 concentrations to provide a confirming measurement of the values used in the dilution calculation. As with other samples, four samples were extracted for each aircraft test for a total of sixteen canister samples. These samples were forwarded to the outside laboratory for analysis of CO_2 and light hydrocarbon species. The plan was to determine the concentration of CO_2 in a first test and hydrocarbon species in a second test. The external laboratory measured CO_2 concentrations in eleven of the sixteen canisters at about the same value as used in the dilution calculations, and CO_2 less than detection limit for the remaining five analyses. For example, the CO_2 levels were below detection for the samples collected at the idle modes and for Mode 2 for N435WN and N353SW. For the second test of the hydrocarbons species in the SUMMA canisters, the laboratory reported that all hydrocarbon species were below detection limits. It is unclear as to what happened on the second test of the SUMMA canisters.

Table 38: Alkene mass concentrations – N435WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
2-methylpropene	(ug/m3)	1.28	BDL	BDL	0.220
1-butene	(ug/m3)	1.30	0.250	0.107	4.38
t-2-butene	(ug/m3)	2.11	0.093	BDL	0.231
c-2-butene	(ug/m3)	1.21	BDL	BDL	3.08
1,3-butadiene	(ug/m3)	0.193	0.003	0.022	0.294
3-methyl-1-butene	(ug/m3)	0.097	BDL	0.508	0.254
1-pentene	(ug/m3)	BDL	BDL	0.015	BDL
2-methyl-1-butene	(ug/m3)	0.123	0.103	0.238	BDL
2-methyl-1,3-butadiene	(ug/m3)	BDL	0.045	0.037	0.693
t-2-pentene	(ug/m3)	0.301	0.004	BDL	BDL
3,3-dimethyl-1-butene	(ug/m3)	5.53	BDL	BDL	0.229
c-2-pentene	(ug/m3)	0.054	BDL	BDL	0.661
cyclopentene	(ug/m3)	0.133	0.248	BDL	BDL
4-methyl-1-pentene	(ug/m3)	0.259	0.041	0.086	N/A
3-methyl-1-pentene	(ug/m3)	0.365	BDL	0.051	5.65
2-methyl-2-butene	(ug/m3)	BDL	BDL	BDL	1.21
cyclopentadiene	(ug/m3)	BDL	BDL	BDL	0.412
4-methyl-c-2-pentene	(ug/m3)	0.059	BDL	0.031	0.072
4-methyl-t-2-pentene	(ug/m3)	0.021	BDL	BDL	0.304
2-methyl-1-pentene	(ug/m3)	0.990	BDL	BDL	0.072
1-hexene	(ug/m3)	0.147	0.082	5.64	0.237
t-3-hexene	(ug/m3)	0.093	BDL	BDL	BDL
c-3-hexene	(ug/m3)	0.055	BDL	BDL	0.057
t-2-hexene	(ug/m3)	BDL	BDL	BDL	0.351
3-methyl-t-2-pentene	(ug/m3)	0.309	BDL	0.039	BDL
2M-2-pentene	(ug/m3)	0.117	BDL	BDL	0.756
3-methylcyclopentene	(ug/m3)	BDL	BDL	BDL	BDL
c-2-hexene	(ug/m3)	0.100	BDL	0.028	0.275
3-methyl-c-2-pentene	(ug/m3)	0.043	BDL	BDL	2.21
3,4-dimethyl-1-pentene	(ug/m3)	0.029	BDL	0.023	0.709
3-M-1-hexene	(ug/m3)	BDL	BDL	BDL	N/A
cyclohexene	(ug/m3)	BDL	BDL	BDL	BDL
1-heptene	(ug/m3)	0.019	BDL	0.053	0.279
t-3-heptene	(ug/m3)	0.015	BDL	0.026	2.00
3-methyl-t-3-hexene	(ug/m3)	0.056	0.271	0.022	0.094
t-2-heptene	(ug/m3)	0.042	BDL	0.021	0.475
2-methyl-2-hexene	(ug/m3)	0.124	0.007	0.717	5.61
3-ethyl-c-2-pentene	(ug/m3)	0.022	BDL	0.101	0.200
2,4,4-trimethyl-1-pentene	(ug/m3)	0.091	0.036	0.028	0.145
2,3-dimethyl-2-pentene	(ug/m3)	0.111	BDL	0.036	0.181
c-2-heptene	(ug/m3)	0.031	BDL	0.008	0.075
1-octene	(ug/m3)	0.692	BDL	0.114	BDL
t-4-octene	(ug/m3)	BDL	BDL	0.067	BDL
t-2-octene	(ug/m3)	0.087	BDL	BDL	0.283

c-2-octene	(ug/m3)	0.134	BDL	BDL	0.058
1-nonene	(ug/m3)	0.159	BDL	0.042	5.09
1-butyne	(ug/m3)	1.94	BDL	BDL	BDL
2-butyne	(ug/m3)	BDL	0.085	0.012	BDL

Table 39: **Alkene mass concentrations – N353SW**

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
2-methylpropene	(ug/m3)	1.03	BDL	BDL	7.10
1-butene	(ug/m3)	1.84	0.156	0.015	1.03
t-2-butene	(ug/m3)	0.829	0.010	BDL	0.116
c-2-butene	(ug/m3)	0.329	0.006	BDL	0.166
1,3-butadiene	(ug/m3)	0.307	0.026	0.088	0.119
3-methyl-1-butene	(ug/m3)	BDL	0.004	BDL	BDL
1-pentene	(ug/m3)	1.46	BDL	BDL	BDL
2-methyl-1-butene	(ug/m3)	1.41	BDL	BDL	N/A
2-methyl-1,3-butadiene	(ug/m3)	0.195	BDL	0.072	BDL
t-2-pentene	(ug/m3)	0.021	0.058	0.405	0.160
3,3-dimethyl-1-butene	(ug/m3)	0.257	BDL	0.040	0.187
c-2-pentene	(ug/m3)	0.025	0.018	0.099	N/A
cyclopentene	(ug/m3)	0.080	0.264	BDL	BDL
4-methyl-1-pentene	(ug/m3)	0.168	BDL	0.015	BDL
3-methyl-1-pentene	(ug/m3)	0.233	0.123	0.055	BDL
2-methyl-2-butene	(ug/m3)	0.029	1.24	0.021	0.825
cyclopentadiene	(ug/m3)	0.011	BDL	BDL	0.347
4-methyl-c-2-pentene	(ug/m3)	0.022	0.491	BDL	0.136
4-methyl-t-2-pentene	(ug/m3)	0.018	BDL	0.034	BDL
2-methyl-1-pentene	(ug/m3)	0.418	0.027	BDL	BDL
1-hexene	(ug/m3)	0.098	BDL	BDL	BDL
t-3-hexene	(ug/m3)	BDL	BDL	BDL	BDL
c-3-hexene	(ug/m3)	0.078	BDL	BDL	BDL
t-2-hexene	(ug/m3)	0.108	0.175	0.040	BDL
3-methyl-t-2-pentene	(ug/m3)	0.024	BDL	BDL	BDL
2M-2-pentene	(ug/m3)	0.079	0.017	BDL	BDL
3-methylcyclopentene	(ug/m3)	0.032	0.018	BDL	0.073
c-2-hexene	(ug/m3)	0.038	BDL	BDL	BDL
3-methyl-c-2-pentene	(ug/m3)	BDL	BDL	BDL	BDL
3,4-dimethyl-1-pentene	(ug/m3)	0.023	BDL	0.035	0.146
3-M-1-hexene	(ug/m3)	BDL	BDL	BDL	0.078
cyclohexene	(ug/m3)	BDL	BDL	BDL	BDL
1-heptene	(ug/m3)	0.105	BDL	0.022	BDL
t-3-heptene	(ug/m3)	0.030	0.021	BDL	BDL
3-methyl-t-3-hexene	(ug/m3)	BDL	0.022	BDL	BDL
t-2-heptene	(ug/m3)	BDL	0.055	BDL	BDL
2-methyl-2-hexene	(ug/m3)	BDL	BDL	0.025	BDL
3-ethyl-c-2-pentene	(ug/m3)	BDL	BDL	BDL	BDL
2,4,4-trimethyl-1-pentene	(ug/m3)	BDL	0.041	BDL	0.280
2,3-dimethyl-2-pentene	(ug/m3)	0.056	BDL	BDL	BDL
c-2-heptene	(ug/m3)	BDL	BDL	BDL	BDL
1-octene	(ug/m3)	0.642	0.007	BDL	0.076
t-4-octene	(ug/m3)	0.209	0.048	BDL	0.278
t-2-octene	(ug/m3)	BDL	0.014	0.086	BDL

c-2-octene	(ug/m3)	BDL	0.277	0.037	BDL
1-nonene	(ug/m3)	0.129	0.149	BDL	0.201
1-butyne	(ug/m3)	0.067	BDL	BDL	BDL
2-butyne	(ug/m3)	0.121	BDL	0.081	BDL

Table 40: **Alkene mass concentrations – N695SW**

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
2-methylpropene	(ug/m3)	14.0	BDL	BDL	BDL
1-butene	(ug/m3)	11.1	0.953	BDL	3.35
t-2-butene	(ug/m3)	3.93	0.156	BDL	0.225
c-2-butene	(ug/m3)	2.40	0.031	BDL	BDL
1,3-butadiene	(ug/m3)	0.168	0.297	BDL	0.246
3-methyl-1-butene	(ug/m3)	0.037	0.032	BDL	0.239
1-pentene	(ug/m3)	1.01	1.01	BDL	BDL
2-methyl-1-butene	(ug/m3)	0.226	0.639	BDL	BDL
2-methyl-1,3-butadiene	(ug/m3)	6.21	0.016	BDL	BDL
t-2-pentene	(ug/m3)	0.501	0.189	BDL	BDL
3,3-dimethyl-1-butene	(ug/m3)	0.559	0.073	BDL	BDL
c-2-pentene	(ug/m3)	0.059	0.063	BDL	BDL
cyclopentene	(ug/m3)	0.078	0.061	0.131	BDL
4-methyl-1-pentene	(ug/m3)	0.223	0.316	0.004	BDL
3-methyl-1-pentene	(ug/m3)	0.061	0.028	0.020	BDL
2-methyl-2-butene	(ug/m3)	0.764	0.058	BDL	BDL
cyclopentadiene	(ug/m3)	0.971	0.036	BDL	BDL
4-methyl-c-2-pentene	(ug/m3)	0.510	0.015	0.436	BDL
4-methyl-t-2-pentene	(ug/m3)	0.043	0.091	0.659	BDL
2-methyl-1-pentene	(ug/m3)	1.65	0.082	0.047	0.056
1-hexene	(ug/m3)	1.93	0.083	1.54	BDL
t-3-hexene	(ug/m3)	BDL	0.123	0.059	0.046
c-3-hexene	(ug/m3)	0.650	BDL	BDL	BDL
t-2-hexene	(ug/m3)	BDL	0.077	BDL	0.039
3-methyl-t-2-pentene	(ug/m3)	0.904	BDL	BDL	0.023
2M-2-pentene	(ug/m3)	0.037	BDL	BDL	0.037
3-methylcyclopentene	(ug/m3)	0.859	BDL	0.006	BDL
c-2-hexene	(ug/m3)	0.664	BDL	0.049	0.302
3-methyl-c-2-pentene	(ug/m3)	0.158	BDL	BDL	BDL
3,4-dimethyl-1-pentene	(ug/m3)	0.096	BDL	0.083	0.052
3-M-1-hexene	(ug/m3)	0.049	BDL	0.088	0.370
cyclohexene	(ug/m3)	BDL	BDL	BDL	BDL
1-heptene	(ug/m3)	0.239	0.083	0.156	0.220
t-3-heptene	(ug/m3)	0.208	0.096	0.021	BDL
3-methyl-t-3-hexene	(ug/m3)	0.026	0.113	0.046	0.362
t-2-heptene	(ug/m3)	0.369	BDL	0.070	0.094
2-methyl-2-hexene	(ug/m3)	0.101	0.282	0.023	0.131
3-ethyl-c-2-pentene	(ug/m3)	0.021	BDL	0.006	BDL
2,4,4-trimethyl-1-pentene	(ug/m3)	0.038	BDL	BDL	0.042
2,3-dimethyl-2-pentene	(ug/m3)	0.108	0.012	BDL	0.037
c-2-heptene	(ug/m3)	0.029	BDL	BDL	0.064
1-octene	(ug/m3)	6.85	0.017	0.115	BDL
t-4-octene	(ug/m3)	1.44	0.038	BDL	BDL
t-2-octene	(ug/m3)	0.104	BDL	BDL	10.17172

c-2-octene	(ug/m3)	1.07	BDL	BDL	0.035
1-nonene	(ug/m3)	2.67	0.015	BDL	0.322
1-butyne	(ug/m3)	0.633	0.141	N/A	1.660732
2-butyne	(ug/m3)	BDL	0.315	BDL	BDL

Table 41: Alkene mass concentrations – N429WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
2-methylpropene	(ug/m3)	8.30	BDL	0.076	BDL
1-butene	(ug/m3)	1.50	0.133	2.09	0.477
t-2-butene	(ug/m3)	BDL	0.025	0.161	1.23
c-2-butene	(ug/m3)	BDL	0.230	BDL	BDL
1,3-butadiene	(ug/m3)	BDL	0.026	0.311	0.047
3-methyl-1-butene	(ug/m3)	BDL	BDL	BDL	BDL
1-pentene	(ug/m3)	BDL	0.009	0.047	BDL
2-methyl-1-butene	(ug/m3)	BDL	0.044	0.070	0.067
2-methyl-1,3-butadiene	(ug/m3)	BDL	0.098	0.135	0.055
t-2-pentene	(ug/m3)	BDL	0.012	0.064	0.274
3,3-dimethyl-1-butene	(ug/m3)	BDL	0.010	0.031	0.030
c-2-pentene	(ug/m3)	BDL	0.014	0.020	0.186
cyclopentene	(ug/m3)	BDL	0.039	0.022	BDL
4-methyl-1-pentene	(ug/m3)	BDL	0.007	BDL	BDL
3-methyl-1-pentene	(ug/m3)	BDL	BDL	BDL	BDL
2-methyl-2-butene	(ug/m3)	BDL	1.85	0.016	0.056
cyclopentadiene	(ug/m3)	BDL	BDL	0.013	BDL
4-methyl-c-2-pentene	(ug/m3)	BDL	BDL	0.010	BDL
4-methyl-t-2-pentene	(ug/m3)	0.077	BDL	0.103	BDL
2-methyl-1-pentene	(ug/m3)	0.010	0.167	0.096	BDL
1-hexene	(ug/m3)	0.006	0.038	0.028	0.120
t-3-hexene	(ug/m3)	BDL	0.029	BDL	BDL
c-3-hexene	(ug/m3)	BDL	BDL	BDL	BDL
t-2-hexene	(ug/m3)	BDL	BDL	1.65	0.889
3-methyl-t-2-pentene	(ug/m3)	0.020	BDL	BDL	BDL
2M-2-pentene	(ug/m3)	BDL	0.010	BDL	BDL
3-methylcyclopentene	(ug/m3)	BDL	BDL	0.006	BDL
c-2-hexene	(ug/m3)	0.020	BDL	BDL	BDL
3-methyl-c-2-pentene	(ug/m3)	0.004	BDL	BDL	BDL
3,4-dimethyl-1-pentene	(ug/m3)	0.020	0.021	0.114	BDL
3-M-1-hexene	(ug/m3)	BDL	BDL	BDL	BDL
cyclohexene	(ug/m3)	BDL	BDL	BDL	BDL
1-heptene	(ug/m3)	N/A	BDL	0.015	BDL
t-3-heptene	(ug/m3)	0.504	BDL	0.016	BDL
3-methyl-t-3-hexene	(ug/m3)	0.031	0.016	0.031	0.270
t-2-heptene	(ug/m3)	0.138	BDL	BDL	BDL
2-methyl-2-hexene	(ug/m3)	N/A	BDL	0.018	BDL
3-ethyl-c-2-pentene	(ug/m3)	N/A	BDL	BDL	BDL
2,4,4-trimethyl-1-pentene	(ug/m3)	N/A	0.027	BDL	BDL
2,3-dimethyl-2-pentene	(ug/m3)	0.048	BDL	0.009	BDL
c-2-heptene	(ug/m3)	0.018	BDL	BDL	0.084
1-octene	(ug/m3)	0.054	BDL	0.026	BDL
t-4-octene	(ug/m3)	0.031	0.015	BDL	BDL
t-2-octene	(ug/m3)	N/A	BDL	BDL	BDL

c-2-octene	(ug/m3)	0.086	BDL	0.044	0.444
1-nonene	(ug/m3)	0.127	BDL	BDL	BDL
1-butyne	(ug/m3)	BDL	0.023	BDL	BDL
2-butyne	(ug/m3)	BDL	0.019	BDL	BDL

Table 42: Alkane mass concentrations – N435WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
octane	(ug/m3)	0.057	BDL	BDL	0.081
2-methylpropane	(ug/m3)	2.28	BDL	BDL	BDL
butane	(ug/m3)	0.162	0.026	0.039	0.405
2,2-dimethylpropane	(ug/m3)	0.075	0.105	0.043	0.669
2-methylbutane	(ug/m3)	0.031	0.116	0.045	BDL
pentane	(ug/m3)	0.411	0.030	0.140	BDL
2,2-dimethylbutane	(ug/m3)	0.074	0.524	BDL	0.223
cyclopentane	(ug/m3)	1.79	BDL	0.085	BDL
2,3-dimethylbutane	(ug/m3)	0.204	0.027	0.076	BDL
2-methylpentane	(ug/m3)	0.026	BDL	0.021	0.076
3-methylpentane	(ug/m3)	0.088	0.044	BDL	0.920
hexane	(ug/m3)	0.241	BDL	BDL	0.489
methylcyclopentane	(ug/m3)	BDL	0.009	BDL	BDL
2,2-dimethylpentane	(ug/m3)	0.028	BDL	BDL	0.111
2,4-dimethylpentane	(ug/m3)	BDL	BDL	0.054	0.116
2,2,3-trimethylbutane	(ug/m3)	BDL	BDL	BDL	0.063
3,3-dimethylpentane	(ug/m3)	0.101	BDL	BDL	0.113
cyclohexane	(ug/m3)	BDL	BDL	BDL	0.248
2-methylhexane	(ug/m3)	BDL	0.051	0.043	0.679
2,3-dimethylpentane	(ug/m3)	0.025	0.005	0.038	0.246
3-methylhexane	(ug/m3)	BDL	0.007	0.097	N/A
c-1,3-dimethylcyclopentane	(ug/m3)	0.187	BDL	0.141	0.082
3-ethylpentane	(ug/m3)	BDL	0.004	0.019	0.553
t-1,2-dimethylcyclopentane	(ug/m3)	BDL	0.004	0.012	0.191
2,2,4-trimethylpentane (i-octane)	(ug/m3)	0.497	0.020	0.040	0.085
heptane	(ug/m3)	0.018	BDL	0.074	0.125
methylcyclohexane	(ug/m3)	0.038	BDL	0.013	N/A
2,4,4-trimethyl-2-pentene	(ug/m3)	0.035	0.006	0.028	BDL
2,2-dimethylhexane	(ug/m3)	0.078	BDL	0.069	BDL
2,5-dimethylhexane	(ug/m3)	0.128	BDL	0.164	BDL
2,4-dimethylhexane	(ug/m3)	0.137	BDL	BDL	0.078
3,3-dimethylhexane	(ug/m3)	0.303	BDL	0.022	0.134
2,3,4-trimethylpentane	(ug/m3)	0.348	BDL	0.026	0.228
2,3-dimethylhexane	(ug/m3)	0.138	BDL	0.020	BDL
2-methylheptane	(ug/m3)	0.083	BDL	BDL	0.280
4-methylheptane	(ug/m3)	BDL	BDL	0.010	0.233
3-methylheptane	(ug/m3)	0.039	BDL	0.018	1.22
1c,2t,3-trimethylcyclopentane	(ug/m3)	0.437	BDL	0.012	0.110
c-1,3-dimethylcyclohexane	(ug/m3)	0.044	BDL	BDL	0.129
t-1,4-dimethylcyclohexane	(ug/m3)	0.035	0.014	0.033	0.115
2,2,5-TM-hexane	(ug/m3)	BDL	BDL	BDL	0.330
t-1,3-dimethylcyclohexane	(ug/m3)	0.066	0.019	BDL	N/A
2,3,5-trimethylhexane	(ug/m3)	0.014	BDL	0.294	0.123
2,4-dimethylheptane	(ug/m3)	0.079	BDL	BDL	0.177
NN-DM-	(ug/m3)	0.007	BDL	BDL	0.027
c-1,2-dimethylcyclohexane	(ug/m3)	0.247	BDL	BDL	0.644
ethylcyclohexane	(ug/m3)	0.169	BDL	0.026	0.114
3,5-dimethylheptane	(ug/m3)	0.632	BDL	0.063	0.148
2,3-dimethylheptane	(ug/m3)	1.27	BDL	0.027	0.177
2-methyloctane	(ug/m3)	1.78	BDL	0.027	BDL
3-methyloctane	(ug/m3)	0.118	BDL	0.036	0.291
nonane	(ug/m3)	0.099	BDL	0.073	0.204
2,2-dimethyloctane	(ug/m3)	0.010	BDL	0.031	0.268
2,4-dimethyloctane	(ug/m3)	0.011	BDL	0.023	0.393
decane	(ug/m3)	0.385	0.024	0.435	0.971
undecane	(ug/m3)	0.234	BDL	0.079	N/A

Table 43: Alkane mass concentrations – N353SW

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
octane	(ug/m3)	BDL	BDL	BDL	BDL
2-methylpropane	(ug/m3)	0.863	BDL	BDL	BDL
butane	(ug/m3)	0.311	0.023	0.011	0.157
2,2-dimethylpropane	(ug/m3)	0.013	0.018	BDL	0.089
2-methylbutane	(ug/m3)	1.00	BDL	0.050	BDL
pentane	(ug/m3)	0.204	BDL	BDL	4.02
2,2-dimethylbutane	(ug/m3)	0.023	0.731	BDL	BDL
cyclopentane	(ug/m3)	0.052	BDL	BDL	BDL
2,3-dimethylbutane	(ug/m3)	0.016	BDL	BDL	BDL
2-methylpentane	(ug/m3)	0.073	BDL	BDL	BDL
3-methylpentane	(ug/m3)	0.122	BDL	BDL	BDL
hexane	(ug/m3)	BDL	BDL	BDL	BDL
methylcyclopentane	(ug/m3)	BDL	BDL	BDL	BDL
2,2-dimethylpentane	(ug/m3)	BDL	BDL	0.069	BDL
2,4-dimethylpentane	(ug/m3)	BDL	0.545	BDL	BDL
2,2,3-trimethylbutane	(ug/m3)	BDL	0.014	BDL	0.786
3,3-dimethylpentane	(ug/m3)	0.042	0.018	BDL	BDL
cyclohexane	(ug/m3)	BDL	BDL	BDL	BDL
2-methylhexane	(ug/m3)	BDL	BDL	BDL	BDL
2,3-dimethylpentane	(ug/m3)	0.029	BDL	BDL	BDL
3-methylhexane	(ug/m3)	0.045	0.327	BDL	BDL
c-1,3-dimethylcyclopentane	(ug/m3)	0.094	0.020	BDL	BDL
3-ethylpentane	(ug/m3)	0.327	BDL	BDL	BDL
t-1,2-dimethylcyclopentane	(ug/m3)	BDL	BDL	BDL	BDL
2,2,4-trimethylpentane (i-octane)	(ug/m3)	BDL	BDL	0.022	BDL
heptane	(ug/m3)	0.094	BDL	0.023	0.082
methylcyclohexane	(ug/m3)	BDL	BDL	BDL	BDL
2,4,4-trimethyl-2-pentene	(ug/m3)	BDL	BDL	BDL	BDL
2,2-dimethylhexane	(ug/m3)	BDL	BDL	BDL	BDL
2,5-dimethylhexane	(ug/m3)	0.072	BDL	BDL	BDL
2,4-dimethylhexane	(ug/m3)	1.52	BDL	BDL	BDL
3,3-dimethylhexane	(ug/m3)	0.030	BDL	0.056	BDL
2,3,4-trimethylpentane	(ug/m3)	0.100	BDL	BDL	BDL
2,3-dimethylhexane	(ug/m3)	0.063	BDL	BDL	BDL
2-methylheptane	(ug/m3)	0.143	0.017	BDL	BDL
4-methylheptane	(ug/m3)	0.038	0.009	BDL	BDL
3-methylheptane	(ug/m3)	0.155	BDL	BDL	BDL
1c,2t,3-trimethylcyclopentane	(ug/m3)	0.290	BDL	0.217	BDL
c-1,3-dimethylcyclohexane	(ug/m3)	BDL	BDL	BDL	BDL
t-1,4-dimethylcyclohexane	(ug/m3)	BDL	0.049	BDL	BDL
2,2,5-TM-hexane	(ug/m3)	0.007	0.000	BDL	BDL
t-1,3-dimethylcyclohexane	(ug/m3)	0.125	0.129	BDL	BDL
2,3,5-trimethylhexane	(ug/m3)	0.025	0.014	0.014	BDL
2,4-dimethylheptane	(ug/m3)	0.121	BDL	0.014	BDL
NN-DM-	(ug/m3)	0.003	BDL	0.002	0.008
c-1,2-dimethylcyclohexane	(ug/m3)	0.045	0.006	BDL	BDL
ethylcyclohexane	(ug/m3)	0.078	0.014	BDL	0.243
3,5-dimethylheptane	(ug/m3)	0.223	0.010	BDL	0.137
2,3-dimethylheptane	(ug/m3)	1.14	BDL	BDL	0.194
2-methyloctane	(ug/m3)	0.025	BDL	BDL	BDL
3-methyloctane	(ug/m3)	0.128	BDL	BDL	0.398
nonane	(ug/m3)	0.058	BDL	BDL	0.178
2,2-dimethyloctane	(ug/m3)	0.100	0.012	BDL	BDL
2,4-dimethyloctane	(ug/m3)	0.050	0.008	BDL	BDL
decane	(ug/m3)	0.274	0.190	0.015	BDL
undecane	(ug/m3)	0.084	0.023	BDL	BDL

Table 44: Alkane mass concentrations – N695SW

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
octane	(ug/m3)	0.135	0.037	BDL	BDL
2-methylpropane	(ug/m3)	0.630	BDL	BDL	BDL
butane	(ug/m3)	0.301	0.165	BDL	0.205
2,2-dimethylpropane	(ug/m3)	0.125	0.264	#N/A	1.58
2-methylbutane	(ug/m3)	0.137	0.755	BDL	BDL
pentane	(ug/m3)	1.50	0.040	BDL	BDL
2,2-dimethylbutane	(ug/m3)	0.010	0.037	0.109	BDL
cyclopentane	(ug/m3)	0.678	0.020	0.035	BDL
2,3-dimethylbutane	(ug/m3)	BDL	0.258	0.302	BDL
2-methylpentane	(ug/m3)	N/A	0.038	0.066	BDL
3-methylpentane	(ug/m3)	0.524	0.146	0.075	BDL
hexane	(ug/m3)	4.46	0.125	0.030	0.417
methylcyclopentane	(ug/m3)	0.108	0.135	0.063	0.068
2,2-dimethylpentane	(ug/m3)	0.455	BDL	0.115	0.233
2,4-dimethylpentane	(ug/m3)	0.061	BDL	BDL	0.117
2,2,3-trimethylbutane	(ug/m3)	0.012	0.108	0.021	0.026
3,3-dimethylpentane	(ug/m3)	0.022	BDL	0.261	BDL
cyclohexane	(ug/m3)	0.389	BDL	0.010	BDL
2-methylhexane	(ug/m3)	0.041	N/A	0.013	N/A
2,3-dimethylpentane	(ug/m3)	0.123	0.261	0.009	0.103
3-methylhexane	(ug/m3)	0.069	0.083	0.254	0.144
c-1,3-dimethylcyclopentane	(ug/m3)	0.145	BDL	0.143	0.106
3-ethylpentane	(ug/m3)	N/A	BDL	0.008	BDL
t-1,2-dimethylcyclopentane	(ug/m3)	0.280	BDL	0.040	0.215
2,2,4-trimethylpentane (i-octane)	(ug/m3)	0.021	0.089	0.268	N/A
heptane	(ug/m3)	0.012	0.113	0.082	0.022
methylcyclohexane	(ug/m3)	0.161	0.026	0.026	BDL
2,4,4-trimethyl-2-pentene	(ug/m3)	0.250	0.023	BDL	0.056
2,2-dimethylhexane	(ug/m3)	0.029	0.007	BDL	0.049
2,5-dimethylhexane	(ug/m3)	0.131	BDL	0.006	N/A
2,4-dimethylhexane	(ug/m3)	6.92	BDL	0.024	0.071
3,3-dimethylhexane	(ug/m3)	0.091	0.053	0.010	0.113
2,3,4-trimethylpentane	(ug/m3)	1.19	0.012	0.013	0.040
2,3-dimethylhexane	(ug/m3)	BDL	0.038	0.015	BDL
2-methylheptane	(ug/m3)	0.189	0.007	BDL	BDL
4-methylheptane	(ug/m3)	0.375	0.007	BDL	0.034
3-methylheptane	(ug/m3)	0.166	0.057	BDL	BDL
1c,2t,3-trimethylcyclopentane	(ug/m3)	0.189	0.035	BDL	BDL
c-1,3-dimethylcyclohexane	(ug/m3)	0.327	0.022	BDL	0.158
t-1,4-dimethylcyclohexane	(ug/m3)	N/A	0.010	0.032	BDL
2,2,5-TM-hexane	(ug/m3)	0.030	0.006	BDL	BDL
t-1,3-dimethylcyclohexane	(ug/m3)	0.156	BDL	BDL	BDL
2,3,5-trimethylhexane	(ug/m3)	0.127	0.309	0.077	0.519
2,4-dimethylheptane	(ug/m3)	0.456	0.011	BDL	0.076
NN-DM-	(ug/m3)	0.046	0.002	BDL	BDL
c-1,2-dimethylcyclohexane	(ug/m3)	0.055	0.015	BDL	BDL
ethylcyclohexane	(ug/m3)	1.03	0.024	BDL	BDL
3,5-dimethylheptane	(ug/m3)	1.46	BDL	0.037	BDL
2,3-dimethylheptane	(ug/m3)	0.347	BDL	BDL	BDL
2-methyloctane	(ug/m3)	1.42	BDL	BDL	BDL
3-methyloctane	(ug/m3)	BDL	0.040	BDL	BDL
nonane	(ug/m3)	0.180	0.177	BDL	BDL
2,2-dimethyloctane	(ug/m3)	0.060	0.055	BDL	0.046
2,4-dimethyloctane	(ug/m3)	0.251	0.044	BDL	BDL
decane	(ug/m3)	0.223	0.267	BDL	0.438
undecane	(ug/m3)	0.109	0.394	BDL	BDL

Table 45: Alkane mass concentrations – N429WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
octane	(ug/m3)	0.179	BDL	BDL	BDL
2-methylpropane	(ug/m3)	3.95	BDL	BDL	0.237
butane	(ug/m3)	BDL	0.010	0.043	0.051
2,2-dimethylpropane	(ug/m3)	BDL	BDL	0.049	BDL
2-methylbutane	(ug/m3)	BDL	0.030	BDL	BDL
pentane	(ug/m3)	BDL	0.011	0.042	0.168
2,2-dimethylbutane	(ug/m3)	BDL	0.009	0.010	N
cyclopentane	(ug/m3)	BDL	0.053	0.022	0.161
2,3-dimethylbutane	(ug/m3)	BDL	BDL	BDL	0.048
2-methylpentane	(ug/m3)	0.101	BDL	BDL	BDL
3-methylpentane	(ug/m3)	0.006	0.026	0.035	BDL
hexane	(ug/m3)	0.280	0.040	0.024	BDL
methylcyclopentane	(ug/m3)	#N/A	BDL	BDL	BDL
2,2-dimethylpentane	(ug/m3)	0.010	BDL	BDL	BDL
2,4-dimethylpentane	(ug/m3)	0.021	0.047	BDL	BDL
2,2,3-trimethylbutane	(ug/m3)	BDL	BDL	0.020	BDL
3,3-dimethylpentane	(ug/m3)	BDL	BDL	0.157	BDL
cyclohexane	(ug/m3)	BDL	BDL	BDL	BDL
2-methylhexane	(ug/m3)	BDL	BDL	0.036	BDL
2,3-dimethylpentane	(ug/m3)	BDL	BDL	0.247	0.369
3-methylhexane	(ug/m3)	0.014	BDL	BDL	BDL
c-1,3-dimethylcyclopentane	(ug/m3)	#N/A	BDL	BDL	BDL
3-ethylpentane	(ug/m3)	#N/A	0.039	BDL	BDL
t-1,2-dimethylcyclopentane	(ug/m3)	#N/A	0.015	BDL	BDL
2,2,4-trimethylpentane (i-octane)	(ug/m3)	#N/A	0.010	BDL	BDL
heptane	(ug/m3)	#N/A	0.010	0.021	0.078
methylcyclohexane	(ug/m3)	0.010	0.191	0.009	BDL
2,4,4-trimethyl-2-pentene	(ug/m3)	0.109	BDL	BDL	BDL
2,2-dimethylhexane	(ug/m3)	#N/A	BDL	BDL	BDL
2,5-dimethylhexane	(ug/m3)	0.066	BDL	BDL	BDL
2,4-dimethylhexane	(ug/m3)	0.052	BDL	BDL	BDL
3,3-dimethylhexane	(ug/m3)	0.077	BDL	BDL	BDL
2,3,4-trimethylpentane	(ug/m3)	0.024	BDL	BDL	0.026
2,3-dimethylhexane	(ug/m3)	#N/A	BDL	BDL	BDL
2-methylheptane	(ug/m3)	0.207	BDL	BDL	BDL
4-methylheptane	(ug/m3)	0.079	BDL	BDL	BDL
3-methylheptane	(ug/m3)	0.018	BDL	BDL	BDL
1c,2t,3-trimethylcyclopentane	(ug/m3)	0.479	BDL	BDL	BDL
c-1,3-dimethylcyclohexane	(ug/m3)	0.018	BDL	BDL	BDL
t-1,4-dimethylcyclohexane	(ug/m3)	0.023	0.161	BDL	0.043
2,2,5-TM-hexane	(ug/m3)	0.065	BDL	0.002	0.005
t-1,3-dimethylcyclohexane	(ug/m3)	0.165	BDL	BDL	BDL
2,3,5-trimethylhexane	(ug/m3)	0.016	0.108	0.249	BDL
2,4-dimethylheptane	(ug/m3)	0.019	BDL	BDL	BDL
NN-DM-	(ug/m3)	0.003	BDL	BDL	BDL
c-1,2-dimethylcyclohexane	(ug/m3)	0.275	BDL	BDL	BDL
ethylcyclohexane	(ug/m3)	0.203	BDL	BDL	BDL
3,5-dimethylheptane	(ug/m3)	0.068	0.019	BDL	BDL
2,3-dimethylheptane	(ug/m3)	0.076	BDL	BDL	BDL
2-methyloctane	(ug/m3)	0.047	BDL	BDL	BDL
3-methyloctane	(ug/m3)	0.019	BDL	BDL	BDL
nonane	(ug/m3)	0.032	BDL	BDL	BDL
2,2-dimethyloctane	(ug/m3)	0.011	0.055	BDL	BDL
2,4-dimethyloctane	(ug/m3)	0.014	0.069	BDL	BDL
decane	(ug/m3)	0.022	BDL	0.086	BDL
undecane	(ug/m3)	0.315	0.027	BDL	BDL

Table 46: Aromatic mass concentrations – N435WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N435WN		Mode 1	Mode 2	Mode 3	Mode 4
benzene	(ug/m3)	0.640	0.015	0.056	8.19
toluene	(ug/m3)	0.480	0.030	0.054	7.31
ethylbenzene	(ug/m3)	0.065	BDL	0.021	0.277
1,2-DM-benzene	(ug/m3)	0.135	0.025	0.018	2.44
1,3-DM-benzene	(ug/m3)	0.003	BDL	0.003	0.195
styrene	(ug/m3)	0.015	BDL	0.049	4.69
i-propylbenzene	(ug/m3)	0.068	BDL	0.021	0.276
benzaldehyde	(ug/m3)	0.197	BDL	0.094	0.098
n-propylbenzene	(ug/m3)	0.676	BDL	0.060	0.528
1-ethyl-3-methylbenzene	(ug/m3)	0.110	BDL	0.040	0.343
1E-4M-benzene	(ug/m3)	0.182	BDL	0.035	14.85
1,3,5-trimethyl benzene	(ug/m3)	0.060	BDL	0.022	0.281
1E-2M-benzene	(ug/m3)	0.114	BDL	0.035	0.135
1,2,4-TMB	(ug/m3)	0.182	0.030	0.031	1.01
2M-propylbenzene	(ug/m3)	0.072	BDL	0.079	1.43
s-butylbenzene	(ug/m3)	0.113	BDL	0.007	0.691
1M-3-(1-methylethyl)-benzene	(ug/m3)	0.115	0.011	0.021	0.802
1,2,3-trimethylbenzene	(ug/m3)	0.134	BDL	0.021	2.71
1M-4-(1-methylethyl)-benzene	(ug/m3)	0.226	BDL	0.025	BDL
2,3-dihydro-1H-indene	(ug/m3)	0.977	BDL	0.058	0.794
1M-2-(1-methylethyl)-benzene	(ug/m3)	0.310	0.027	0.025	4.36
1,3-diethylbenzene	(ug/m3)	0.180	BDL	0.012	0.532
1,4-DE-benzene	(ug/m3)	0.211	BDL	0.036	2.09
1-methyl-3-n-propylbenzene	(ug/m3)	0.207	0.011	0.206	13.2
1-methyl-4-n-propylbenzene	(ug/m3)	0.204	0.022	#N/A	2.13
1,2-diethylbenzene	(ug/m3)	0.256	0.031	#N/A	5.84
1M-2P-benzene	(ug/m3)	0.147	BDL	0.079	15.4
1,4-dimethyl-2-ethylbenzene	(ug/m3)	0.476	0.015	0.052	7.48
1,3-dimethyl-4-ethylbenzene	(ug/m3)	0.168	BDL	0.032	0.913
1,2-dimethyl-4-ethylbenzene	(ug/m3)	0.183	BDL	0.066	1.16
1,3-dimethyl-2-ethylbenzene	(ug/m3)	0.223	0.033	0.024	73.8
1,2-dimethyl-3-ethylbenzene	(ug/m3)	0.561	BDL	0.025	4.11
1,2,4,5-tetM-benzene	(ug/m3)	0.143	0.013	0.016	#N/A
2-methyl-butylbenzene	(ug/m3)	0.272	0.032	0.038	2.96
1,2,3,5-tetM-benzene	(ug/m3)	0.476	0.014	0.062	17.2
tert-1-butyl-2-methyl-benzene	(ug/m3)	0.041	0.016	0.028	1.50
1,2,3,4-tetM-benzene	(ug/m3)	0.039	BDL	0.009	1.50
n-pent-benzene	(ug/m3)	0.454	0.048	0.010	2.43
tert-1-butyl-3,5-dimethyl-benzene	(ug/m3)	0.111	0.010	0.055	5.86

Table 47: **Aromatic mass concentrations – N353SW**

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N353SW		Mode 1	Mode 2	Mode 3	Mode 4
benzene	(ug/m3)	0.053	0.155	0.027	BDL
toluene	(ug/m3)	0.065	0.154	0.025	BDL
ethylbenzene	(ug/m3)	BDL	BDL	BDL	BDL
1,2-DM-benzene	(ug/m3)	1.85	0.019	0.477	BDL
1,3-DM-benzene	(ug/m3)	0.216	0.004	0.002	BDL
styrene	(ug/m3)	0.062	0.236	BDL	BDL
i-propylbenzene	(ug/m3)	0.018	0.023	BDL	0.074
benzaldehyde	(ug/m3)	0.158	0.016	BDL	BDL
n-propylbenzene	(ug/m3)	0.382	0.018	BDL	BDL
1-ethyl-3-methylbenzene	(ug/m3)	0.043	0.009	BDL	BDL
1E-4M-benzene	(ug/m3)	0.174	0.012	BDL	BDL
1,3,5-trimethyl benzene	(ug/m3)	0.031	0.007	BDL	BDL
1E-2M-benzene	(ug/m3)	0.126	0.017	0.264	BDL
1,2,4-TMB	(ug/m3)	0.314	0.016	0.221	BDL
2M-propylbenzene	(ug/m3)	0.162	0.045	BDL	BDL
s-butylbenzene	(ug/m3)	0.056	0.092	BDL	BDL
1M-3-(1-methylethyl)-benzene	(ug/m3)	0.078	BDL	BDL	BDL
1,2,3-trimethylbenzene	(ug/m3)	0.090	BDL	BDL	BDL
1M-4-(1-methylethyl)-benzene	(ug/m3)	0.120	0.016	BDL	BDL
2,3-dihydro-1H-indene	(ug/m3)	0.493	BDL	BDL	BDL
1M-2-(1-methylethyl)-benzene	(ug/m3)	0.108	0.080	BDL	BDL
1,3-diethylbenzene	(ug/m3)	0.108	0.008	BDL	BDL
1,4-DE-benzene	(ug/m3)	0.090	0.012	BDL	BDL
1-methyl-3-n-propylbenzene	(ug/m3)	0.079	0.032	BDL	BDL
1-methyl-4-n-propylbenzene	(ug/m3)	0.115	0.013	BDL	BDL
1,2-diethylbenzene	(ug/m3)	#N/A	0.043	BDL	BDL
1M-2P-benzene	(ug/m3)	#N/A	0.058	BDL	BDL
1,4-dimethyl-2-ethylbenzene	(ug/m3)	0.300	0.008	BDL	BDL
1,3-dimethyl-4-ethylbenzene	(ug/m3)	0.068	0.040	BDL	BDL
1,2-dimethyl-4-ethylbenzene	(ug/m3)	0.135	0.038	0.084	BDL
1,3-dimethyl-2-ethylbenzene	(ug/m3)	0.037	0.050	BDL	BDL
1,2-dimethyl-3-ethylbenzene	(ug/m3)	0.162	0.181	BDL	BDL
1,2,4,5-tetM-benzene	(ug/m3)	0.045	0.017	BDL	BDL
2-methyl-butylbenzene	(ug/m3)	0.055	0.029	BDL	BDL
1,2,3,5-tetM-benzene	(ug/m3)	0.143	0.050	0.135	BDL
tert-1-butyl-2-methyl-benzene	(ug/m3)	0.013	0.025	BDL	BDL
1,2,3,4-tetM-benzene	(ug/m3)	0.037	0.052	BDL	BDL
n-pent-benzene	(ug/m3)	0.107	0.076	BDL	BDL
tert-1-butyl-3,5-dimethyl-benzene	(ug/m3)	0.056	0.091	0.092	BDL

Table 48: Aromatic mass concentrations – N695SW

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N695SW		Mode 1	Mode 2	Mode 3	Mode 4
benzene	(ug/m3)	1.52	0.325	0.044	0.151
toluene	(ug/m3)	0.732	0.407	0.056	0.108
ethylbenzene	(ug/m3)	0.222	0.170	BDL	BDL
1,2-DM-benzene	(ug/m3)	8.44	0.575	BDL	BDL
1,3-DM-benzene	(ug/m3)	0.153	0.054	0.001	0.004
styrene	(ug/m3)	0.230	0.022	0.014	0.149
i-propylbenzene	(ug/m3)	0.304	0.050	BDL	BDL
benzaldehyde	(ug/m3)	0.055	0.046	BDL	BDL
n-propylbenzene	(ug/m3)	0.357	0.081	BDL	0.110
1-ethyl-3-methylbenzene	(ug/m3)	0.072	0.097	BDL	0.119
1E-4M-benzene	(ug/m3)	0.064	0.159	BDL	0.187
1,3,5-trimethyl benzene	(ug/m3)	0.124	0.136	BDL	0.088
1E-2M-benzene	(ug/m3)	0.212	0.128	0.015	0.078
1,2,4-TMB	(ug/m3)	0.240	0.080	0.032	N/A
2M-propylbenzene	(ug/m3)	0.545	0.319	BDL	0.089
s-butylbenzene	(ug/m3)	0.015	0.400	BDL	BDL
1M-3-(1-methylethyl)-benzene	(ug/m3)	0.046	0.092	BDL	BDL
1,2,3-trimethylbenzene	(ug/m3)	0.025	0.158	BDL	BDL
1M-4-(1-methylethyl)-benzene	(ug/m3)	0.121	BDL	BDL	0.228
2,3-dihydro-1H-indene	(ug/m3)	0.306	BDL	BDL	BDL
1M-2-(1-methylethyl)-benzene	(ug/m3)	0.069	BDL	BDL	0.087
1,3-diethylbenzene	(ug/m3)	0.151	0.066	BDL	0.057
1,4-DE-benzene	(ug/m3)	0.091	0.229	BDL	0.112
1-methyl-3-n-propylbenzene	(ug/m3)	0.093	0.246	BDL	0.164
1-methyl-4-n-propylbenzene	(ug/m3)	0.281	0.065	BDL	0.074
1,2-diethylbenzene	(ug/m3)	0.152	0.018	BDL	BDL
1M-2P-benzene	(ug/m3)	0.098	0.168	BDL	BDL
1,4-dimethyl-2-ethylbenzene	(ug/m3)	0.218	0.014	BDL	BDL
1,3-dimethyl-4-ethylbenzene	(ug/m3)	0.063	0.026	BDL	BDL
1,2-dimethyl-4-ethylbenzene	(ug/m3)	0.109	0.089	BDL	0.202
1,3-dimethyl-2-ethylbenzene	(ug/m3)	0.159	0.451	BDL	BDL
1,2-dimethyl-3-ethylbenzene	(ug/m3)	0.320	0.059	BDL	BDL
1,2,4,5-tetM-benzene	(ug/m3)	0.047	0.243	BDL	0.076
2-methyl-butylbenzene	(ug/m3)	0.062	0.429	BDL	BDL
1,2,3,5-tetM-benzene	(ug/m3)	0.119	0.467	BDL	0.572
tert-1-butyl-2-methyl-benzene	(ug/m3)	0.020	0.575	0.028	0.043
1,2,3,4-tetM-benzene	(ug/m3)	0.038	0.660	BDL	0.153
n-pent-benzene	(ug/m3)	0.200	0.610	BDL	0.047
tert-1-butyl-3,5-dimethyl-benzene	(ug/m3)	0.208	0.926	BDL	0.100

Table 49: Aromatic mass concentrations - N429WN

*(** Note: data in this table may not be useful since they were measured using TDS on the low flow side of the sampling system where a leak occurred**)*

N429WN		Mode 1	Mode 2	Mode 3	Mode 4
benzene	(ug/m3)	3.456	0.172	0.009	0.066
toluene	(ug/m3)	3.631	0.232	BDL	0.036
ethylbenzene	(ug/m3)	0.076	BDL	BDL	BDL
1,2-DM-benzene	(ug/m3)	0.056	BDL	BDL	BDL
1,3-DM-benzene	(ug/m3)	0.019	0.002	BDL	BDL
styrene	(ug/m3)	0.037	BDL	BDL	BDL
i-propylbenzene	(ug/m3)	0.043	BDL	BDL	BDL
benzaldehyde	(ug/m3)	0.057	BDL	BDL	BDL
n-propylbenzene	(ug/m3)	0.055	BDL	BDL	BDL
1-ethyl-3-methylbenzene	(ug/m3)	0.005	0.067	BDL	BDL
1E-4M-benzene	(ug/m3)	0.019	BDL	BDL	BDL
1,3,5-trimethyl benzene	(ug/m3)	0.017	BDL	0.006	BDL
1E-2M-benzene	(ug/m3)	0.079	BDL	0.006	BDL
1,2,4-TMB	(ug/m3)	0.018	BDL	0.016	0.351
2M-propylbenzene	(ug/m3)	0.288	BDL	BDL	BDL
s-butylbenzene	(ug/m3)	0.059	BDL	BDL	BDL
1M-3-(1-methylethyl)-benzene	(ug/m3)	0.023	BDL	BDL	BDL
1,2,3-trimethylbenzene	(ug/m3)	0.049	BDL	BDL	BDL
1M-4-(1-methylethyl)-benzene	(ug/m3)	0.041	0.033	BDL	BDL
2,3-dihydro-1H-indene	(ug/m3)	0.078	BDL	BDL	BDL
1M-2-(1-methylethyl)-benzene	(ug/m3)	0.020	BDL	BDL	BDL
1,3-diethylbenzene	(ug/m3)	0.046	BDL	BDL	BDL
1,4-DE-benzene	(ug/m3)	0.038	BDL	BDL	BDL
1-methyl-3-n-propylbenzene	(ug/m3)	0.043	0.014	BDL	BDL
1-methyl-4-n-propylbenzene	(ug/m3)	0.067	0.038	BDL	BDL
1,2-diethylbenzene	(ug/m3)	0.052	BDL	BDL	BDL
1M-2P-benzene	(ug/m3)	0.013	BDL	BDL	BDL
1,4-dimethyl-2-ethylbenzene	(ug/m3)	0.147	BDL	BDL	BDL
1,3-dimethyl-4-ethylbenzene	(ug/m3)	0.085	BDL	BDL	BDL
1,2-dimethyl-4-ethylbenzene	(ug/m3)	0.029	0.032	0.010	BDL
1,3-dimethyl-2-ethylbenzene	(ug/m3)	0.124	BDL	BDL	BDL
1,2-dimethyl-3-ethylbenzene	(ug/m3)	0.064	BDL	0.010	BDL
1,2,4,5-tetM-benzene	(ug/m3)	0.008	BDL	BDL	BDL
2-methyl-butylbenzene	(ug/m3)	0.049	0.035	BDL	BDL
1,2,3,5-tetM-benzene	(ug/m3)	0.013	BDL	BDL	BDL
tert-1-butyl-2-methyl-benzene	(ug/m3)	0.012	BDL	BDL	0.139
1,2,3,4-tetM-benzene	(ug/m3)	0.063	0.036	0.034	BDL
n-pent-benzene	(ug/m3)	#N/A	BDL	BDL	BDL
tert-1-butyl-3,5-dimethyl-benzene	(ug/m3)	0.014	BDL	0.012	BDL

3.3.11 Estimation of EIs for VOCs

After the field campaign was completed and analysis of the DNPH cartridges, thermal desorption tubes and SUMMA canisters was undertaken, the EIs were calculated using the earlier described protocol. However, calculated EIs were much lower when compared with other investigators in this project or literature. It appeared that a leak had occurred in the subsystem designated for light hydrocarbon and carbonyl analysis. The sampling system, under vacuum, had allowed ambient air to enter at a leak and dilute the samples by an unknown amount.

3.3.11.1 Post Analysis of the Sampler

C_4-C_{12} hydrocarbon values were explored based on the concentrations measured from the Thermal Desorption Tubes (TDS) tubes but the values were much lower than expected from APEX1 and other research. This finding lead to an extensive evaluation of the UCR sampling system, especially given that in-field and post test calibrations indicated accurate flow through the sample media. Given that the samples collected on Teflon and quartz media matched expected values and that the carbonyl was close to the expected EI value than the sorption tubes, it was presumed that a small leak must have occurred near the split point for the thermal desorption system. The leak would have resulted in significant dilution with ambient air without affecting the PM, quartz, and quartz-PUF sample trains. This conclusion is easily reached by looking at the design flows in Figure 54. Note that the approximate flows in the quartz (qz) line was 80 liter per minute (LPM), for PTFE about 35LPM, for (QZ+PUF) about 25LPM, for DNPH about 1LPM and for thermal desorption tubes about 0.2LPM. Thus since the system was pressure and vacuum checked for leaks, it became clear that a small leak in the vicinity of the TDS collection tube would be consistent with the findings for the TDS tubes.

The design included a redundancy on the emission rates for the trace hydrocarbon gases; namely collection of gas phase samples in SUMMA canisters for subsequent analyses. The SUMMA canisters also allowed an internal check of the dilution ratio since CO_2 was also measured. Unfortunately, all Summa canisters analyzed by the external lab reported no measurable hydrocarbons but the CO_2 values matched the value measured from sampling ports adjacent to UCR's ports. With no trace hydrocarbons reported from the TDS tubes or the SUMMA canisters, meant that the data collected for C_1-C_8 analyses are not available for this study. All data on C_1-C_{12} speciated hydrocarbons provided in the report is thus given as measured $\mu g\ m^{-3}$ as opposed to EI data.

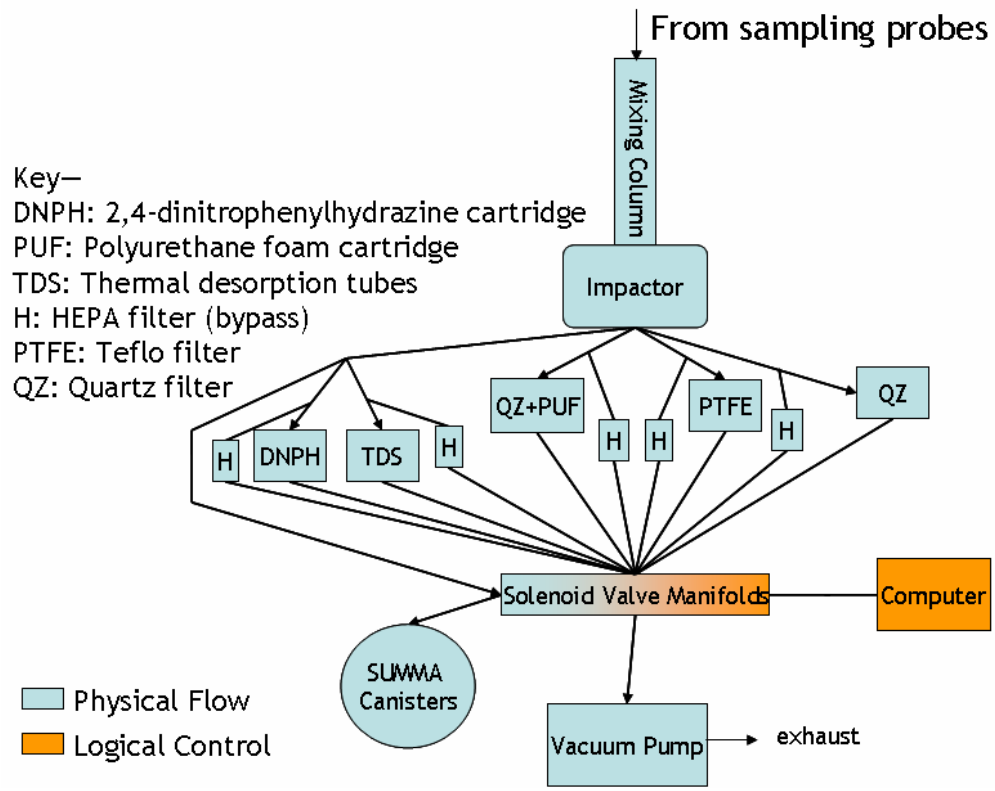


Figure 54: Schematic of Flow Patterns in the Sampling System

The observations during the testing were:

- In-field and post test calibrations indicated design flow through the sample lines.
- Recorded data of continuous ΔP logs across the critical flow orifices show critical flow during the test.
- Continuous temperature logs indicated the quartz and Teflon sections near the inlet were hot and remained hot during the testing.
- CO_2 values in the recorded SUMMA canisters that showed any CO_2 were the same as measured by the adjacent NASA probes.

Based on the calculated EIs, for the light hydrocarbon and carbonyl VOCs, we believe there was a leak in the low-flow section of the sampler. Since the critical flow devices and the laminar flow element showed the flow matched design, we presume a leak occurred upstream of the laminar flow element. This conclusion is consistent with the observation that the carbonyl EI values were closer to the expected values than values for the desorption tubes. However, we were not able to determine the size of the leak and subsequent dilution so as to adjust the data set.

A small leak in the low-flow side would not affect the other data and there are a number of confirming measurements that indicate the samples collected on the Teflon and quartz pathways were correct. First, PM mass matched values from the quartz filters and second,

UCR values were similar to those reported by UMR, especially if the UCR values are increased by the 30% correction factor used by UMR. This is not surprising since a small leak in the low-flow side would not affect the EIs calculated in the high-flow side. Thus EI values for PM mass, EC, OC, ions, or the semi-volatile hydrocarbons should be accurate and unaffected by a small leak near the TDS.

Given the field checks, how could a leak go undetected? The overall system was checked in the field for leaks and the leak rate. The resultant value was within 0.5% of the maximum flow (or 1LPM) as specified by the International Standards Organization (ISO). However, the whole system was checked and the field procedure only assured that the major flow lines were leak-free, rather than applying the 0.5% to the flow in the TDS tubes. In any case, note that a small leak found in a 0.2 LPM line is unlikely to show up in this procedure. Further it will not affect a line flowing over 50LPM. Thus a small leak in the vicinity of the TDS collection tube would be consistent with the flow and analytical results.

3.3.11.2 Implications for Carbonyl Analysis

For JETS APEX2, UCR's and ARI's EIs for formaldehyde, acetaldehyde and the ratio are shown in Table 50. The goal of presenting this table was to look for opportunities to scale the UCR data. Several results are evident from the table. One is that a single scaling factor did not exist between the ARI and UCR data set, in fact the scaling factor varied in an unpredictable manner. The other observation was that most of the data for N429WN were suspect due to the very low carbonyl recovery. However, the UCR ratios of acetaldehyde to formaldehyde at idle agreed with the published value of Spicer and we believe the remaining carbonyl values for those samples are accurate.

Table 50: Comparison of UCR and ARI Data for Carbonyls

		Formaldehyde EI (g/kg fuel)		Acetaldehyde EI (g/kg fuel)		Acetaldehyde EI/ Formaldehyde EI ratio	
Aircraft	**Mode**	**UCR**	**ARI**	**UCR**	**ARI**	**UCR**	**ARI**
N435WN	Mode 1	0.0791	0.4802	0.0272	0.2215	0.34	0.46
	Mode 2	0.0017	0.0019	0.0012	0.0036	0.69	1.91
	Mode 3	0.0016	0.0013	0.0012	0.0027	0.78	2.07
	Mode 4	0.0019	0.0020	0.0024	0.0032	1.24	1.56
N353SW	Mode 1	0.0492	0.4491	0.0170	0.2092	0.35	0.47
	Mode 2	0.0080	0.0020	0.0006	0.0030	0.07	1.49
	Mode 3	0.0070	0.0012	0.0008	0.0030	0.11	2.41
	Mode 4	0.0049	0.0018	0.0025	0.0036	0.51	1.95
N695SW	Mode 1	0.1140	0.4991	0.0304	0.2328	0.27	0.47
	Mode 2	0.0055	0.0134	0.0015	0.0029	0.28	0.22
	Mode 3	0.0023	0.0103	0.0010	0.0029	0.42	0.29
	Mode 4	0.0027	0.0073	0.0020	0.0024	0.73	0.33

N429WN	Mode 1	0.0008	0.7098	0.0008	0.3341	1.04	0.47
	Mode 2	0.0010	0.0069	0.0010	0.0065	0.97	0.94
	Mode 3	0.0044	0.0015	0.0009	0.0035	0.20	2.32
	Mode 4	0.0068	0.0005	0.0024	0.0036	0.35	7.11

3.3.11.3 Implications for Light Hydrocarbon Analysis

Data from the thermal desorption tubes were analyzed for light hydrocarbons from butadiene to naphthalene (C_4 to C_{10}). The amount of light hydrocarbons collected was found to be above the minimum detection level but much less than that observed in APEX1. By way of example, Figure 55 shows chromatograms for similar volume samples from APEX1 and JETS APEX2. For benzene, the measured level at JETS APEX2 was found to be about 30 times less than that at APEX1.

Ambient benzene levels at JETS APEX2 ranged from 0.1 to 0.2 ppbv based on the canister readings. Values measured in the TDS ranged from 0.02 to 1.10 ppbv. As for the carbonyl data, the jet exhaust sampled with the TDS tubes was diluted by an unknown amount of ambient air. As the scaling factor determined from APEX1 would be about 30, it did not seem prudent to adjust the raw data. Some example numbers are presented in the Table 51.

Table 51: Benzene and Toluene concentration data from JETS APEX2

Aircraft	Mode	benzene (µg/m3)	toluene (µg/m3)
N435WN	Mode1	0.64	0.48
	Mode2	0.015	0.03
	Mode3	0.056	0.054
	Mode4	8.19	7.31
N353SW	Mode1	0.053	0.065
	Mode2	0.155	0.154
	Mode3	0.027	0.025
	Mode4	BDL	BDL
N695SW	Mode1	1.52	0.732
	Mode2	0.325	0.407
	Mode3	0.044	0.056
	Mode4	0.151	0.108
N429WN	Mode1	3.456	3.631
	Mode2	0.172	0.232
	Mode3	0.009	BDL
	Mode4	0.066	0.036

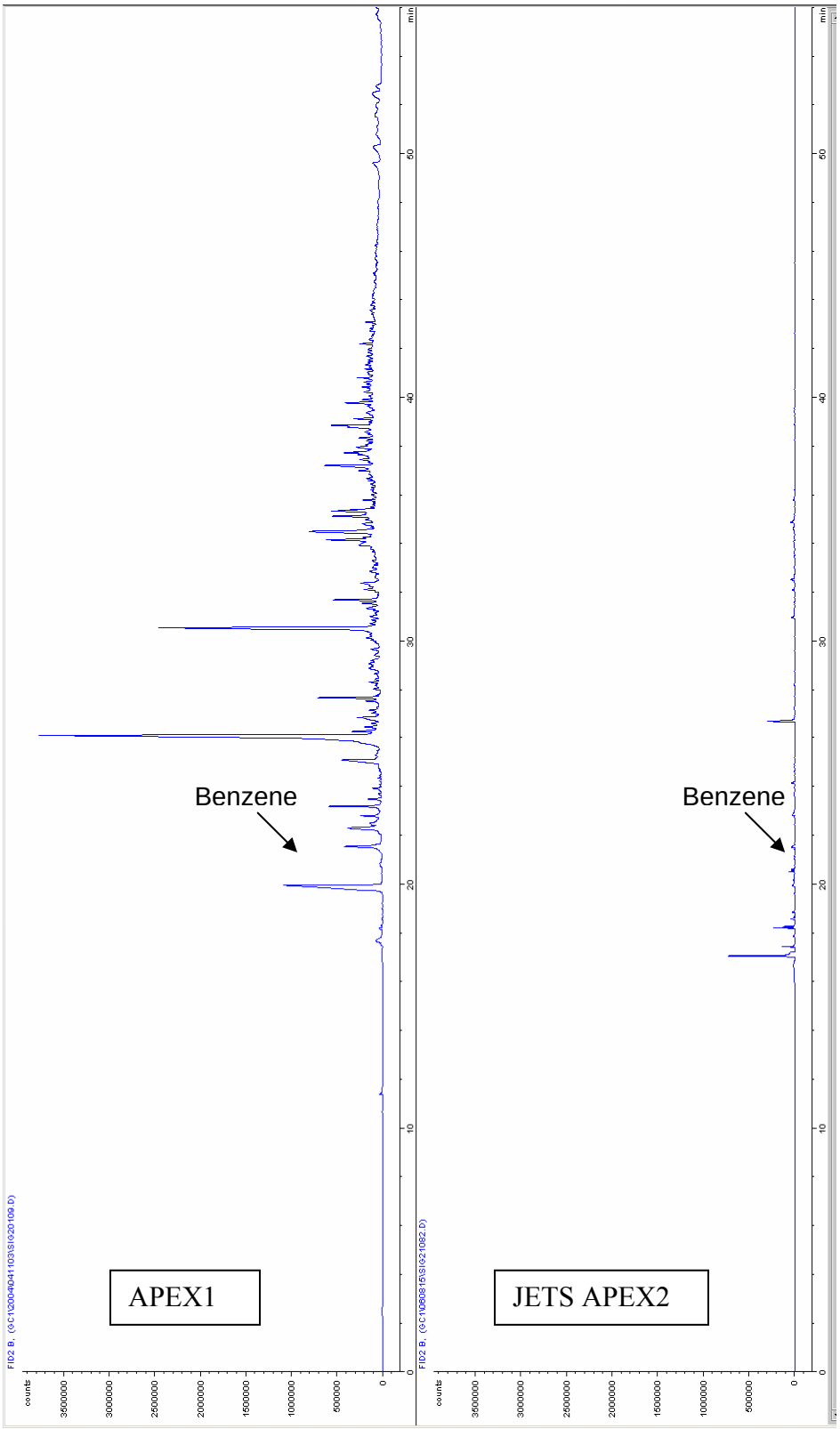


Figure 55: Comparison of Light Hydrocarbons Measured with TDS in APEX1 and JETS APEX2.

3.3.12 UCR QA/QC Protocol

The contributions of UCR were focused in two areas. One was the development of the sampling system to match the engine test cycle (see Figure 11) and the other contribution was the sampling and off-line analysis of the speciated hydrocarbons and speciated PM. Both areas were given considerable thought on the QA/QC.

Sampling System

The original plan for the quality control and quality assurance of the sampling system was designed at two levels, since the sampler was a complex assembly of mechanical and electronic equipment with a computer precisely controlling all the equipment to fit within the sampling window allowed by the selected test cycle. Because this sampler was quite complex and the first-of-a-kind design, quality control runs at UCR were planned to compare the measured values with those measured in UCR's recognized mobile emissions laboratory. Quality assurance in the field was to follow the protocol outlined in ISO 8178-1 Chapter 8-4 "Leakage Test". This planned quality check could not be implemented because construction of the complex sampling system was completed at the Oakland airport the day before testing began.

However, once the sampling equipment was assembled, UCR did perform the second level of quality assurance testing as specified in ISO: "The maximum allowable leakage rate on the vacuum side shall be 0.5 % of the in-use flow rate for the portion of the system being checked." Early trials indicated the leakage rate exceeded the allowed value and the sampling system was made leak tight by sealing leaks on the pipe threads with epoxy resins. Other components in the sampling system were leak tight. The system easily passed the ISO leakage rate specification after the repairs. The leakage rate was checked against the whole system flow of 200 LPM and not against the smallest flow component of 0.25 LPM where the Thermal Desorption Tubes were located. Other reports in the literature with similar sampling systems apply the QA test in the same manner as UCR did but the test should have been applied to the lowest flow element in the system.

Chemical Collection and Analysis

A key element in the quality plan was to build a number of redundancies in the collection and analyses of the exhaust since the samples were quite difficult to collect and so few data existed in the literature. Some of the redundancies are illustrated in the Table 52 below. ARI was collecting selected hydrocarbons from the mixtures collected and analyzed by UCR.

All data, except for the VOCs, was successfully collected and collaborated against the redundant measurement. For example, Teflon mass was matched with the combination of EC plus OC from the quartz filter and also by the values calculated from the UMR instruments. However, for the VOCs, both the SUMMA canisters and the thermal desorption tubes failed to provide the expected results.

Table 52: Species measured by UCR and ARI

Species	UCR1	UCR2	ARI
VOCs (C1-C6)	SUMMA (C1-C6)	TDS (C3-C8)	Some with TDL (C2)
Carbonyls	DNPH		TDL (formaldehyde) PTR-MS
SVOCs	Quartz 1	Quartz 2	
PM mass	Teflon	Quartz 1&2	UMR mass
PM EC/OC	Quartz 1	Quartz 2	
Ions	X-ray	Ion chromatography	

Quality control in the laboratory

Samples collected in the field were analyzed in the laboratory. From an overview perspective, there are numerous quality control and quality assurance procedures built into the operation of UCR's analytical lab. Documentation of the analytical methods and results include Standard Operating Procedure (SOPs) or each method, Checklists, Log Books, Data Files, Reports to Management, and Reports to Clients.

The quality control program involves the use of standards and quality assurance is achieved by monitoring the repeatability of the standards and whether the standards are within the expected range or showing a bias; other corrective actions are carried out to bring the analysis back into statistical control.

As an example for the balance measuring the mass on a Teflon filter, checklists are maintained for

- Start-up
- Calibration
- Shutdown
- Test operations
- Test QC

Other very detailed information is documented for the operation of the balance used for Teflon mass. Selected excerpts follow:

Special Training Requirements for Balance Room Technicians

Balance room technicians are generally students or other part time workers. The technicians must be able to weigh substrates with quantifiable accuracy and precision. To accomplish this, balance operations are conducted following very specific protocols that produce substantial amounts of QC data. It takes practice and experience to follow these procedures correctly. New technicians are given practice sets of substrates for weighing, and practice following the balance protocols. The technicians report results for the practice sets to the Project Manager. The Project Manager evaluates the practice results and identifies any problems. Problems are corrected and the new technicians try again with a new practice set, until Project Manager is satisfied that they are able to follow the protocols correctly.

Sample Handling and Custody of PM samples

Particle samples are collected on Teflon filters. The use of particle filters requires numerous sample handling and custody issues to prevent contamination, to ensure proper sample identification, and to ensure equilibration requirements of the CFR. Throughout the procedures, filters are handled only using forceps. The filters never leave the custody of CE-CERT. The steps involved are as follows:

- unused filter numbers are assigned to new plastic Petri dishes
- new filters are placed into the numbered plastic Petri dishes
- the Petri dishes with unexposed filters are placed into a temperature and humidity controlled equilibration chamber
- after 12 hours the filters are weighed
- filters are reweighed daily until two filter weights within 3 μg of each other
- filters with consistent weights are transported for testing
- prior to the test, filters are transferred from Petri dishes to filter holders at the test site, the filter ID numbers are recorded on the particle Filter Data log sheet
- at the end of the test filters are returned to their original Petri dishes
- the Petri dishes of the exposed filters are marked with an X
- the filters are returned to the balance room and placed in the equilibration chamber and equilibrated 12 to 72 hours
- the exposed filters are weighed once daily until two weights with 3 μg are obtained

The procedures for weighing the filters are detailed in Balance Protocol A1 R1.1 Appendix C. These procedures define specific detailed sequences for checking and recording the equilibration chamber conditions, zero and spanning the balance, weighing reference objects, weighing filters, performing zero and span checks, performing replicates. In summary, filter weights are only considered valid if environmental chamber conditions are within tolerance, and the filter weight was preceded and followed by a valid zero and valid span.

For future projects

For future efforts to measure organic compounds under similar field conditions, the following should be considered:

- Begin and complete the design, fabrication and checkout testing of the sampling system well before the field campaign begins; this will allow time to correct any problems before the system is required for use
- Analyze a statistically significant subset of samples as soon as possible after collection, and before completion of the field campaign; this will allow detection of invalid samples while time remains during the campaign to correct any problems and to obtain valid samples
- Wherever possible, replace batch sampling techniques with more advanced instrumentation that provides real-time measurement capabilities; this will allow evaluation of sampling system performance during test operation.

The leak in the sampling system would have been detected and corrected if this protocol had been followed, and the desired organic compound data would have been obtained.

4.0 Discussion

4.1 Gaseous Emissions

NOx, CO, and specific hydrocarbon species were measured for seven different engines representing three engine models.

NO_x and CO were generally consistent with both ICAO data for the CFM56 engine models and with the corresponding NO_x and CO data acquired on a different CFM56 engine model measured in the APEX1 campaign. CO data had significant variability due to variation in ambient conditions affecting the engine performance, but APEX1 data analysis has suggested that this variation can be reduced significantly when fuel flow variations are properly accounted for. Fuel flow data was not available from these tests, so these corrections have not been made for the data presented here. While generally consistent with ICAO data in trends (decreasing with increasing engine power) and magnitude, the CO emissions for two engine models are below the regulatory values.

NO_x emissions also agree well with the trends in ICAO data (increasing with increasing engine power) and agree well in magnitude for each engine model. Some decreases in NO_x EIs at the downstream measurements locations were observed and this warrants further analysis.

Selected hydrocarbon species were measured in real-time for all of the engines studied. Formaldehyde (HCHO) is one of the most prevalent and it demonstrates a decreasing trend with increasing engine power as does the Unburned Hydrocarbon (UHC) data in the ICAO data. As was observed in APEX1, the measured emission indices for individual HC species decrease in proportion with HCHO as the engine power increases, suggesting that HCHO (or other major HC emissions like ethylene, C_2H_4) is a good indicator for HC emission levels. In addition, the ratio of the individual HCs to HCHO all agree reasonably well with the landmark data of Spicer et al., (1994) on speciated HCs in the CFM56 engine. The major deviation from excellent agreement with Spicer is that several species (notably the higher alkenes, as well as C4 benzenes, and phenols), where the present measurement are significantly higher than Spicer et al. The question of potential loss mechanisms in the Spicer approach may need to be considered. Either chemical transformation (oxidation) or incomplete desorption from the concentration devices used in those measurements could potentially result in reducing the reported levels for the higher alkanes in those earlier studies, but the actual causes for these discrepancies are currently unknown.

4.2 Particulate Emissions

Black Carbon (BC) measurements were made using a Multi-Angle Absorption Photometer (MAAP) for all seven engines. All demonstrated a similar trend, increasing with increasing engine power, especially above 60% rated thrust (although there is also a minor increase in BC when the power decreases to the very lowest idle powers). The

newer engine designs (-7B22) had lower emissions than that of the APEX1 engine (–2C1).

The volatile contributions to the particulate emissions were measured with an Aerosol Mass Spectrometer (AMS). Sulfate and organic contributions were identified and quantified. The sulfate contribution was largely independent of engine power, and was similar to levels observed in APEX1 when compared at 30 or 50 m downstream locations. Sulfate in the particle phase is dependent on the level of sulfur in the fuel, and the overall sulfate levels are expected to correspond to the fuel sulfur levels. The organic contributions were generally significantly lower than APEX1, which requires further analysis but, like APEX1, the contributions have a local maximum at the lowest power conditions when HC emissions are highest. Another increase occurs at the highest power and, although the increase is more dramatic in APEX1 than in the current tests, this increase is most evident at the furthest downstream location.

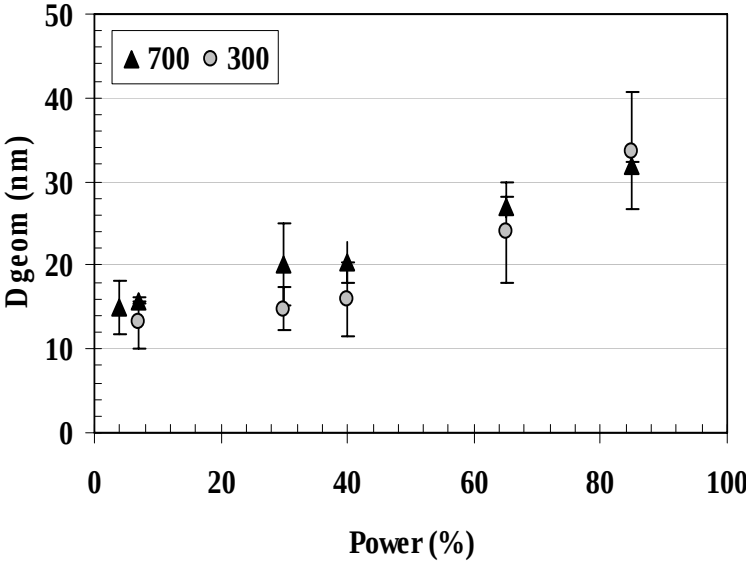
4.3 PM Physical characterization

One objective of the JETS APEX2 study was to perform a PM emission comparison between old (-300) and new (-700) technology engines currently powering the B737 commercial fleets. A first step in doing this is to examine the variance in PM emissions within a technology type and the second is then to determine whether any engine technology differences are statistically significant for a given PM parameter. It should be noted that the sample size per technology type was extremely small (3 engines per type) and this may make it difficult to discern subtle differences. However, it should also be noted that this study was the first of its kind where multiple engines within a given technology type were made available for measurement.

Figures on the left below (Figures 56a - 60a) present the technology type average PM parameter data (total aerosol) as a function of engine power at 1m measured at JETS APEX2. The triangles represent new technology and the circles represent the old. The error bars indicate uncertainty given by 1 standard deviation in the average. Figures on the right below (Figures 56b - 60b) present the JETS APEX2 data along with the CFM56-2C1 engine data acquired at APEX1 (Lobo et al., 2007).

Dgeom

In the case of Dgeom, both engine types demonstrate an increase in Dgeom with power but no statistically significant difference between engine technologies is discernable since for all data points the error bars overlap (Figure 56a). This is also the case for the CFM56-2C1 engine studied in APEX1 (Figure 56b).



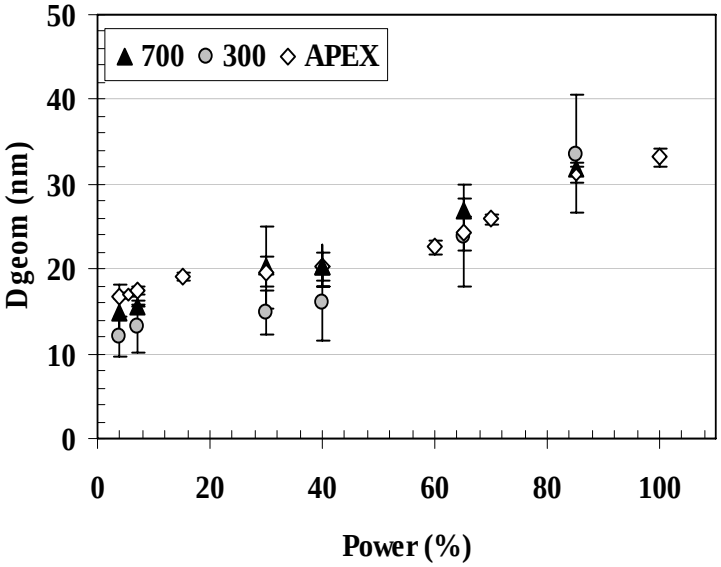


Figure 56a: Dgeom as a function of power for -300 and -700 series.
Figure 56b: Comparison with APEX1 data

Sigma

In the case of Sigma, both engine types demonstrate a weak positive trend with power but no statistically significant difference between engine technologies is discernable (Figure 57a). This is also the case for the CFM56-2C1 engine studied in APEX1 (Figure 57b).

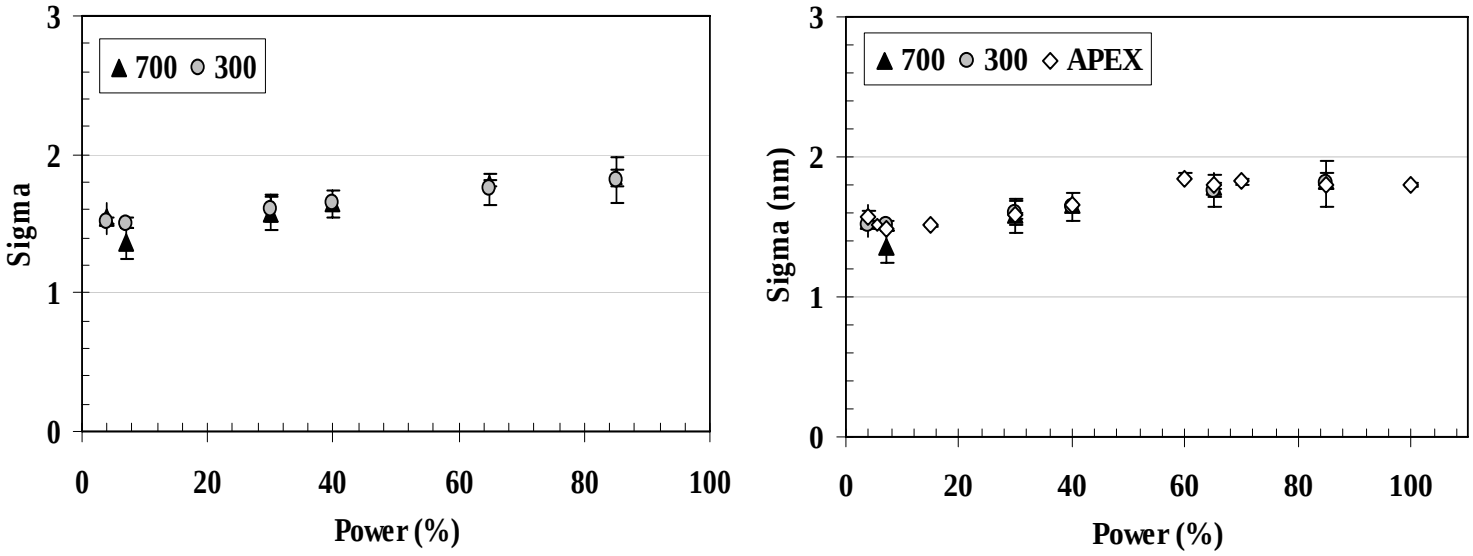


Figure 57a: Sigma as a function of power for -300 and -700 series.
Figure 57b: Comparison with APEX1 data

DgeomM

In the case of DgeomM, both engine types demonstrate an increase with power but no statistically significant difference between engine technologies is discernable (Figure 58a). This is not the case when comparison is made to the even older technology engine (CFM56-2C1) data from APEX1 (Figure 58b). On average, the DgeomM value for the CFM56-2C1 engine exceeds that for the engine studied in JETS APEX2 by ~60%.

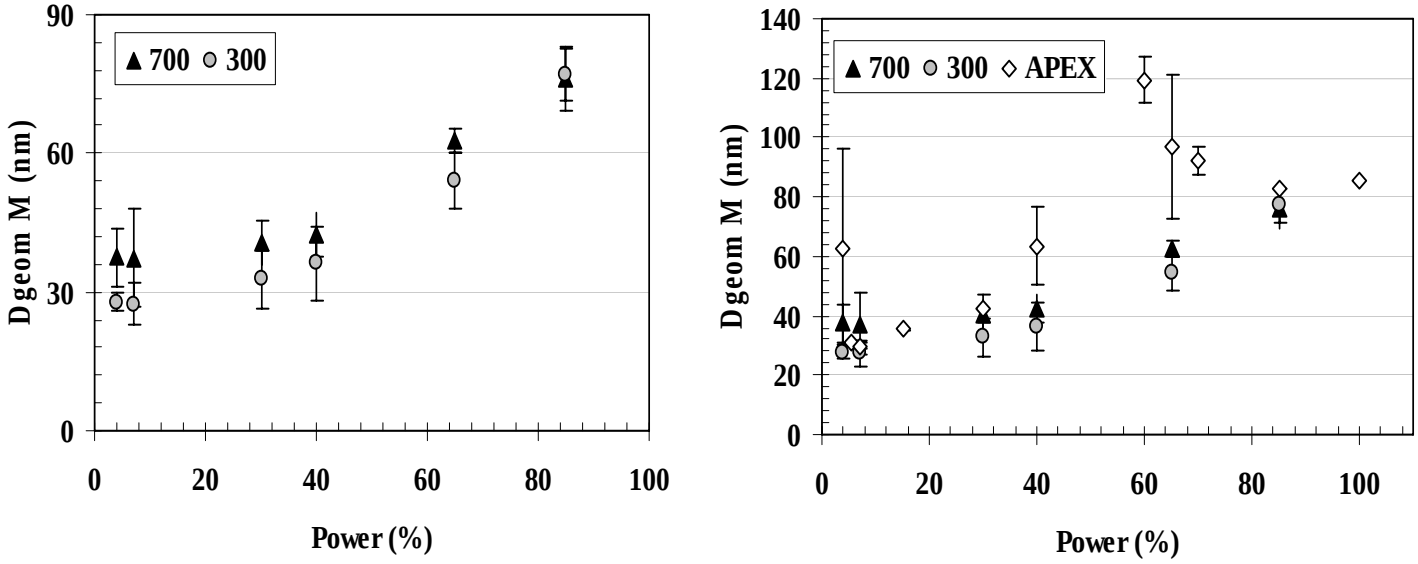


Figure 58a: DgeomM as a function of power for -300 and -700 series.
Figure 58b: Comparison with APEX1 data

EIn

In the case of EIn, the -700 and -300 engine types demonstrate a minimum ~ 20% power (Figure 59a). The new technology engines produce fewer particles per kilogram of fuel burned. This difference is large and statistically significant. Averaged across all powers, this difference represents a (79 ± 12) % reduction in number-based emissions normalized to fuel flow.

EIn for the APEX1 engine falls between those of the -300 and -700 series and the differences between all engines are statistically significant at higher powers (Figure 59b).

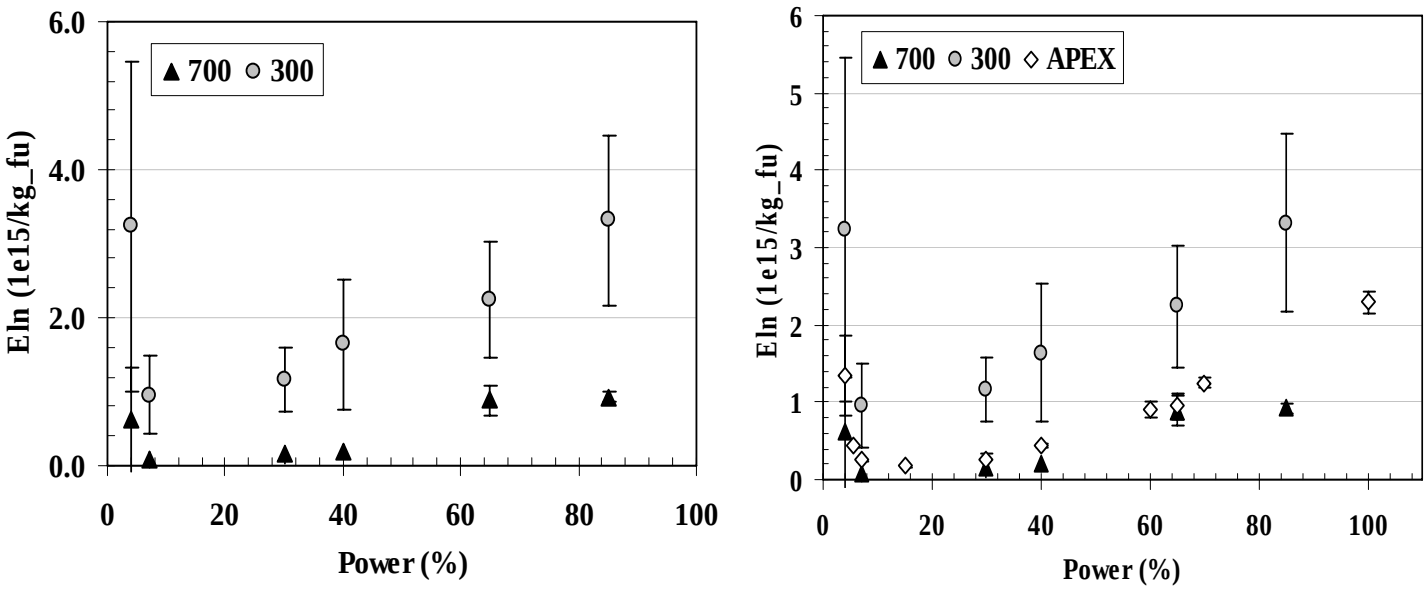
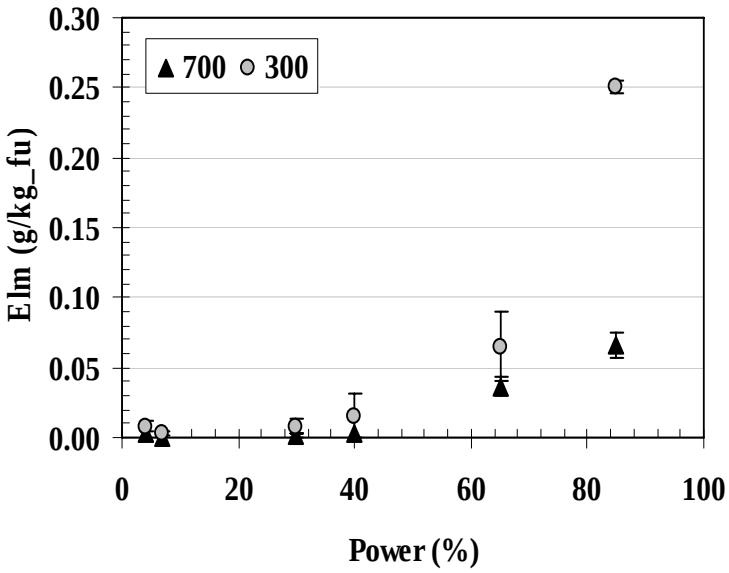


Figure 59a: EIn as a function of power for -300 and -700 series.
Figure 59b: Comparison with APEX1 data

EIm

Mass-based emission index exhibited a trend to increase with power. The trend is stronger for the older engine technology (-300 series). There is a large and statistically significant difference at high power representing a 72% reduction in mass-based emissions normalized for fuel flow at 85% power (Figure 60a). This is also the case for the CFM56-2C1 engine studied in APEX1 (Figure 60b).



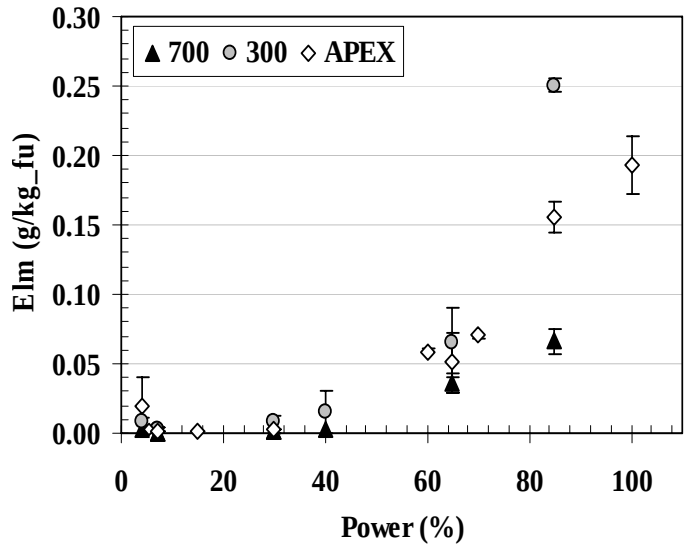


Figure 60a: EIm as a function of power for -300 and -700 series.
Figure 60b: Comparison with APEX1 data

4.3.1 Engine Warm-up Effect

Measurements of emissions were taken on each engine following the test matrix shown in Figure 61. This test sequence immediately followed an engine cold start and nominal 5 minute warm-up period. Measurements began only after the engine operator declared the engine stable. An unanticipated effect associated with engine warm-up was observed. The number-based emission indices, EIn, for a given operating power were observed to decrease with engine on-time. This effect is clearly demonstrated in both 1m and 50m data sets. Figure 61 is a typical example observed on a -700 series engine when the exhaust was sampled at 50m. To illustrate the time dependent nature of this data, each test matrix point is given a chronological sequence number and this number is used to label the appropriate data point in Figure 61. Sequence numbers 1-6 were taken during the time power was incrementally increased (left side of the test matrix), and sequence numbers 7-11 were taken as power was incrementally decreased. Thus sequence numbers 1 and 11 indicate emissions taken at the same engine operating power (4%), but separated

in engine on-time by a period of ~100 minutes. The difference in EIn for this 4% case represents a 63% reduction in number-based emissions normalized to fuel flow. The absolute reduction at 40% power was found to be 64%.

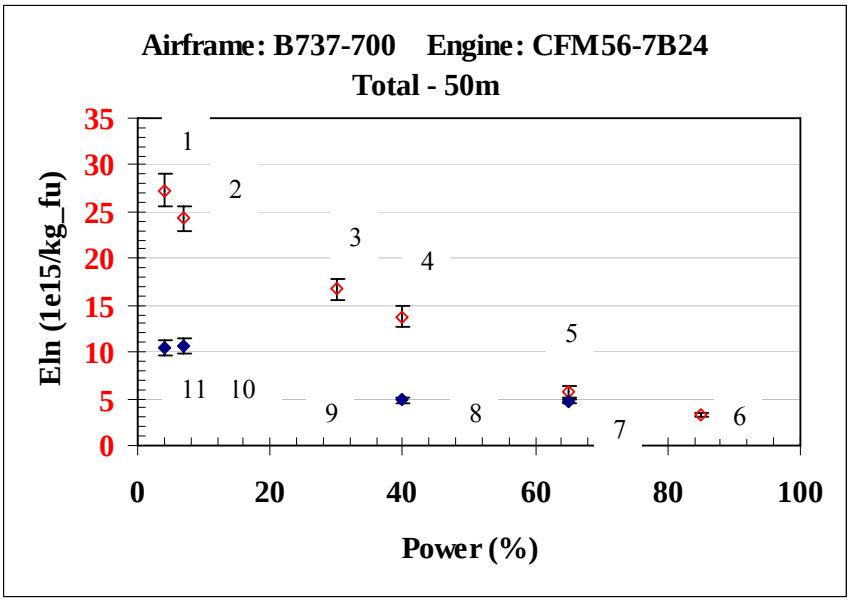


Figure 61: Example of the warm up effect observed on a -700 series engine when the exhaust was sampled at 50m

4.3.2 Discussion of aerosol volatility at 1m

The exhaust temperature is too high at the 1m sampling location to allow the formation of volatile material. Hence only the non-volatile aerosol is considered here in this comparison of the 300 and 700 series engines.

Dgeom

There was no statistically significant variation in mean particle size for either engine technology. At all power settings, except for the 65% case, the 1-sigma error bars overlap for the data points from the two engine classes. The error bars almost overlap at the 65% point.

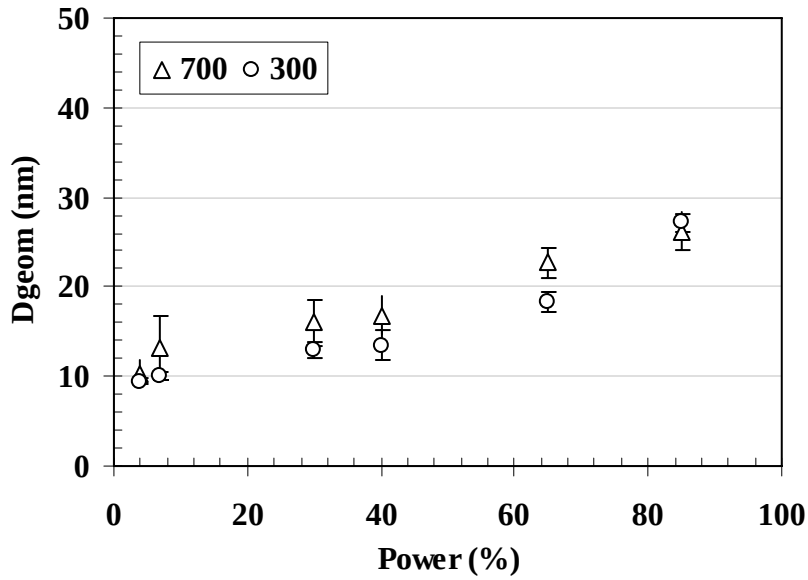


Figure 62: Comparison of Dgeom for the non-volatile aerosol at 1m as a function of power for the -300 and -700 series

Sigma

No statistically significant variation in the width of the particle size distribution for either engine technology was observed. The error bar overlap is very pronounced and holds at all engine powers.

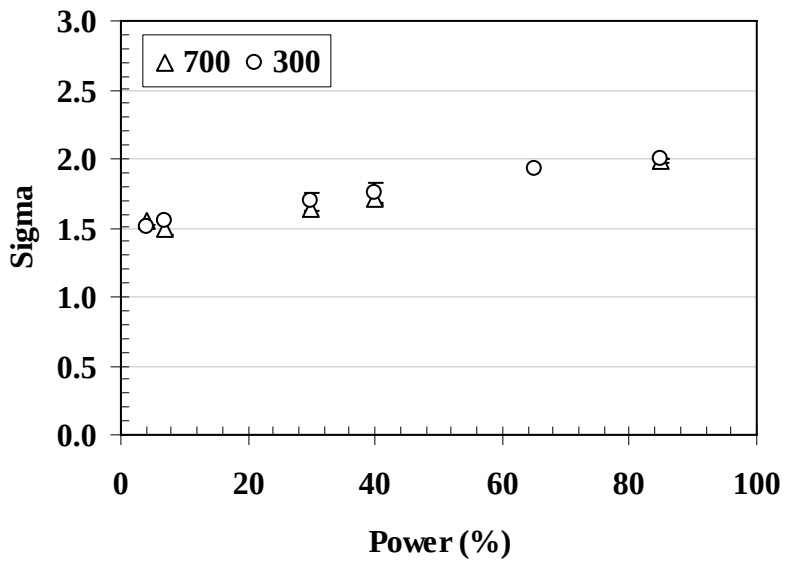


Figure 63: Comparison of Sigma for the non-volatile aerosol at 1m as a function of power for the -300 and -700 series

DgeomM

There was no significant difference in mass-based mean particle size between engine technologies. The error bars overlap except for a slight separation at the 65% power setting.

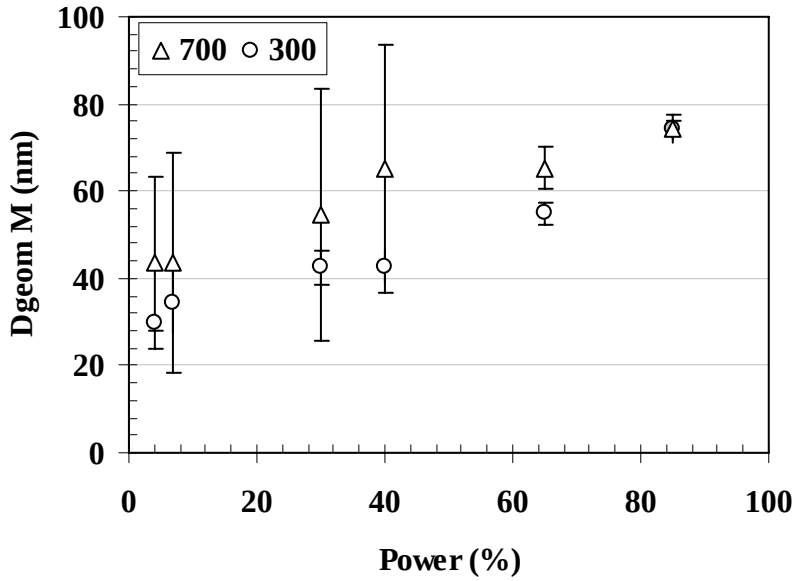


Figure 64: Comparison of DgeomM for the non-volatile aerosol at 1m as a function of power for the -300 and -700 series

EIn

Statistically meaningful differences in EIns at mid and high powers were observed with the older technology engines demonstrating larger values. The newer technology engines are cleaner with respect to particle number.

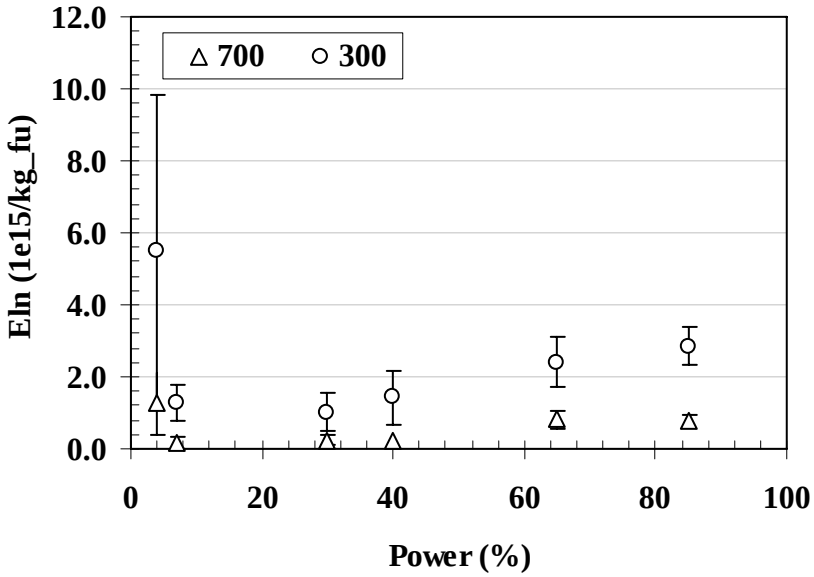


Figure 65: Comparison of EIn for the non-volatile aerosol at 1m as a function of power for the -300 and -700 series

EIm

Statistically meaningful differences are observed at high power with the older technology engines demonstrating larger EIms. The newer technology engines are cleaner with respect to particle mass.

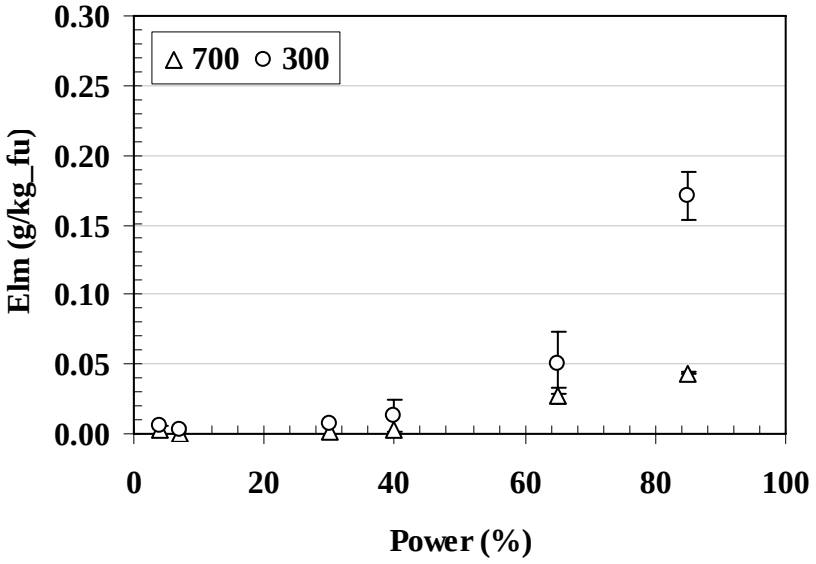


Figure 66: Comparison of EIm for the non-volatile aerosol at 1m as a function of power for the -300 and -700 series

4.3.3 Comparison of 1m Total and Non-volatile Aerosol Data

A comparison of total and non-volatile aerosol parameters – Dgeom, Sigma and DgeomM for the -300 and -700 series engines are presented in Figure 67 and a similar comparison for EIn and EIm are presented in Figure 68.

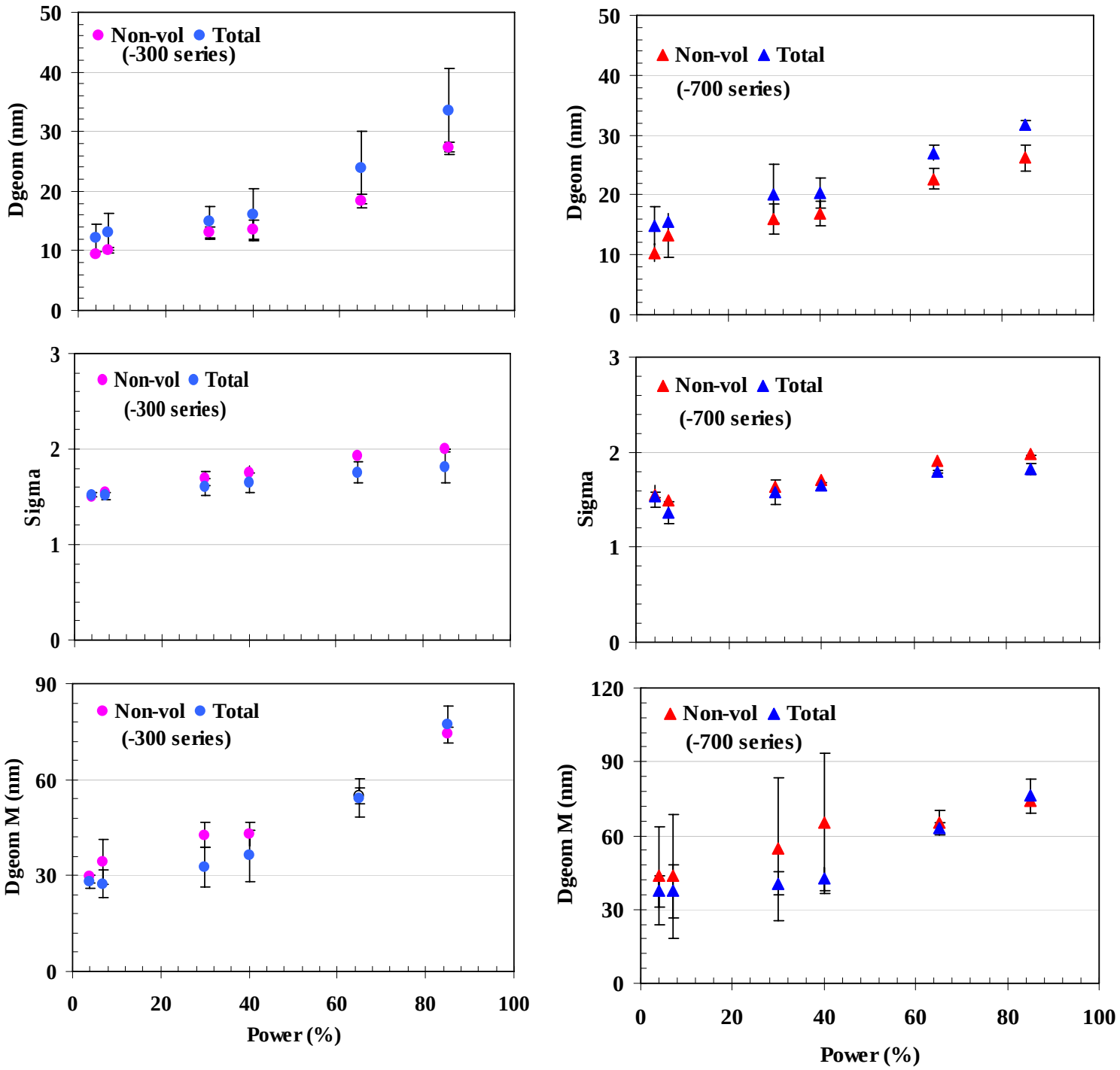


Figure 67: Comparison of total and non-volatile aerosol parameters – Dgeom, Sigma and DgeomM for the -300 and -700 series

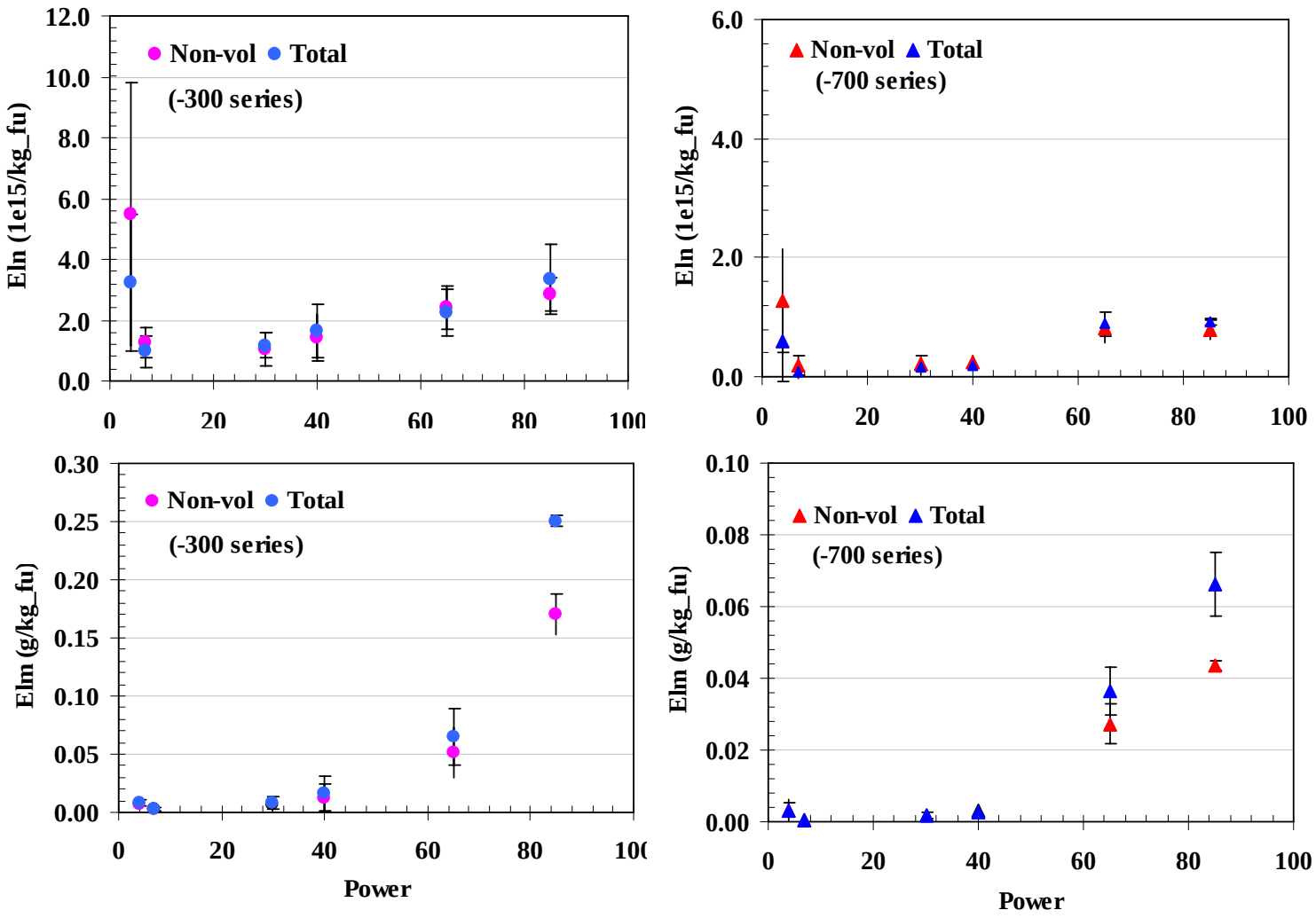


Figure 68: Comparison of total and non-volatile number and mass-based emission indices for the -300 and -700 series

The data for the total and non-volatile aerosol are in good agreement with each other except for a difference observed at the highest power condition for Dgeom and EIm. Good agreement would be anticipated since no condensation can occur before sample capture at the 1m location. Differences in Dgeom and EIm at the highest powers indicate minor line processing under these conditions may have taken place.

4.3.4 Effect of plume processing (difference between 1m and 50m)

The exhaust sample is diluted with relatively cold ambient air as it travels away from the engine exit, and the lower mixed gas temperatures can trigger gas-to-particle conversion processes (nucleation and condensation) leading to the formation of large numbers of

volatile particles and volatile coatings on the original soot particles. The nucleation processes tend to create small particles and the volatile coatings on soot tend to be thin; hence the left side of the size distribution is impacted more than the right side. The production of these small particles serves to shift Dgeom to smaller values and results in an order of magnitude increase in EIn. These particles do not significantly contribute to the mass dependent parameter values and no significant changes are observed in DgeomM and EIm. It should be noted that the sample experiences ambient temperature and pressure as it passes through the large diameter (5cm) 50m sample line. No further dilution is imposed on the sample beyond that which naturally occurs during plume expansion in transit to the 50m sampling probe. Under these conditions, it is reasonable to conclude that any gas-to-particle conversion in the sample line merely mimics that which would have occurred in the atmosphere. This plume processing is a major effect. Typically the downstream aerosol is substantially different from that found at the engine exit. It should be noted that the final downstream aerosol depends not just on the engine emission characteristics (gas + particulate), but also strongly on the ambient air conditions (e.g. temperature and humidity).

4.4 Organic gases and aerosol chemical speciation

Dramatic increases in the PM concentrations are observed as the power increased to 85% power. The relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer et al.1992, 1994 (see Figures 48, 49). There was a sharp decrease in the relative contribution of substituted naphthalenes at the higher load points. Trends in the non-naphthalenic compounds are also noted with acenaphthylene, present significantly only in the idle mode, and fluoranthene decreasing with increasing power.

With respect to Chromium (VI), results for the aircraft were as expected, except for the sample from N429WN which showed a large response for Chromium (VI). It is important to note that the sample from N429WN was only one of 6 samples collected by UCR that had high chromium (VI). The variability in the metal distributions was much greater between engines than between engine loads (see Figure 52).

The mass of the ions collected on the Teflo filter were so low that only sulfate ions were above the detection limits of the instrument. In the case of the sulfate, the extracted ions (<1 ppm in water) were very close to the lower detection limit of the instrument.

Analysis of the DNPH cartridges and SUMMA canisters revealed anomalous CO_2 concentrations which were attributed to a leak in a sub-system of the sampler. Consequently emission factor calculations could not be performed since any dilution taking place in these filter media were no longer quantifiable. As a result, only the mass concentration of species was measured. The major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone. Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions.

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5.0 Summary and Conclusions

The objectives of the JETS APEX2 study were to produce a comprehensive data set of emission factors for total organic gases and PM for old and new technology CFM56 class engines operating out of a medium size hub airport in the State of California (i.e. Port of Oakland). This study was successful in producing the first state of the art measurements for PM physical characterization of in-service CFM56 type engines. Unfortunately, as a result of the failure of one of the non-real-time sampling systems, the TOG analysis was limited and from that perspective not all of the objectives set out in the proposed effort were accomplished. However, even with the limited TOG data this study represents the first extensive physico-chemical analysis of a series of in-service commercial engines and as such is an extremely valuable dataset. This study is part of a greater multi-agency effort that includes emissions measurements downwind of an active runway at Oakland during normal airport operations, and the results presented here are essential for the interpretation of the downwind measurements which is to follow (not a deliverable in the CARB-funded component of JETS APEX2). Preliminary analysis was presented at the APEX3 Conference in Cleveland, OH (Whitefield et al. 2006, Herndon et al. 2006) [these presentations can be found by accessing the URL: http://particles.grc.nasa.gov/data/apex3_conf/]

The emission factors reported here lead to the following conclusions:

- Measurement of NOx indicated that the general emissions performance of the engines was in keeping with certification measurements for the engines studied.
- Measurements of individual hydrocarbon species suggest that the Emission Indices for most of the major species decrease with increasing engine power, in proportion to each other, and specifically with formaldehyde, which is one of the most plentiful emitted hydrocarbons and can be measured accurately.
- The particle composition includes both sulfate and organic volatile fractions at downstream distances, adding to the carbonaceous aerosol that is present already at the engine exit plane. The sulfate contribution has little dependence on engine power, while the organic contribution is greatest at low engine powers.
- The relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer et al.1992, 1994.
- Chromium (VI) results, for all but one of the engines studied, were as expected.
- The major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone. Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions.
- The aerosol properties were calculated for the entire aerosol size distribution and not individual size modes.
- Size distributions for exit plane were generally lognormal. Strong and sometimes non-linear dependencies were observed with engine power settings.
- The onset of gas-to-particle conversion was apparent at 50m for low to medium powers. In this data non-lognormal size distributions were often observed, where the mean sizes decreased and EIn increased relative to the 1m size distributions.

- The aerosol Soluble Mass Fraction was found to increase with distance from the engine exit plane. Its value was negligible at the engine exit plane and was ~10% at 50m.

6.0 Recommendations

The results of this study proved that accurate emission factors can be acquired in a cost effective manner. Since the data is clearly engine/airframe specific, studies of this nature should now be performed on other important engine/airframe combinations e.g. B747/CF6-80.

The GRE at Oakland proved to be an ideal open air laboratory for dedicated aircraft engine emission studies in the exhaust nozzle and near field plumes for B737 commercial transports. The weather conditions and prevailing winds experienced on the east side of San Francisco Bay in late August were also favorable. These factors lead to the recommendation that the GRE at Oakland should be considered a high priority venue for any future scheduled tests.

It should be noted that the mix of transports routinely operating in and out of Oakland will limit the range of engines/airframes that can be studied. For future studies where B747, B757, B767, and B777 and the larger Airbus transports A320, A340 etc. are anticipated test vehicles, it will be necessary to consider attracting other aircraft to the Oakland test site or using GREs located at other airports provided appropriate weather conditions prevail.

In this study, engine operating conditions were recorded only once during each stable engine operating condition. In future tests it is recommended that high frequency data acquisition be employed for engine operating conditions. This may be difficult for older airframes but straight forward for newer additions to the commercial fleet that digitally record engine operating conditions.

Most of the data was gathered and initially analyzed in real-time. However, this was not the case for the UCR samples that were analyzed off-site post test. For future studies efforts should be expended to assure that the analysis could be undertaken for these samples on-site. This would provide quasi-real-time feedback on the integrity of such samples.

Engine to engine variability is difficult to estimate when the engine sample size is small (in this study ≤ 4 engines per model). The value of accurately estimating this parameter warrants the consideration of a longer period of study than the 4 days afforded this project, especially since the per-day costs are small compared to planning, preparation, set-up, and post test analysis costs.

As described in this report, valid measurements for TOG and multiple significant speciated VOCs were not obtained because of sampling and laboratory issues for the light hydrocarbon and carbonyl analyses. These measurements should be repeated at a future engine test, when the opportunity arises, to get better estimates of TOG and speciated VOCs.

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List of inventions reported and publications produced

At this time there are no inventions to report and none to be anticipated. With respect to publications, there are no publications at this time; however, several are in preparation once approval for public release of this data has been provided.

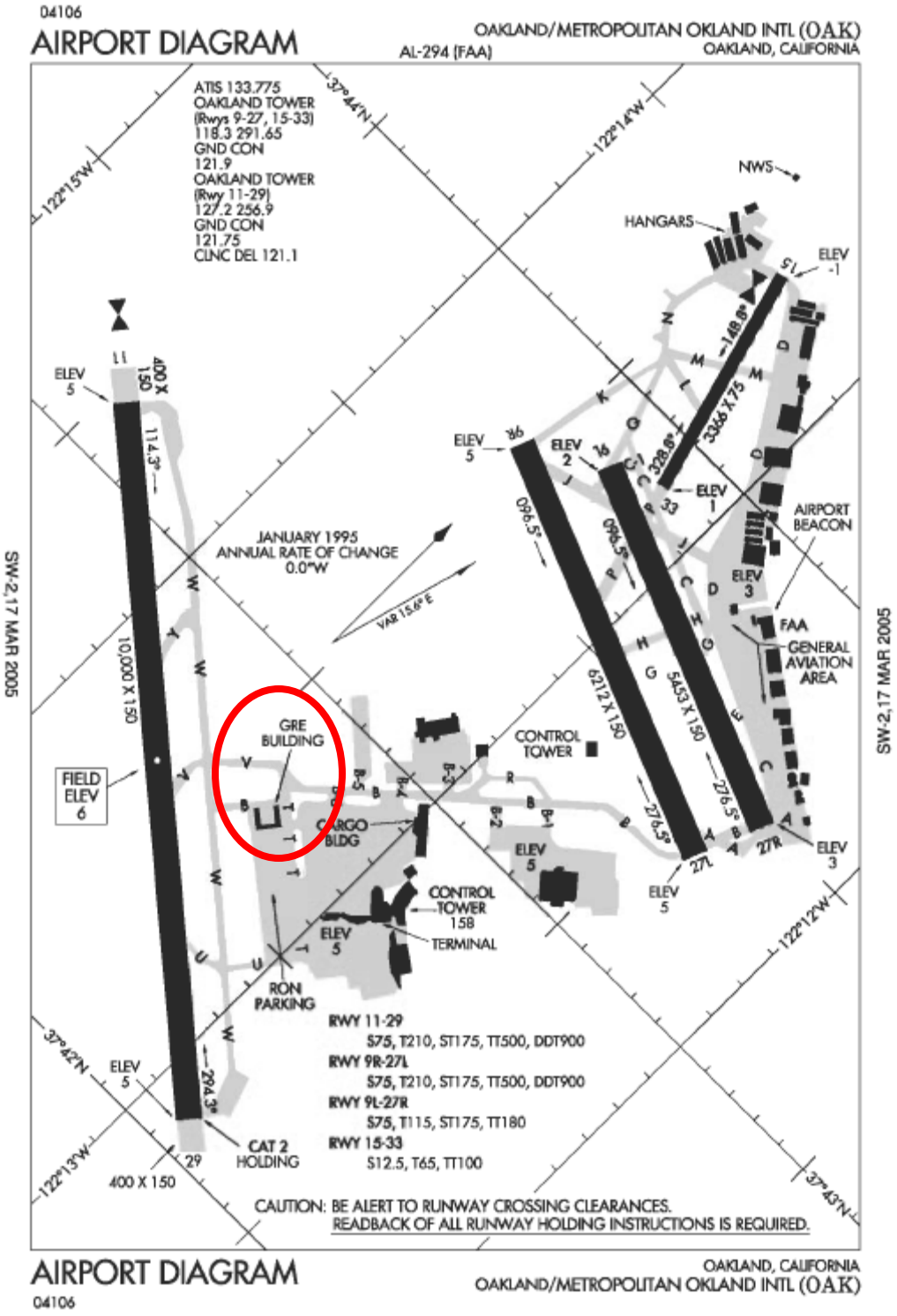
Glossary of terms, abbreviations and symbols

AMS	Aerosol Mass Spectrometer
APU	Auxiliary Power Unit
ARI	Aerodyne Research Inc.
BC	Black Carbon aerosol
BDL	Below Detection Limit
CAEP	Committee on Aviation and Environmental Protection
CFO	critical flow element
CFR	Code of Federal Regulations
CH_2O	formaldehyde
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counters
Dgeom	Number-based geometric mean diameter
DMA	Differential Mobility Analyzers
DMS	Differential Mobility Spectrometers
DNPH	dinitrophenylhydrazine
DoD	Department of Defense
EC	Elemental Carbon
EI's	emission indices
EIm	Mass-based emission index
EIR	Environmental Impact Report
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FID	flame ionization detector
GC	gas chromatograph
GC/FID	field ionization detector
GC/MS	mass spectrometer detector
GRE	Ground Runup Enclosure
GSEs	ground support equipment
H_2O	Water
HC	hydrocarbon
HCHO	Formaldehyde
HNO_3	nitric acid
HPLC	high performance liquid chromatograph
HRGC	high resolution gas chromatography
HRMS	high resolution mass spectrometry
ICAO	International Civil Aviation Organization
LPC	laser particle counter
LPM	liter per minute
LTO	landing and takeoff
MAAP	Multi-Angle Absorption Photometer
mz	mass-to-charge ratio
NASA	National Aeronautics and Space Administration
NCAR's	National Center for Atmospheric Research

NEPAIR	New Emissions Parameter
NH_4^+	ammonium
NIOSH	National Institute of Occupational Safety and Health
NMVOCs -C_2–C_{10}	non-methane hydrocarbons
NO	Nitric Oxide
n_o	total particle concentration
NO_x	oxides of nitrogen
OAK	Oakland International Airport
OC	organic carbon
PAHs	Polycyclic Aromatic Hydrocarbons
PCDD's	polychlorinated dibenzo-p-dioxins
PCDF's	polychlorinated dibenzofurans
Pen	penetration factor
PM	particulate matter
PTR-MS	Proton-Transfer Reaction Mass Spectroscopy
PUF/XAD-4	polyurethane foam
R	concentration of a HC emission component
SMF	Soluble Mass Fraction
SN	smoke number
SO_2	Sulfur Dioxide
SVOCs	semi-volatile organic compounds
SWA	Southwest Airlines
TEM	Transmission Electronic Microscopy
THC	total hydrocarbons
TILDAS	Tunable Infrared Laser Differential Absorption Spectroscopy
TOG	total organic gases
UCR	University of California-Riverside
UHCs	unburned/partially combusted hydrocarbons
UMR	University of Missouri-Rolla
UMRCOE	University of Missouri-Rolla Center of Excellence
VOC	Volatile Organic Compounds
VVOCs	very volatile organic carbon gases

APPENDIX A

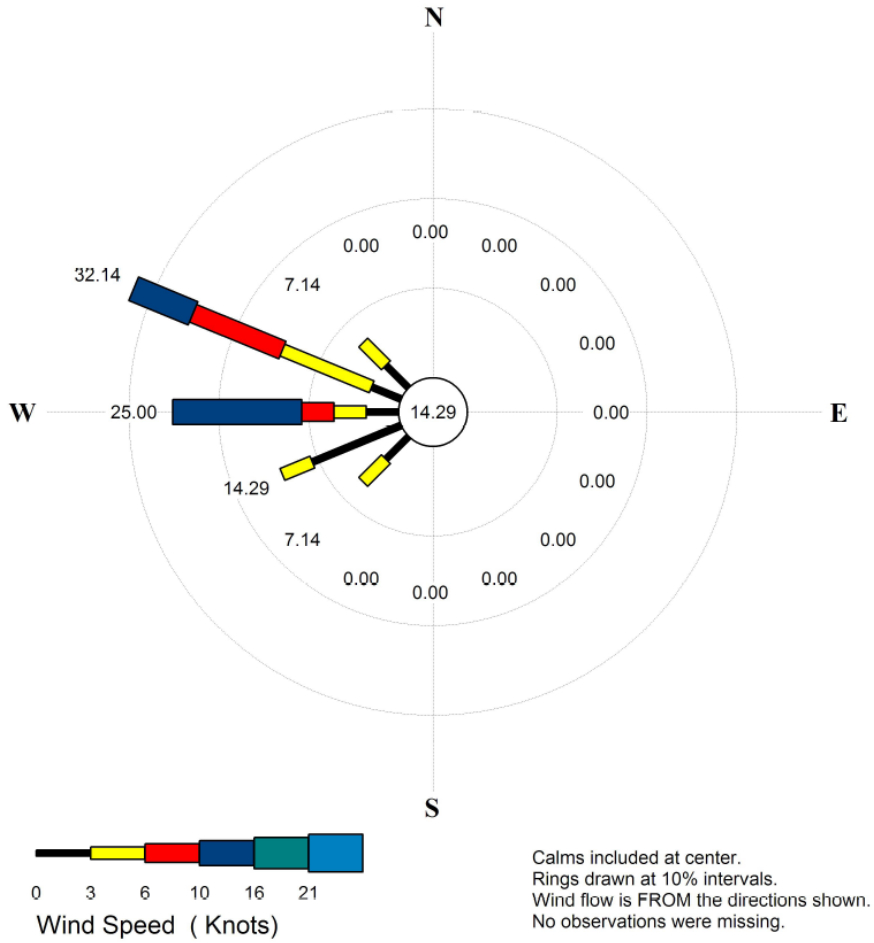
Oakland International Airport Diagram



APPENDIX B

Wind Roses (all times in Pacific Standard Time)

Wind Rose
Jets Emission Testing for Speciation (JETS)
At Oakland International Airport
August 22, 2005 from 00:00 to 23:00 hrs (1 hour averages)



Calms included at center.
Rings drawn at 10% intervals.
Wind flow is FROM the directions shown.
No observations were missing.

PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
N	0.00	0.00	0.00	0.00	0.00	0.00
NNE	0.00	0.00	0.00	0.00	0.00	0.00
NE	0.00	0.00	0.00	0.00	0.00	0.00
ENE	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00
ESE	0.00	0.00	0.00	0.00	0.00	0.00
SE	0.00	0.00	0.00	0.00	0.00	0.00
SSE	0.00	0.00	0.00	0.00	0.00	0.00

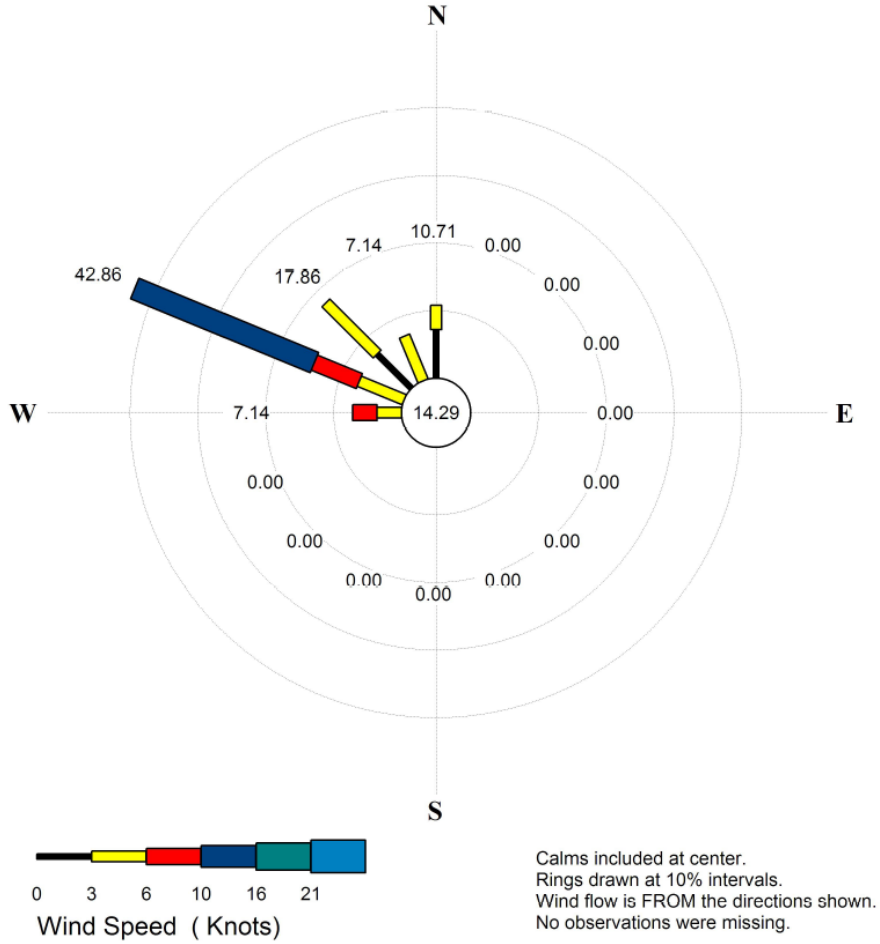
TOTAL OBS = 28 MISSING OBS = 0

PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
S	0.00	0.00	0.00	0.00	0.00	0.00
SSW	0.00	0.00	0.00	0.00	0.00	0.00
SW	3.57	3.57	0.00	0.00	0.00	0.00
WSW	10.71	3.57	0.00	0.00	0.00	0.00
W	3.57	3.57	3.57	14.29	0.00	0.00
WNW	3.57	10.71	10.71	7.14	0.00	0.00
NW	3.57	3.57	0.00	0.00	0.00	0.00
NNW	0.00	0.00	0.00	0.00	0.00	0.00

CALM OBS = 4 PERCENT CALM = 14.29

Wind Rose
Jets Emission Testing for Speciation (JETS)
At Oakland International Airport
August 23, 2005 from 00:00 to 23:00 hrs (1 hour averages)



Calms included at center.
Rings drawn at 10% intervals.
Wind flow is FROM the directions shown.
No observations were missing.

PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
N	7.14	3.57	0.00	0.00	0.00	0.00
NNE	0.00	0.00	0.00	0.00	0.00	0.00
NE	0.00	0.00	0.00	0.00	0.00	0.00
ENE	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00
ESE	0.00	0.00	0.00	0.00	0.00	0.00
SE	0.00	0.00	0.00	0.00	0.00	0.00
SSE	0.00	0.00	0.00	0.00	0.00	0.00

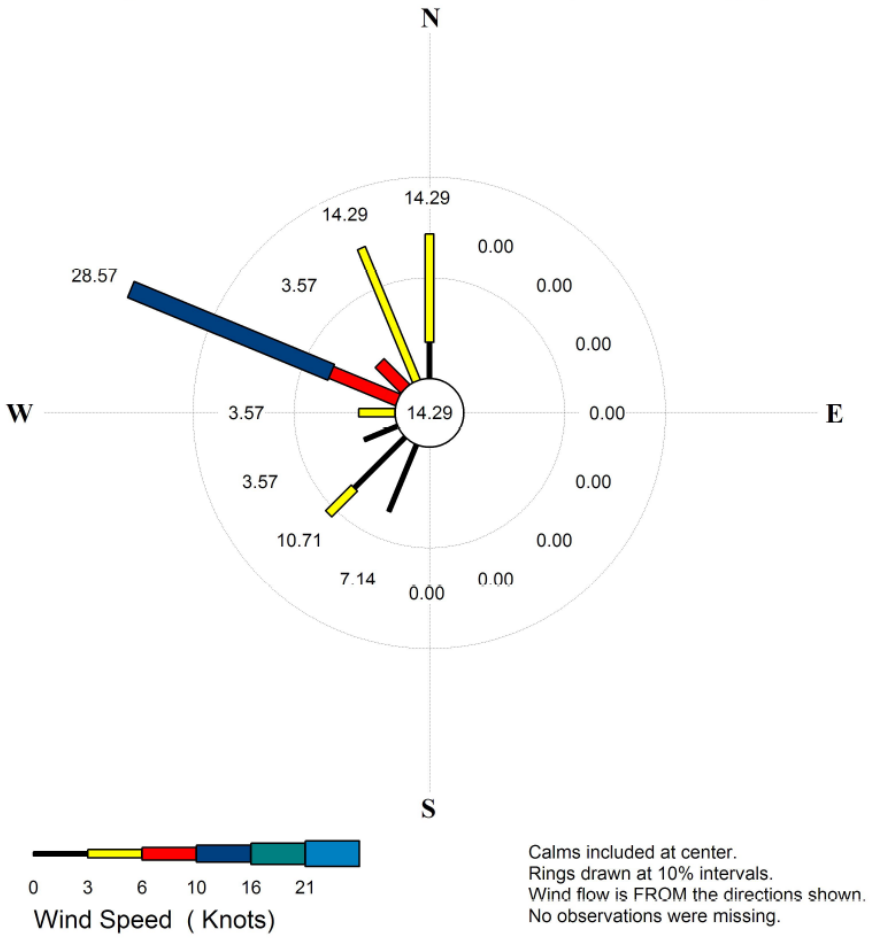
TOTAL OBS = 28 MISSING OBS = 0

PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
S	0.00	0.00	0.00	0.00	0.00	0.00
SSW	0.00	0.00	0.00	0.00	0.00	0.00
SW	0.00	0.00	0.00	0.00	0.00	0.00
WSW	0.00	0.00	0.00	0.00	0.00	0.00
W	0.00	3.57	3.57	0.00	0.00	0.00
WNW	0.00	7.14	7.14	28.57	0.00	0.00
NW	7.14	10.71	0.00	0.00	0.00	0.00
NNW	0.00	7.14	0.00	0.00	0.00	0.00

CALM OBS = 4 PERCENT CALM = 14.29

Wind Rose
Jets Emission Testing for Speciation (JETS)
At Oakland International Airport
August 24, 2005 from 00:00 to 23:00 hrs (1 hour averages)



Calms included at center.
Rings drawn at 10% intervals.
Wind flow is FROM the directions shown.
No observations were missing.

PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
N	3.57	10.71	0.00	0.00	0.00	0.00
NNE	0.00	0.00	0.00	0.00	0.00	0.00
NE	0.00	0.00	0.00	0.00	0.00	0.00
ENE	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00
ESE	0.00	0.00	0.00	0.00	0.00	0.00
SE	0.00	0.00	0.00	0.00	0.00	0.00
SSE	0.00	0.00	0.00	0.00	0.00	0.00

TOTAL OBS = 28 MISSING OBS = 0

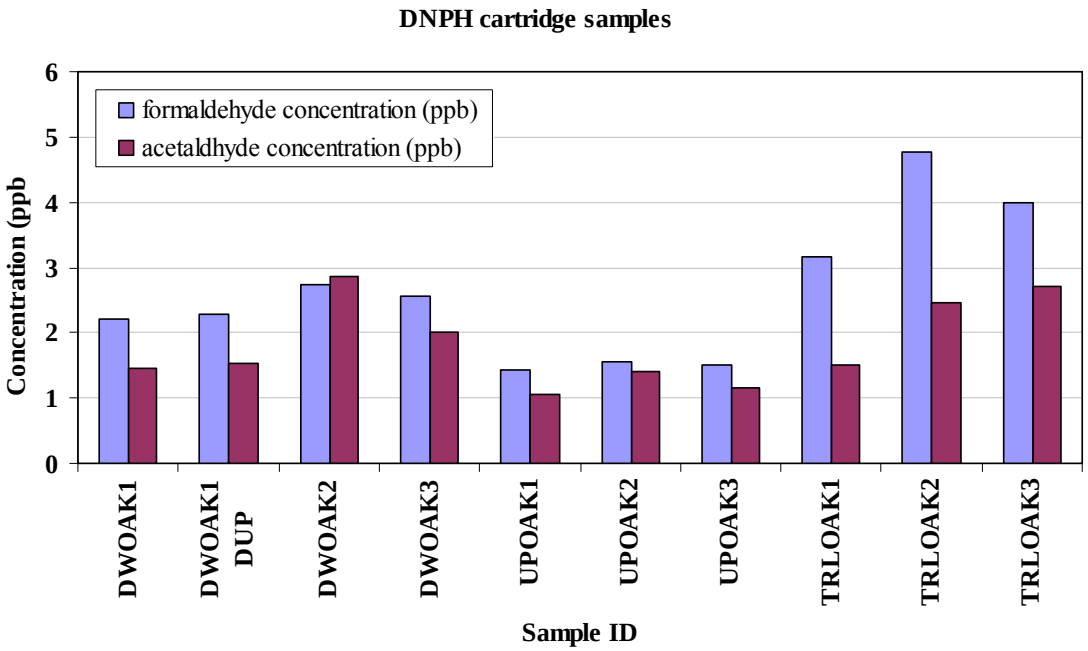
PERCENT OCCURRENCE: Wind Speed (Knots)
LOWER BOUND OF CATEGORY

DIR	0	3	6	10	16	21
S	0.00	0.00	0.00	0.00	0.00	0.00
SSW	7.14	0.00	0.00	0.00	0.00	0.00
SW	7.14	3.57	0.00	0.00	0.00	0.00
WSW	3.57	0.00	0.00	0.00	0.00	0.00
W	0.00	3.57	0.00	0.00	0.00	0.00
WNW	0.00	0.00	7.14	21.43	0.00	0.00
NW	0.00	0.00	3.57	0.00	0.00	0.00
NNW	0.00	14.29	0.00	0.00	0.00	0.00

CALM OBS = 4 PERCENT CALM = 14.29

APPENDIX C

Ambient DNPH cartridge sample results

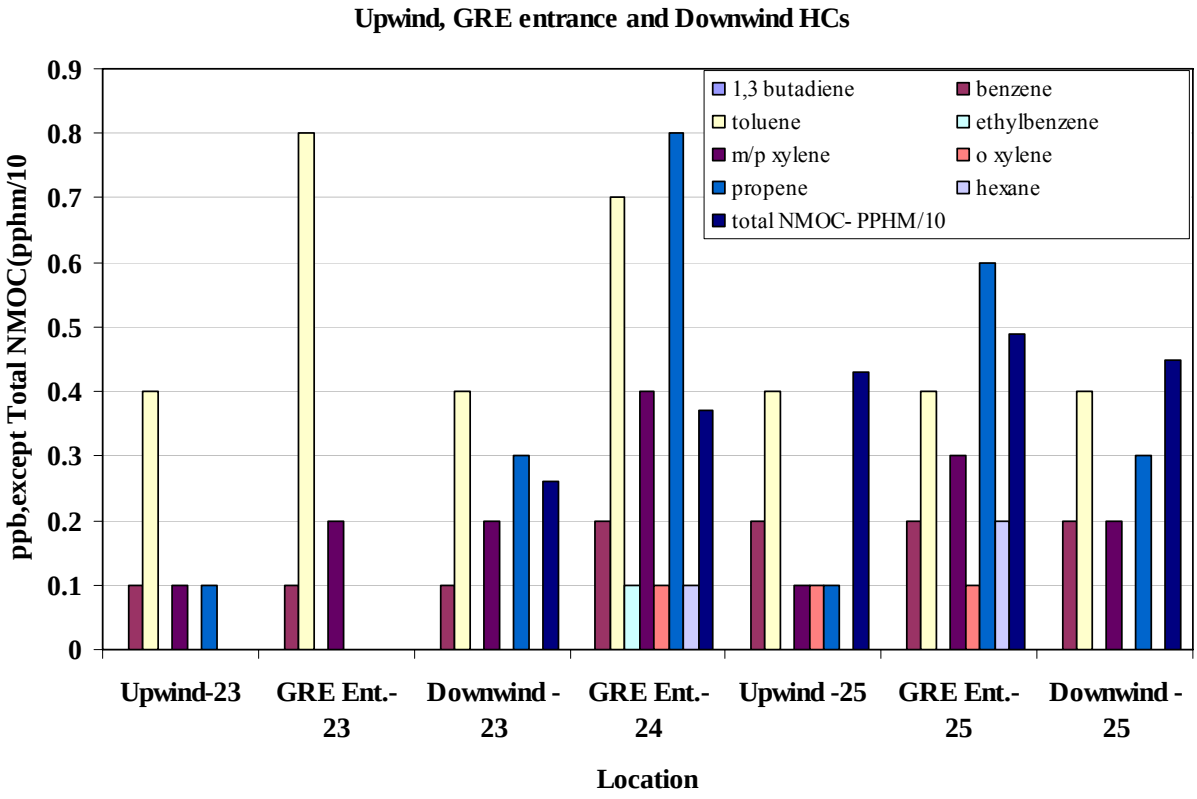


Sample ID	Definition	Start day, Time	End day, Time
DWOAK1	Downwind	8/22/2005 6:06 pm	8/23/2005 4:39 am
DWOAK1 DUP	Downwind Duplicate	8/22/2005 6:06 pm	8/23/2005 4:39 am
DWOAK2	Downwind	8/23/2005 8:04 pm	8/24/2005 5:56 am
DWOAK3	Downwind	8/24/2005 7:52 pm	8/25/2005 5:37 am
UPOAK1	Upwind	8/22/2005 7:19 pm	8/23/2005 5:15 am
UPOAK2	Upwind	8/23/2005 8:36 pm	8/24/2005 6:18 am
UPOAK3	Upwind	8/24/2005 8:17 pm	8/25/2005 6:21 am
TRLOAK1	ARB trailer	8/22/2005 6:52 pm	8/23/2005 5:53 am
TRLOAK2	ARB trailer	8/23/2005 7:39 pm	8/24/2005 6:45 am
TRLOAK3	ARB trailer	8/24/2005 7:33 pm	8/25/2005 2:28 am

The following compounds were undetectable:
Propanal, Acetone, Crotonaldehyde, Methyl Ethyl Ketone/Butyraldehydes, Benzaldehyde, Isopentanal, Pentanal, o-Tolualdehyde, m,p-Tolualdehyde , Hexanal

APPENDIX D

Ambient canister sample results



Location	Date	Start time	End time
Upwind-23	8/23/2005	8/22-19:03	batt. died
GRE Ent.-23	8/23/2005	8/22-19:59	8/23-06:04
Downwind -23	8/23/2005	8/22-18:00	batt. died
GRE Ent.-24	8/24/2005	8/23-20:55	8/24-06:50
Upwind -25	8/25/2005	8/24-18:25	8/25-06:14
GRE Ent.-25	8/25/2005	8/24-20:40	8/25-03:43
Downwind -25	8/25/2005	8/24-17:53	8/25-05:30

Notes:
Propene and hexane analyzed using MLD 24
Total NMOC analyzed using TO-12
All other compounds analyzed using MLD 52

Two canister samples from 8/24 sampling date did not fill

APPENDIX E

Spatial arrangement of sampling probes

Probe Configuration of the Left and Right Rakes

JETS-APEX2

Aircraft #1 (737-700), #2 & 3 (737-300)

<u>Port Rake (aft looking forward)</u>
Pr1 - Spare
T1 - AEDC
Pr2 –NASA Pressure Transducer
Gx1 - AEDC SM/AFR OSM
P1 - Particle Sampling Group (ganged w/P2)
G1 - NASA CGA & MGA
Gx2 - UCR Dioxin & Cr+6
P2 - Particle Sampling Group (ganged w/P1)
G2 - NASA TEOM
G3 – NASA CGA & MGA
T2 - AEDC
Pr3 - Spare

<u>Starboard Rake (aft looking forward)</u>
T1 - AEDC
Gx1 - Spare
Gx2 - UCR Speciated HC/PM
Gx3 - UCR Speciated HC/PM
P1 - Particle Sampling Group (ganged w/P2)
G1 - AEDC MGA/NASA CGA
Gx4 - UCR Speciated HC/PM
P2 - Particle Sampling Group (ganged w/P1)
Gx5 - UCR Speciated HC/PM
Gx6 - AEDC SM/ AFR OSM
P3 - instrumented with TCs (T1 & T2)– AEDC
T2 - AEDC

G = Gas Probes with 0.062” inlet orifice (incidental water cooling)
Gx = Gas Probes with 0.152” inlet orifice (no water cooling)
P = Particle Probes

APPENDIX F

Willard Dodds' (GEAE) Reports on Representativeness of Engine Performance and Emissions

Apex2 Engine Performance

Precise characterization of engine performance would require more and/or better quality data and detailed data analysis

- Data are not available for all aircraft
- Ambient temperature/pressure were not provided
- Hand logged steady state engine data accuracy is not always adequate to get significant details (e.g. 1% fuel flow is significant), but we can observe main effects.

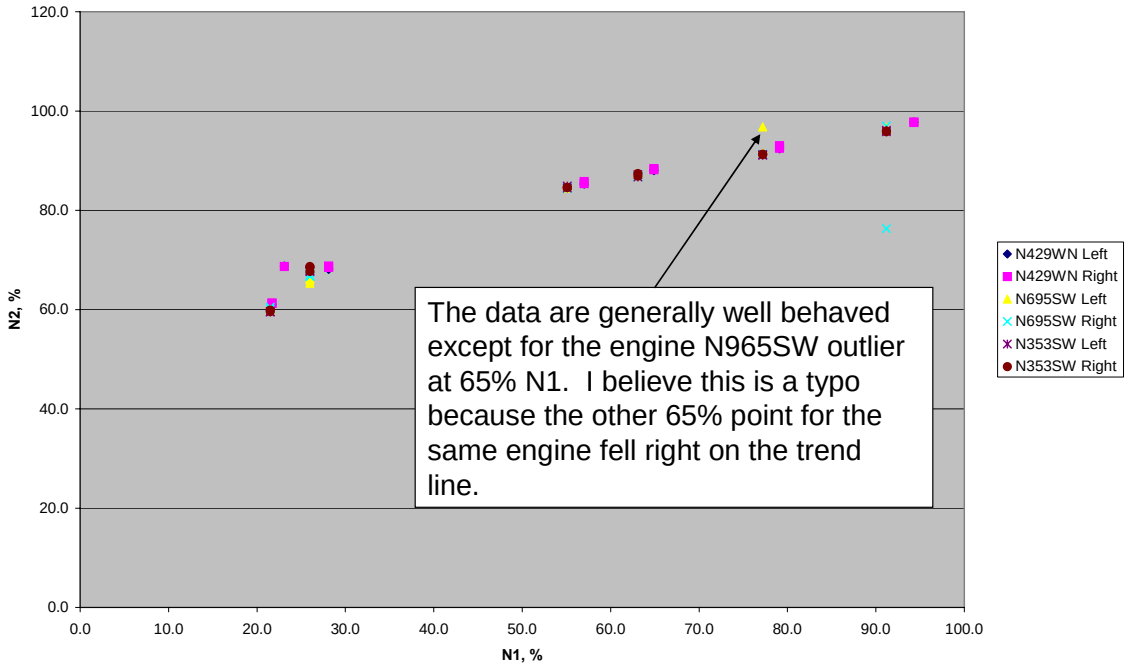
What are We Looking For?

We expect core Speed (N2) to correlate closely with fan speed (N1). This is just a check of the general engine data quality.

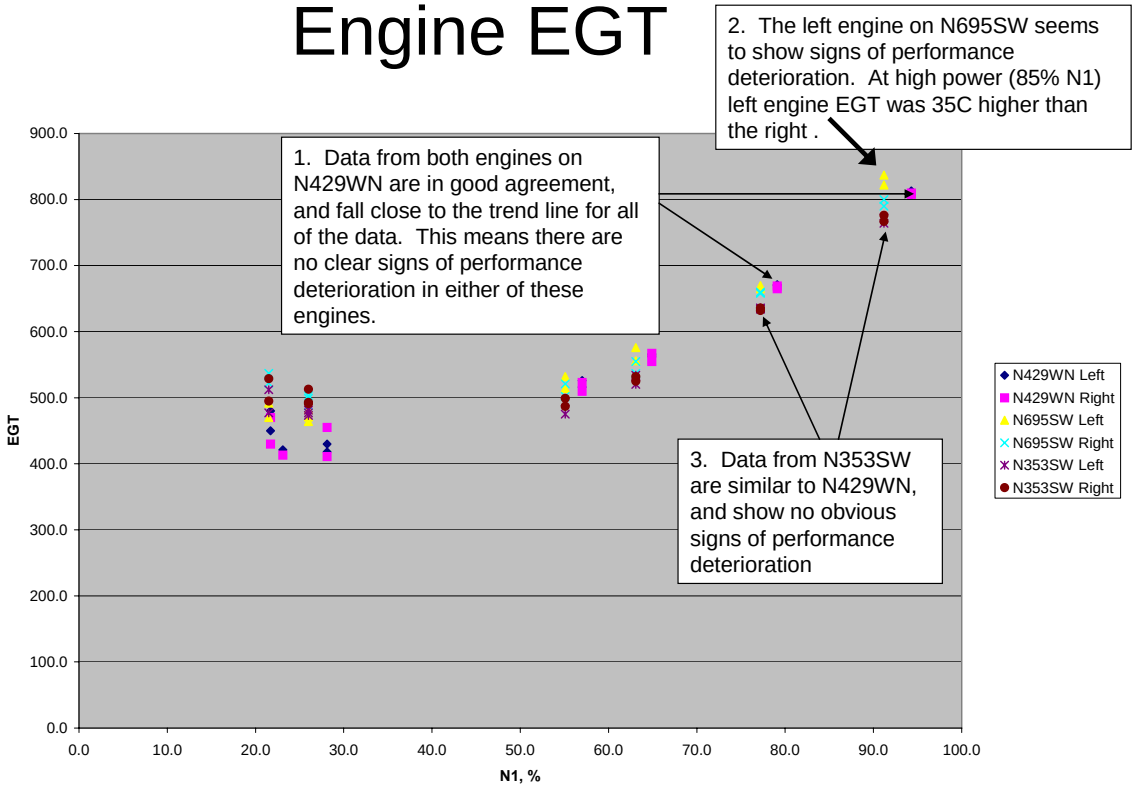
Exhaust gas temperature (EGT) is a measure of performance deterioration. Higher than average EGT at the high thrust points is an indication of deterioration. EGT was logged to the nearest degree, but uncertainty in reading the gages is probably 2 to 3 degrees. Considering gage readability, a difference of 5 to 10 degrees is probably a significant indicator of deterioration.

Fuel flow (FF) is another indicator of performance deterioration. A two percent change in fuel flow is significant, but gage readability might not be adequate to see such a small change.

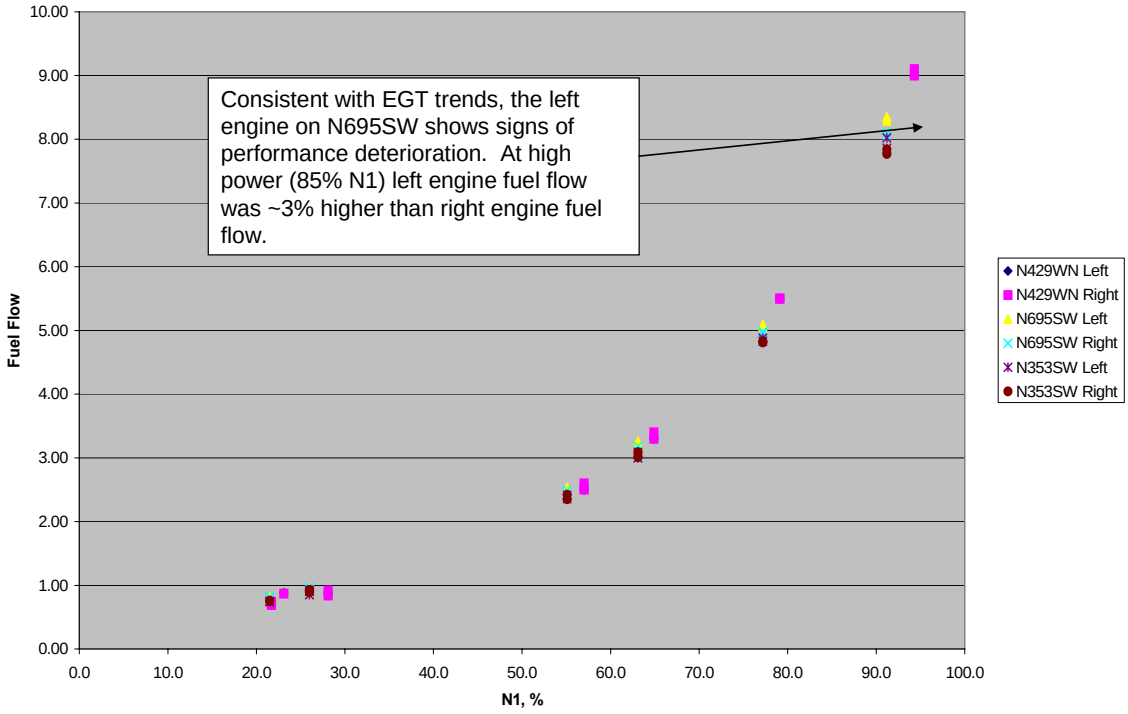
Engine Core Speed (N2)



Engine EGT



Engine Fuel Flow



Summary

Trends in engine core speed, EGT and fuel flow data are generally consistent with expectations.

The only apparent indication of performance deterioration was on the left engine of N695SW.

Performance deterioration would tend to increase combustor inlet temperature and fuel-air ratio, which would increase smoke emissions.

Additional detailed engine performance data analysis could be completed, if needed.

APEX2 - Gaseous Emission Results of First 737-700 Engine Test

Willard Dodds, GEAE

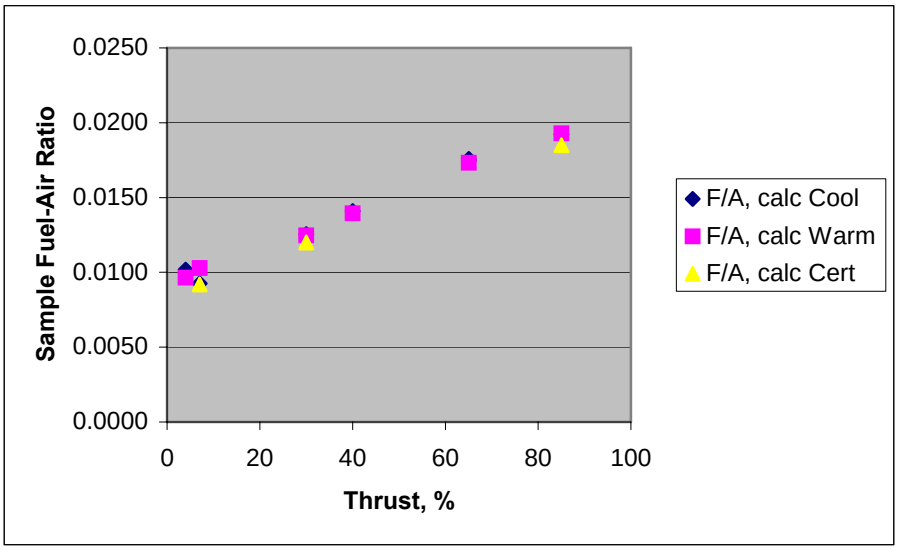
Changlie Wey, QSS/NASA GRC

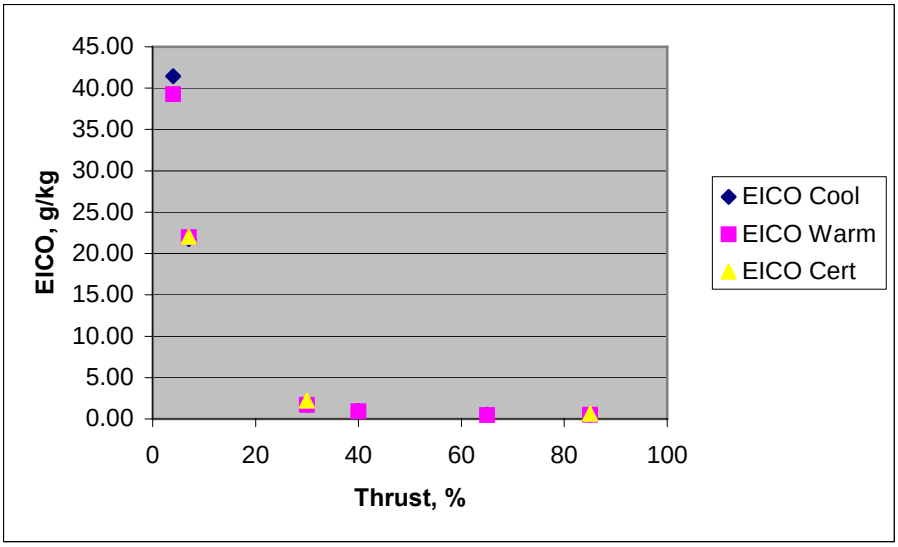
Gaseous emissions and sample fuel air ratio from Probe GR1, as measured by NASA Glenn, are compared to CFM56-7B24 engine certification results in the four plots below. All of the preliminary gaseous emission data are in Tables 1 and 2.

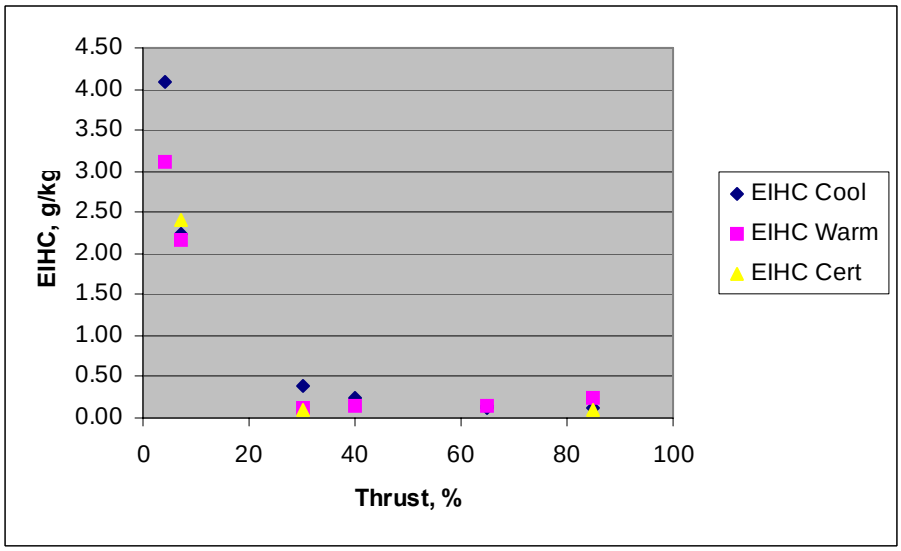
The sample fuel air ratios at all conditions were within 5% of expected levels (based on certification tests). During the certification tests, the fuel air ratio at each point was shown to be within 10% of the expected core flow value, based on engine cycle calculations. This indicates that Rake LG1 was measuring a representative sample of the core engine exhaust. The NASA data indicate that the core engine gas samples entering Probes LG3 and RG1 were diluted by about 30 to 40% fan air, but emissions indexes are in reasonable agreement with LG1. The sample collected at 30 meters is diluted by a factor of more than 10, and NASA emissions indexes for the 30-meter probe do not agree with LG1. This could be due to the low concentrations of CO, HC and NOx at 30 meters, which are not in the normal calibration range for gas sample measurements.

All gaseous emissions measured with probe LG1 are in good agreement with certification results. At 30% thrust, HC levels are higher when the engine is cool (during the initial run up from start to 85% thrust). This effect has been noted in previous tests. Certification tests are run on a warm engine (high power points are run first).

Based on these results, the emissions from this engine seem to be representative of the CFM56-7B engine type, and the samples from Probes LG1 and nearby probes were well within the core stream during the test. The effect of potential dilution by fan air should be considered in looking at data from other probe locations.




45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
EICO, g/kg
0
20
40
60
80
100
Thrust, %
EICO Cool
EICO Warm
EICO Cert


4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
EIHC, g/kg
0
20
40
60
80
100
Thrust, %
EIHC Cool
EIHC Warm
EIHC Cert

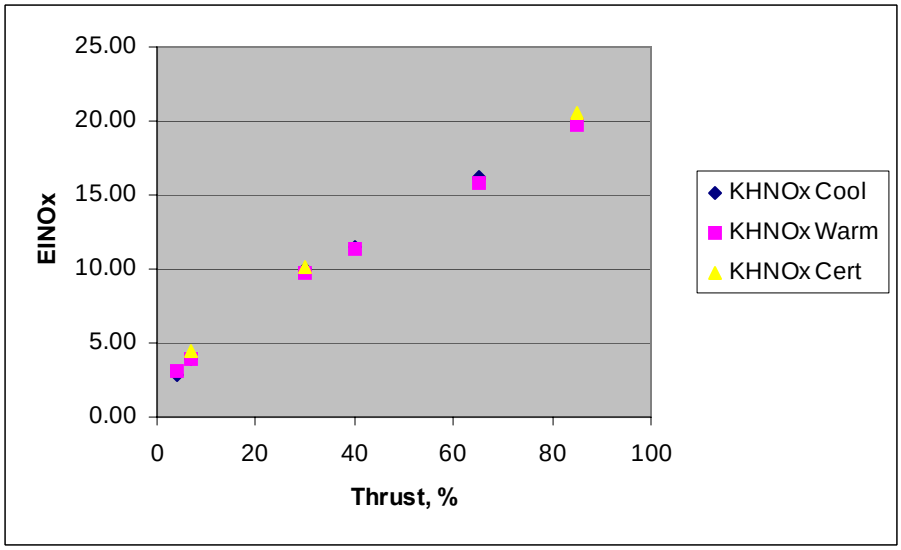

25.00
20.00
15.00
10.00
5.00
0.00
EINOx
0
20
40
60
80
100
Thrust, %
KHNOx Cool
KHNOx Warm
KHNOx Cert

Table 1. Preliminary Raw Emissions Data.

Date	Power	Probe	Time	CO2 (dry)	CO (dry)	O2 (dry)	NOx (wet)	NO(wet)	NO2 (wet)	HC (wet)	P,psia	Tdew,F
				ppm	ppm	%	ppm	ppm	ppm	ppm		
8/23/2005	4	LG1	2:08:20	21182.7	440.98	18.55	16.75	15.35	1.40	73.31	14.64	52
8/23/2005	4	LG3	2:10:31	13209.6	280.46	19.73	8.78	1.47	7.29	53.76	14.63	52
8/23/2005	4	30M	2:12:20	1596.9	12.32	21.30	0.81	0.33	0.47	14.27	14.63	52
8/23/2005	4	RG1	2:15:26	13776.0	263.92	19.77	9.60	1.36	8.22	50.53	14.63	52
8/23/2005	7	LG1	2:18:55	19505.1	210.41	18.97	21.62	20.67	0.91	36.60	14.64	52
8/23/2005	7	LG3	2:20:59	13773.3	180.19	19.73	12.43	5.42	6.98	36.15	14.63	52
8/23/2005	7	30M	2:22:53	1826.1	7.73	21.38	1.08	0.58	0.50	11.22	14.63	52
8/23/2005	7	RG1	2:25:11	12573.6	105.00	19.95	12.91	7.54	5.36	17.29	14.63	52
8/23/2005	30	LG1	2:30:36	26700.0	22.43	18.07	74.00	72.68	1.31	8.59	14.63	52
8/23/2005	30	LG3	2:32:16	19470.3	15.91	19.05	50.48	45.96	4.44	7.63	14.63	52
8/23/2005	30	30M	2:34:19	2275.5	2.23	21.41	2.66	2.09	0.56	7.37	14.63	52
8/23/2005	30	RG1	2:36:21	17534.5	14.64	19.36	41.99	37.78	4.18	6.01	14.63	52
8/23/2005	40	LG1	2:40:43	29993.9	14.16	17.68	95.07	93.25	1.79	5.75	14.63	52
8/23/2005	40	LG3	2:42:33	21588.1	9.90	18.80	65.06	60.30	4.78	5.37	14.63	52
8/23/2005	40	30M	2:44:24	2470.9	1.82	21.44	3.76	2.86	0.89	5.98	14.63	52
8/23/2005	40	RG1	2:46:37	18642.7	9.33	19.30	52.05	46.85	5.18	4.78	14.63	52
8/23/2005	65	LG1	2:52:12	37240.5	9.27	16.73	164.42	157.13	7.33	4.48	14.63	52
8/23/2005	65	LG3	2:54:12	26917.3	5.77	18.17	115.50	105.12	9.96	4.24	14.63	52
8/23/2005	65	30M	2:56:04	2949.0	3.81	21.44	6.55	5.03	1.51	5.48	14.63	52
8/23/2005	65	RG1	2:58:01	23026.5	5.16	18.73	93.16	84.46	8.69	3.89	14.63	52
8/23/2005	65	LG1	3:00:19	37469.3	9.03	16.74	167.61	159.45	7.95	3.70	14.63	52
8/23/2005	85	LG1	3:03:03	41009.3	9.81	16.24	226.51	213.60	12.56	3.82	14.63	52
8/23/2005	7	LG1	3:06:11	21612.7	236.02	18.88	23.81	20.52	3.25	39.42	14.63	52
8/23/2005	7	LG3	3:08:03	13803.5	192.45	19.95	12.58	4.59	7.98	41.68	14.63	52
8/23/2005	7	30M	3:10:10	2186.8	7.08	21.56	1.59	0.67	0.92	9.58	14.63	52
8/23/2005	7	RG1	3:12:12	12071.9	112.12	20.23	11.84	5.98	5.81	17.56	14.63	52
8/23/2005	85	LG1	3:17:12	41146.7	10.33	16.22	222.47	208.40	13.61	8.06	14.63	52
8/23/2005	65	LG1	3:20:08	36907.0	8.37	16.79	161.02	149.35	11.55	4.72	14.63	52
8/23/2005	65	LG3	3:22:14	26018.8	4.72	18.29	110.88	99.34	11.25	4.57	14.63	52
8/23/2005	65	30M	3:24:11	2752.8	1.55	21.48	6.43	4.50	1.90	5.21	14.63	52
8/23/2005	65	RG1	3:26:18	22425.6	4.47	18.80	88.09	78.69	9.41	3.88	14.63	52
8/23/2005	40	LG1	3:31:16	29663.9	13.34	17.80	93.04	85.74	6.73	3.37	14.63	52
8/23/2005	40	LG3	3:33:16	20781.3	9.55	19.01	61.16	53.67	7.03	3.48	14.63	52
8/23/2005	40	30M	3:35:14	2463.0	1.75	21.53	4.43	3.05	1.38	4.12	14.63	52
8/23/2005	40	RG1	3:37:15	17208.0	7.86	19.54	48.35	42.66	5.66	3.16	14.63	52
8/23/2005	30	LG1	3:42:29	26536.1	22.30	18.26	71.77	66.02	5.76	2.45	14.63	52
8/23/2005	30	LG3	3:44:26	18781.5	14.89	19.30	48.38	42.44	5.89	2.75	14.63	52
8/23/2005	30	30M	3:46:25	2383.6	1.96	21.54	3.49	2.21	1.28	3.45	14.63	52
8/23/2005	30	RG1	3:48:24	17264.3	13.71	19.55	40.96	35.37	5.55	2.59	14.63	52
8/23/2005	4	LG1	3:54:10	20118.5	395.98	18.98	17.39	12.68	4.70	52.90	14.63	52
8/23/2005	4	LG3	3:56:12	11608.7	225.47	20.23	8.62	1.11	7.52	37.45	14.63	52
8/23/2005	4	30M	3:58:12	2037.3	11.79	21.57	1.25	0.36	0.89	9.35	14.63	52
8/23/2005	4	RG1	4:00:12	12364.0	221.11	20.15	9.28	0.99	8.28	39.58	14.63	52

Table 2. Preliminary Emissions Indexes

Date	Power	Probe	Time	F/A, calc	EICO	EIHC	EINOx	EINO	Etac	Factor, H	Factor,P	KHNOx
										0.0063	14.694	
8/23/2005	4	LG1	2:08:20	0.0102	41.44	4.08	2.67	2.45	98.618	1.04	1.00	2.78
8/23/2005	4	LG3	2:10:31	0.0063	42.61	4.80	2.25	0.38	98.519	1.04	1.00	2.34
8/23/2005	4	30M	2:12:20	0.0006	18.98	12.78	2.07	0.85	98.276	1.04	1.00	2.15
8/23/2005	4	RG1	2:15:26	0.0066	38.51	4.33	2.36	0.33	98.662	1.04	1.00	2.45
8/23/2005	7	LG1	2:18:55	0.0093	21.75	2.24	3.79	3.62	99.265	1.04	1.00	3.94
8/23/2005	7	LG3	2:20:59	0.0065	26.48	3.12	3.08	1.34	99.066	1.04	1.00	3.20
8/23/2005	7	30M	2:22:53	0.0007	10.18	8.59	2.36	1.26	98.902	1.04	1.00	2.46
8/23/2005	7	RG1	2:25:11	0.0059	17.05	1.65	3.53	2.06	99.435	1.04	1.00	3.67
8/23/2005	30	LG1	2:30:36	0.0126	1.71	0.39	9.60	9.43	99.921	1.04	1.00	9.98
8/23/2005	30	LG3	2:32:16	0.0091	1.67	0.47	8.96	8.16	99.914	1.04	1.00	9.32
8/23/2005	30	30M	2:34:19	0.0009	2.28	4.38	4.54	3.57	99.509	1.04	1.00	4.72
8/23/2005	30	RG1	2:36:21	0.0082	1.71	0.41	8.28	7.45	99.919	1.04	1.00	8.60
8/23/2005	40	LG1	2:40:43	0.0141	0.96	0.23	11.01	10.80	99.954	1.04	1.00	11.44
8/23/2005	40	LG3	2:42:33	0.0101	0.93	0.30	10.43	9.66	99.948	1.04	1.00	10.84
8/23/2005	40	30M	2:44:24	0.0010	1.69	3.24	5.83	4.44	99.636	1.04	1.00	6.06
8/23/2005	40	RG1	2:46:37	0.0087	1.02	0.31	9.66	8.69	99.945	1.04	1.00	10.04
8/23/2005	65	LG1	2:52:12	0.0175	0.50	0.15	15.41	14.73	99.974	1.04	1.00	16.02
8/23/2005	65	LG3	2:54:12	0.0126	0.44	0.19	14.88	13.54	99.971	1.04	1.00	15.47
8/23/2005	65	30M	2:56:04	0.0013	2.90	2.43	8.32	6.39	99.689	1.04	1.00	8.65
8/23/2005	65	RG1	2:58:01	0.0108	0.46	0.20	14.01	12.70	99.969	1.04	1.00	14.56
8/23/2005	65	LG1	3:00:19	0.0176	0.49	0.12	15.61	14.85	99.976	1.04	1.00	16.23
8/23/2005	85	LG1	3:03:03	0.0192	0.48	0.11	19.33	18.23	99.977	1.04	1.00	20.09
8/23/2005	7	LG1	3:06:11	0.0103	21.99	2.17	3.77	3.25	99.266	1.04	1.00	3.91
8/23/2005	7	LG3	3:08:03	0.0066	28.19	3.59	3.11	1.13	98.979	1.04	1.00	3.23
8/23/2005	7	30M	3:10:10	0.0009	7.55	5.94	2.82	1.18	99.229	1.04	1.00	2.93
8/23/2005	7	RG1	3:12:12	0.0057	18.96	1.74	3.37	1.70	99.380	1.04	1.00	3.50
8/23/2005	85	LG1	3:17:12	0.0193	0.51	0.24	18.92	17.72	99.964	1.04	1.00	19.66
8/23/2005	65	LG1	3:20:08	0.0173	0.46	0.16	15.22	14.12	99.974	1.04	1.00	15.82
8/23/2005	65	LG3	3:22:14	0.0122	0.37	0.21	14.77	13.24	99.970	1.04	1.00	15.35
8/23/2005	65	30M	3:24:11	0.0012	1.28	2.50	8.83	6.19	99.720	1.04	1.00	9.18
8/23/2005	65	RG1	3:26:18	0.0105	0.41	0.21	13.60	12.15	99.970	1.04	1.00	14.14
8/23/2005	40	LG1	3:31:16	0.0139	0.91	0.14	10.89	10.04	99.965	1.04	1.00	11.32
8/23/2005	40	LG3	3:33:16	0.0098	0.94	0.20	10.18	8.93	99.958	1.04	1.00	10.58
8/23/2005	40	30M	3:35:14	0.0010	1.63	2.24	6.91	4.76	99.737	1.04	1.00	7.18
8/23/2005	40	RG1	3:37:15	0.0081	0.93	0.22	9.72	8.58	99.956	1.04	1.00	10.10
8/23/2005	30	LG1	3:42:29	0.0125	1.71	0.11	9.37	8.62	99.949	1.04	1.00	9.74
8/23/2005	30	LG3	3:44:26	0.0088	1.62	0.18	8.91	7.81	99.944	1.04	1.00	9.26
8/23/2005	30	30M	3:46:25	0.0010	1.90	1.95	5.65	3.58	99.760	1.04	1.00	5.87
8/23/2005	30	RG1	3:48:24	0.0081	1.62	0.18	8.21	7.09	99.944	1.04	1.00	8.53
8/23/2005	4	LG1	3:54:10	0.0097	39.29	3.10	2.93	2.13	98.767	1.04	1.00	3.04
8/23/2005	4	LG3	3:56:12	0.0055	39.21	3.82	2.52	0.33	98.697	1.04	1.00	2.62
8/23/2005	4	30M	3:58:12	0.0008	13.63	6.28	2.41	0.68	99.052	1.04	1.00	2.51
8/23/2005	4	RG1	4:00:12	0.0059	36.10	3.79	2.55	0.27	98.773	1.04	1.00	2.65

APPENDIX G

Fuel Aromatic and Sulfur Content Analysis Results

Submitted by: ED **Submitted:** **Affiliation: RD**

ANALYTICAL METHOD		Fuel Analysis & Methods Evaluation Section (FAME) Monitoring and Laboratory Division, CARB							
		ASTM D5186 SFC/FID			ASTM D86 Automatic			ASTM D5453 Antek	ASTM D4052 Density Mtr
Analysis Date		9/30/05 - 11/2/05			10/25/2005			9/21/2005	
Analyst		JJC / EL			JC / AL			EL	
Sample I.D.		*Total Aromatics (vol %)*	*Total Aromatics (mass%)*	*Polycyclic Aromatics (mass%)*	*T10 (deg C)*	*T50 (deg C)*	*T90 (deg C)*	*Sulfur (ppm)*	*Density (g/mL)*
N3535 SWR		20.5	21.0	1.36	174	206	250	206	0.8206
N3535 SWL		20.3	20.8	1.46	174	207	250	239	0.8198
N429 WNR		20.3	20.7	1.98	173	204	248	412	0.8079
N429 WNL		20.2	20.6	1.92	173	203	248	419	0.8080
N435 WNR		19.6	20.0	0.92	179	205	243	132	0.8252
N435 WNL		19.7	20.0	0.98	179	206	244	125	0.8256
N695 SWR		22.8	23.4	1.99	172	206	252	352	0.8120
N695 SWL		22.6	23.2	1.88	173	206	252	355	0.8217

Approved by: _____ **NR: Not Requested** **Date: 11/7/2005**

average	20.75	21.21	1.56	174.63	205.38	248.38	280.00	0.8176
st. dev.	1.16	1.25	0.42	2.60	1.22	3.16	112.16	0.0068
count	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00

APPENDIX H

Fuel Carbon-Hydrogen Content Analysis Results

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CORE LABORATORIES

CRAIG WILLIAMS
ARCADIS INC
4915 PROSPECTUS DR, ST F
DURHAM, NC 27713

Date Reported: 4/10/2006
Date Received: 3/31/2006

Analytical Report

Test	Result	Units	Method	Date	Analyst
Sample Number: 161346-001	**Sample ID: N353SW Jets 2**				**Sample Rcvd: 3/31/2006**
Sample Date:	**Description:**				
Carbon/Hydrogen Content					
Carbon Content	85.89	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.11	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-002	**Sample ID: N429SW Jets 2**				**Sample Rcvd: 3/31/2006**
Sample Date:	**Description:**				
Carbon/Hydrogen Content					
Carbon Content	85.29	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.71	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-003	**Sample ID: N435SW Jets 2**				**Sample Rcvd: 3/31/2006**
Sample Date:	**Description:**				
Carbon/Hydrogen Content					
Carbon Content	85.70	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.30	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-004	**Sample ID: N695SW Jets 2**				**Sample Rcvd: 3/31/2006**
Sample Date:	**Description:**				
Carbon/Hydrogen Content					
Carbon Content	85.25	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.75	WT %	ASTM D-5291	4/9/2006	KC

Approved By: _____
Pat Gideons
Laboratory Supervisor

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APPENDIX I

Summary Tables

In this section, a series of summary tables based on the data presented in section 3.0 have been prepared for the reader's convenience.

The following tables present the PM data and speciation profiles for the eight engines studied. In each table PM shape parameters and number and mass based emissions indices are reported as a function engine percent rated thrust (mode). For the TOG each table includes a list of species for which mode-specific emission indices (see Figure 14) are reported along with the CAS, LOD, measurement method and measurement group.

All data acquired through this contract has been archived on a secure website provided by NASA. It can be accessed with appropriate permissions at the following URL: https://owl.grc.nasa.gov

Table I.1: PM data and speciation profiles for N435WN Port Engine

Aircraft Tail Number:	N435WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
EC							
OC							
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	12.39 ± 0.12	11.81 ± 0.28	17.01 ± 0.41	18.77 ± 0.34	26.94 ± 0.30	NM
Sigma	1.55 ± 0.004	1.45 ± 0.02	1.62 ± 0.02	1.73 ± 0.01	1.80 ± 0.01	NM
DgeomM (nm)	36.54 ± 0.49	31.74 ± 2.09	45.57 ± 0.79	46.63 ± 0.42	61.97 ± 0.20	NM
	Emission Indices (g/kg fuel)					
Number	0.63 ± 0.061	0.06 ± 0.012	0.13 ± 0.010	0.17 ± 0.008	0.92 ± 0.013	NM
Mass	0.005 ± 0.0003	0.0006 ± 0.0001	0.0017 ± 0.0001	0.0029 ± 0.0001	0.04 ± 0.0006	NM
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.70	0.40	0.001	0.003	0.006	NM
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1591 ± .0238	0.0901 ± .0098	0.0018 ± .0003	0.0016 ± .0007	0.0020 ± .0013	NM
Toluene	0.0807 ± .0190	0.0425 ± .0071	0.0032 ± .0008	0.0025 ± .0022	0.0017 ± .0001	NM
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0290 ± .0076	0.0166 ± .0002	0.0007 ± .0005	0.0006 ± .0003	0.0007 ± .0001	NM

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		XAD-PUF/Quartz sampling			
	Acenaphthene	83-32-9					
	Fluorene	86-73-7					
	Phenanthrene	85-01-8					
	Anthracene	120-12-7					
	Fluoranthene	206-44-0					
	Pyrene	129-00-0					
	Benzo(a)pyrene	50-32-8					
	Indeno[1,2,3-c,d]pyrene	193-39-5					
	Dibenz[a,h]anthracene	53-70-3					
	Benzo[ghi]perylene	191-24-2					
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6					
	Octacosane	630-02-4					
	Hexacosane	630-01-3					
	Tetracosane	646-31-1					
	Docosane	629-92-0					
	Eicosane	112-95-8					
	Nonadecane	629-92-5					
	Octadecane	593-46-3					
	Hexadecane	544-76-3					
	Tetradecane	629-59-4					
	Naphthalene	91-20-3					
	Benz(a)anthracene	56-55-3					
	Chrysene	218-01-9					
	Benzo(b)fluoranthene	205-99-2					
	Benzo(k)fluoranthene	207-08-9					
	Dodecane	112-40-3					
Carbonyls							
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	NM		NM		NM	NM
Acenaphthene	NM		NM		NM	NM
Fluorene	NM		NM		NM	NM
Phenanthrene	NM		NM		NM	NM
Anthracene	NM		NM		NM	NM
Fluoranthene	NM		NM		NM	NM
Pyrene	NM		NM		NM	NM
Benzo(a)pyrene	NM		NM		NM	NM
Indeno[1,2,3-c,d]pyrene	NM		NM		NM	NM
Dibenz[a,h]anthracene	NM		NM		NM	NM
Benzo[ghi]perylene	NM		NM		NM	NM
Hexatriacontane	NM		NM		NM	NM
Triacontane	NM		NM		NM	NM
Octacosane	NM		NM		NM	NM
Hexacosane	NM		NM		NM	NM
Tetracosane	NM		NM		NM	NM
Docosane	NM		NM		NM	NM
Eicosane	NM		NM		NM	NM
Nonadecane	NM		NM		NM	NM
Octadecane	NM		NM		NM	NM
Hexadecane	NM		NM		NM	NM
Tetradecane	NM		NM		NM	NM
Naphthalene	NM		NM		NM	NM
Benz(a)anthracene	NM		NM		NM	NM
Chrysene	NM		NM		NM	NM
Benzo(b)fluoranthene	NM		NM		NM	NM
Benzo(k)fluorantene	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Formaldehyde	0.69 ± 0.11	0.38 ± 0.05	0.012 ± 0.0066	0.009 ± 0.0039	0.008 ± 0.0005	NM
Acetaldehyde	0.33 ± 0.04	0.16 ± 0.019	0.004 ± 0.0012	0.002 ± 0.00008	0.003 ± 0.0003	NM
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0.3695 ± 0	0.1790 ± 0	0 ± 0	0 ± 0	0 ± 0	NM
mz59	0.1544 ± .0154	0.0721 ± .0067	0.0031 ± .0008	0.0024 ± .0006	0.0017 ± .0002	NM
mz107	0.1301 ± .0327	0.0666 ± .0013	0.0025 ± .0016	0.0016 ± .0005	0.0014 ± .0002	NM
MTBE	NM	NM	NM	NM	NM	NM

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200				
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000				
	Silicon	7440-21-3	1.200				
	Phosphorous	7723-14-0	0.204				
	Sulfur	63705-05-5	0.204				
	Chlorine	7782-50-5	0.068				
	Potassium	744-09-5	0.017				
	Calcium	7440-70-2	0.017				
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007				
	Titanium	7440-32-6	0.051				
	Vanadium	7440-62-2	0.020				
	Chromium	7440-47-3	0.017				
	Manganese	7439-96-5	0.009				
	Cobalt	7440-48-4	0.007				
	Nickel	7440-2-0	0.003				
	Copper	7440-50-8	0.003				
	Zinc	7440-66-6	0.003				
	Gallium	7440-55-3	0.425				
	Germanium	7440-38-2	0.017				
	Arsenic	7440-38-2	0.003				
	Selenium	7782-49-2	0.017				
	Rbidium		0.007				
	Strontium	7440-24-6	0.017				
	Ytrium		0.003				
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017				
	Palladium	7440-05-3	0.026				
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017				
	Indium	7440-74-6	0.017				
	Tin	7440-31-6	0.026				
	Antimony	7440-36-0	0.024				
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170				
	Lanthanum	4639-91-0	0.425				
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051				
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	NM		NM		NM	NM
Beryllium	NM		NM		NM	NM
Aluminum	NM		NM		NM	NM
Silicon	NM		NM		NM	NM
Phosphorous	NM		NM		NM	NM
Sulfur	NM		NM		NM	NM
Chlorine	NM		NM		NM	NM
Potassium	NM		NM		NM	NM
Calcium	NM		NM		NM	NM
Scandium	NM		NM		NM	NM
Iron	NM		NM		NM	NM
Titanium	NM		NM		NM	NM
Vanadium	NM		NM		NM	NM
Chromium	NM		NM		NM	NM
Manganese	NM		NM		NM	NM
Cobalt	NM		NM		NM	NM
Nickel	NM		NM		NM	NM
Copper	NM		NM		NM	NM
Zinc	NM		NM		NM	NM
Gallium	NM		NM		NM	NM
Germanium	NM		NM		NM	NM
Arsenic	NM		NM		NM	NM
Selenium	NM		NM		NM	NM
Rbidium	NM		NM		NM	NM
Strontium	NM		NM		NM	NM
Ytrium	NM		NM		NM	NM
Niobium	NM		NM		NM	NM
Molybdenum	NM		NM		NM	NM
Palladium	NM		NM		NM	NM
Silver	NM		NM		NM	NM
Cadmium	NM		NM		NM	NM
Indium	NM		NM		NM	NM
Tin	NM		NM		NM	NM
Antimony	NM		NM		NM	NM
Cesium	NM		NM		NM	NM
Barium	NM		NM		NM	NM
Lanthanum	NM		NM		NM	NM
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	NM		NM		NM	NM
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		TILDAS		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8					
	Nitrate	7697-37-2					
NM - no measurement was made							
BDL - Below detection limit							
EI for CO2 determined by elemental analysis of fuel							
Notes:							
UCR comments:							
In the original text LODs were provided for all compounds and species measured on the high-flow side.							
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.							
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.							
UCR only made one measurement so uncertainty cannot be calculated.							
Analytical uncertainty for all measurement methods was provided in the original text.							

Table I.1: PM data and speciation profiles for N435WN Port Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.24	1.70	8.60	9.91	14.67	NM
NO2	2.71	2.09	0.87	0.81	1.02	NM
NOX	2.95	3.78	9.47	10.72	15.68	NM
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	NM	NM	NM	NM	NM	NM
CO	18.05	14.74	1.48	0.85	0.44	NA
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	NM	NM	NM	NM	NM	NM
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.2: PM data and speciation profiles for N435WN Starboard Engine

Aircraft Tail Number:	N435WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
	Mass				X		
EC					X		
OC					X		
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	14.24 ± 0.15	12.04 ± 0.47	17.09 ± 0.39	19.10 ± 0.27	25.74 ± 0.37	31.27 ± 0.64
Sigma	1.60 ± 0.005	1.44 ± 0.04	1.64 ± 0.01	1.69 ± 0.01	1.81 ± 0.01	1.79 ± 0.01
DgeomM (nm)	37.32 ± 0.37	28.4 ± 2.24	43.08 ± 0.63	44.35 ± 0.52	59.81 ± 0.29	71.09 ± 2.56
	Emission Indices (g/kg fuel)					
Number	0.61 ± 0.032	0.15 ± 0.03	0.19 ± 0.013	0.23 ± 0.009	0.83 ± 0.02	0.97 ± 0.033
Mass	0.006 ± 0.0002	0.0005 ± 0.0001	0.003 ± 0.0001	0.004 ± 0.0001	0.03 ± 0.0008	0.06 ± 0.005
Mass	0.0082		0.0209		0.0407	0.0704
	0.0025		0.0017		0.0238	0.0414
	0.0075		0.0030		0.0065	0.0168
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Starboard					
Species	Power					
	0.0400	0.0700	0.3000	0.4000	0.6500	0.8500
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	2.6866	1.8924	0.8558	0.8305	0.9918	1.2119
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1855 ± .0026	0.0627 ± .0124	0.0020 ± .0005	0.0016 ± .0007	0.0013 ± .0004	0.0011 ± 0
Toluene	0.0908 ± .0007	0.0286 ± .0067	0.0011± .0009	0.0014 ± .0004	0.0008 ± 0	0.0009± 0
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0354 ± .0018	0.0109 ± .0022	0.0013 ± .0008	0.0009 ± .0010	0.0008 ± .0002	0.0005 ± 0

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		XAD-PUF/Quartz sampling	X		
	Acenaphthene	83-32-9		XAD-PUF/Quartz sampling	X		
	Fluorene	86-73-7		XAD-PUF/Quartz sampling	X		
	Phenanthrene	85-01-8		XAD-PUF/Quartz sampling	X		
	Anthracene	120-12-7		XAD-PUF/Quartz sampling	X		
	Fluoranthene	206-44-0		XAD-PUF/Quartz sampling	X		
	Pyrene	129-00-0		XAD-PUF/Quartz sampling	X		
	Benzo(a)pyrene	50-32-8		XAD-PUF/Quartz sampling	X		
	Indeno[1,2,3-cd]pyrene	193-39-5		XAD-PUF/Quartz sampling	X		
	Dibenz[a,h]anthracene	53-70-3		XAD-PUF/Quartz sampling	X		
	Benzo[ghi]perylene	191-24-2		XAD-PUF/Quartz sampling	X		
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6		XAD-PUF/Quartz sampling	X		
	Octacosane	630-02-4		XAD-PUF/Quartz sampling	X		
	Hexacosane	630-01-3		XAD-PUF/Quartz sampling	X		
	Tetracosane	646-31-1		XAD-PUF/Quartz sampling	X		
	Docosane	629-92-0		XAD-PUF/Quartz sampling	X		
	Eicosane	112-95-8		XAD-PUF/Quartz sampling	X		
	Nonadecane	629-92-5		XAD-PUF/Quartz sampling	X		
	Octadecane	593-46-3		XAD-PUF/Quartz sampling	X		
	Hexadecane	544-76-3		XAD-PUF/Quartz sampling	X		
	Tetradecane	629-59-4		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-2		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3		XAD-PUF/Quartz sampling	X		
	Chrysene	218-01-9		XAD-PUF/Quartz sampling	X		
	Benzo(b)fluoranthene	205-99-2		XAD-PUF/Quartz sampling	X		
	Benzo(k)fluoranthene	207-08-9		XAD-PUF/Quartz sampling	X		
	Dodecane	112-40-3		XAD-PUF/Quartz sampling	X		
Carbonyls							
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	2.20E-03		1.41E-04		6.35E-05	2.83E-05
Acenaphthene	5.64E-03		2.74E-03		2.28E-04	1.15E-04
Fluorene	5.35E-03		1.31E-04		3.50E-05	4.22E-05
Phenanthrene	5.91E-03		4.78E-04		1.49E-04	4.12E-04
Anthracene	8.99E-03		6.20E-04		2.80E-04	4.90E-04
Fluoranthene	1.57E-04		9.68E-05		7.06E-04	1.20E-03
Pyrene	3.01E-04		2.29E-04		9.74E-06	2.63E-03
Benzo(a)pyrene	9.88E-06		BDL		BDL	BDL
Indeno[1,2,3-cd]pyrene	BDL		BDL		BDL	BDL
Dibenz[a,h]anthracene	BDL		BDL		BDL	BDL
Benzo[ghi]perylene	BDL		BDL		BDL	BDL
Hexatriacontane	NM		NM		NM	NM
Triacontane	1.44E-07		1.60E-07		2.96E-07	1.71E-06
Octacosane	5.98E-07		7.03E-07		7.14E-07	4.15E-06
Hexacosane	2.81E-07		3.80E-07		4.66E-07	1.40E-06
Tetracosane	2.79E-07		2.47E-07		3.63E-07	1.22E-06
Docosane	2.84E-07		2.73E-07		5.19E-76	1.86E-06
Eicosane	2.86E-07		2.97E-07		4.65E-07	2.52E-06
Nonadecane	3.75E-07		3.95E-07		4.75E-07	2.79E-06
Octadecane	5.98E-07		7.03E-07		7.14E-07	4.15E-06
Hexadecane	6.20E-07		6.38E-07		6.48E-07	3.67E-06
Tetradecane	3.03E-07		3.63E-07		3.73E-07	1.78E-06
Naphthalene	1.64E-02		NM		5.30E-01	7.74E-02
Naphthalene	0.0349 ± .0010	0.0161 ± .0012	0.0035 ± .0017	0.0024 ± .0004	0.0017 ± .0001	NM
Benz(a)anthracene	6.31E-05		3.83E-05		6.08E-05	1.18E-04
Chrysene	6.39E-05		3.88E-05		7.89E-05	1.20E-04
Benzo(b)fluoranthene	1.35E-05		6.32E-06		8.42E-06	BDL
Benzo(k)fluorantene	3.75E-05		1.37E-05		7.23E-06	BDL
Dodecane	2.84E-07		2.73E-07		2.63E-04	1.86E-06
Formaldehyde	0.73 ± 0.05	0.27 ± 0.04	0.015 ± 0.008	0.012 ± 0.0026	0.01 ± 0.0002	0.007 ± 0
Acetaldehyde	0.35 ± 0.011	0.11 ± 0.013	0.003 ± 0.0015	0.003 ± 0.0004	0.003 ± 0.0003	0.002 ± 0
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0 ± 0	0.1251 ± 0	0.0129 ± .0022	0.0101 ± .0020	0.0098 ± .0048	0.0237 ± 0
mz59	0.1678 ± .0032	0.0540 ± .0061	0.0032 ± .0015	0.0021 ± .0006	0.0021 ± 0007	0.0022 ± 0
mz107	0.1392 ± .0068	0.0491 ± .0076	0.0041 ± .0027	0.0025 ± .0010	0.0023 ± .0007	0.0027 ± 0
MTBE						

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200		X		
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000		X		
	Silicon	7440-21-3	1.200		X		
	Phosphorous	7723-14-0	0.204		X		
	Sulfur	63705-05-5	0.204		X		
	Chlorine	7782-50-5	0.068		X		
	Potassium	744-09-5	0.017		X		
	Calcium	7440-70-2	0.017		X		
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007		X		
	Titanium	7440-32-6	0.051		X		
	Vanadium	7440-62-2	0.020		X		
	Chromium	7440-47-3	0.017		X		
	Manganese	7439-96-5	0.009		X		
	Cobalt	7440-48-4	0.007		X		
	Nickel	7440-2-0	0.003		X		
	Copper	7440-50-8	0.003		X		
	Zinc	7440-66-6	0.003		X		
	Gallium	7440-55-3	0.425		X		
	Germanium	7440-38-2	0.017		X		
	Arsenic	7440-38-2	0.003		X		
	Selenium	7782-49-2	0.017		X		
	Rbidium		0.007		X		
	Strontium	7440-24-6	0.017		X		
	Ytrium		0.003		X		
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017		X		
	Palladium	7440-05-3	0.026		X		
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017		X		
	Indium	7440-74-6	0.017		X		
	Tin	7440-31-6	0.026		X		
	Antimony	7440-36-0	0.024		X		
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170		X		
	Lanthanum	4639-91-0	0.425		X		
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051		X		
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	BDL		1.42E-04		BDL	BDL
Beryllium	NM		NM		NM	NM
Aluminum	BDL		BDL		BDL	BDL
Silicon	BDL		BDL		BDL	BDL
Phosphorous	BDL		BDL		BDL	BDL
Sulfur	BDL		5.43E-06		2.10E-05	BDL
Chlorine	BDL		BDL		3.58E-05	BDL
Potassium	BDL		BDL		BDL	BDL
Calcium	6.69E-06		9.96E-06		6.18E-06	BDL
Scandium	NM		NM		NM	NM
Iron	2.94E-05		1.54E-05		1.73E-05	7.64E-05
Titanium	5.35E-06		9.05E-07		4.94E-06	BDL
Vanadium	BDL		9.05E-07		BDL	5.09E-06
Chromium	5.22E-05		3.62E-05		1.56E-04	2.09E-04
Manganese	6.69E-06		4.53E-06		2.35E-05	2.04E-05
Cobalt	2.68E-06		BDL		BDL	BDL
Nickel	5.35E-06		4.53E-06		3.71E-06	1.02E-05
Copper	BDL		BDL		BDL	BDL
Zinc	BDL		3.62E-06		BDL	BDL
Gallium	1.74E-05		4.53E-06		6.18E-06	7.64E-05
Germanium	BDL		1.81E-06		BDL	BDL
Arsenic	1.34E-06		BDL		BDL	BDL
Selenium	BDL		BDL		BDL	BDL
Rbidium	BDL		BDL		BDL	BDL
Strontium	BDL		BDL		BDL	BDL
Ytrium	BDL		BDL		1.24E-06	BDL
Niobium	NM		NM		NM	NM
Molybdenum	8.03E-06		3.62E-06		3.71E-06	3.05E-05
Palladium	BDL		9.05E-07		4.94E-06	BDL
Silver	NM		NM		NM	NM
Cadmium	BDL		5.43E-06		6.18E-06	5.09E-06
Indium	1.07E-05		7.24E-06		6.18E-06	6.11E-05
Tin	1.34E-06		1.81E-06		BDL	BDL
Antimony	BDL		BDL		BDL	BDL
Cesium	NM		NM		NM	NM
Barium	BDL		BDL		6.18E-06	2.55E-05
Lanthanum	BDL		BDL		BDL	BDL
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	BDL		BDL		BDL	BDL
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8			X		
	Nitrate	7697-37-2					
NM - no measurement was made							
BDL - Below detection limit							
EI for CO2 determined by elemental analysis of fuel							
Notes:							
UCR comments:							
In the original text LODs were provided for all compounds and species measured on the high-flow side.							
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.							
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.							
UCR only made one measurement so uncertainty cannot be calculated.							
Analytical uncertainty for all measurement methods was provided in the original text.							

Table I.2: PM data and speciation profiles for N435WN Starboard Engine (continued)

Aircraft Tail Number:	N435WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.216	2.04	7.94	9.35	13.6	17.5
NO2	2.69	1.89	0.856	0.830	0.992	1.21
NOX	2.90	3.94	8.80	10.2	14.6	18.7
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	NM	NM	NM	NM	NM	NM
CO	21.2	14.5	1.53	0.898	0.453	0.428
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	0.0012		0.0007		0.0008	0.0029
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.3: PM data and speciation profiles for N353SW Port Engine

Aircraft Tail Number:	N353SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
EC	Mass						
OC							
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	10.01 ± 0.07	11.42 ± 0.10	13.77 ± 0.58	14.02 ± 0.57	19.58 ± 0.31	NM
Sigma	1.50 ± 0.003	1.48 ± 0.0026	1.52 ± 0.03	1.56 ± 0.02	1.78 ± 0.01	NM
DgeomM (nm)	24.45 ± 0.14	22.74 ± 0.14	26.39 ± 1.19	29.15 ± 0.47	49.24 ± 0.21	NM
	Emission Indices (g/kg fuel)					
Number	2.14 ± 0.07	0.74 ± 0.03	0.86 ± 0.16	0.76 ± 0.08	1.70 ± 0.04	NM
Mass	0.01 ± 0.0002	0.003 ± 0.0001	0.004 ± 0.0008	0.005 ± 0.0003	0.04 ± 0.0008	NM
	NM		NM		NM	NM
	NM		NM		NM	NM
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	1.09	0.233	BDL	0.004	BDL	NM
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.2883 ± 0	0.0631 ± .0053	0.0021 ± .0007	0.0020 ± .0017	0.0019 ± .0001	NM
Toluene	0.1355 ± 0	0.0246 ± .0024	0.0043 ± 0	0.0028 ± .0027	0.0011 ± .0004	NM
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0571 ± 0	0.0098 ± .0021	0.0011 ± .0005	0.0007 ± .0003	0.0006 ± 0	NM

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		**XAD-PUF/Quartz sampling**			
	Acenaphthene	83-32-9					
	Fluorene	86-73-7					
	Phenanthrene	85-01-8					
	Anthracene	120-12-7					
	Fluoranthene	206-44-0					
	Pyrene	129-00-0					
	Benzo(a)pyrene	50-32-8					
	Indeno[1,2,3-cd]pyrene	193-39-5					
	Dibenz[a,h]anthracene	53-70-3					
	Benzo[ghi]perylene	191-24-2					
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6					
	Octacosane	630-02-4					
	Hexacosane	630-01-3					
	Tetracosane	646-31-1					
	Docosane	629-92-0					
	Eicosane	112-95-8					
	Nonadecane	629-92-5					
	Octadecane	593-46-3					
	Hexadecane	544-76-3					
	Tetradecane	629-59-4					
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3					
	Chrysene	218-01-9					
	Benzo(b)fluoranthene	205-99-2					
	Benzo(k)fluoranthene	207-08-9					
	Dodecane	112-40-3					
Carbonyls				(DNPH Sampling)			
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	NM		NM		NM	NM
Acenaphthene	NM		NM		NM	NM
Fluorene	NM		NM		NM	NM
Phenanthrene	NM		NM		NM	NM
Anthracene	NM		NM		NM	NM
Fluoranthene	NM		NM		NM	NM
Pyrene	NM		NM		NM	NM
Benzo(a)pyrene	NM		NM		NM	NM
Indeno[1,2,3-cd]pyrene	NM		NM		NM	NM
Dibenz[a,h]anthracene	NM		NM		NM	NM
Benzo[ghi]perylene	NM		NM		NM	NM
Hexatriacontane	NM		NM		NM	NM
Triacontane	NM		NM		NM	NM
Octacosane	NM		NM		NM	NM
Hexacosane	NM		NM		NM	NM
Tetracosane	NM		NM		NM	NM
Docosane	NM		NM		NM	NM
Eicosane	NM		NM		NM	NM
Nonadecane	NM		NM		NM	NM
Octadecane	NM		NM		NM	NM
Hexadecane	NM		NM		NM	NM
Tetradecane	NM		NM		NM	NM
Naphthalene	0.0523 ± 0	0.0112 ± .0024	0.0025 ± .0001	0.0013 ± 0	0.0021 ± .0016	NM
Benz(a)anthracene	NM		NM		NM	NM
Chrysene	NM		NM		NM	NM
Benzo(b)fluoranthene	NM		NM		NM	NM
Benzo(k)fluorantene	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Formaldehyde	1.13 ± 0	0.28 ± 0.017	0.00004 ± 0.004	0.0012 ± 0.002	(-)0.001 ± 0.001	NM
Acetaldehyde	0.49 ± 0	0.13 ± 0.008	0.004 ± 0.0005	0.004 ± 0.00006	0.003 ± 0.0003	NM
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0 ± 0	0.1719 ± .0168	0 ± 0	0.0461 ± 0	0.0129 ± 0	0 ± 0
mz59	0.2055 ± 0	0.0565 ± .0030	0.0033 ± .0005	0.0025 ± 0	0.0016 ± .0004	0 ± 0
mz107	0.2142 ± 0	0.0415 ± .0064	0.0032 ± .0020	0.0021 ± .0003	0.0025 ± .0012	0 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200				
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000				
	Silicon	7440-21-3	1.200				
	Phosphorous	7723-14-0	0.204				
	Sulfur	63705-05-5	0.204				
	Chlorine	7782-50-5	0.068				
	Potassium	744-09-5	0.017				
	Calcium	7440-70-2	0.017				
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007				
	Titanium	7440-32-6	0.051				
	Vanadium	7440-62-2	0.020				
	Chromium	7440-47-3	0.017				
	Manganese	7439-96-5	0.009				
	Cobalt	7440-48-4	0.007				
	Nickel	7440-2-0	0.003				
	Copper	7440-50-8	0.003				
	Zinc	7440-66-6	0.003				
	Gallium	7440-55-3	0.425				
	Germanium	7440-38-2	0.017				
	Arsenic	7440-38-2	0.003				
	Selenium	7782-49-2	0.017				
	Rbidium		0.007				
	Strontium	7440-24-6	0.017				
	Ytrium		0.003				
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017				
	Palladium	7440-05-3	0.026				
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017				
	Indium	7440-74-6	0.017				
	Tin	7440-31-6	0.026				
	Antimony	7440-36-0	0.024				
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170				
	Lanthanum	4639-91-0	0.425				
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051				
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	NM		NM		NM	NM
Beryllium	NM		NM		NM	NM
Aluminum	NM		NM		NM	NM
Silicon	NM		NM		NM	NM
Phosphorous	NM		NM		NM	NM
Sulfur	NM		NM		NM	NM
Chlorine	NM		NM		NM	NM
Potassium	NM		NM		NM	NM
Calcium	NM		NM		NM	NM
Scandium	NM		NM		NM	NM
Iron	NM		NM		NM	NM
Titanium	NM		NM		NM	NM
Vanadium	NM		NM		NM	NM
Chromium	NM		NM		NM	NM
Manganese	NM		NM		NM	NM
Cobalt	NM		NM		NM	NM
Nickel	NM		NM		NM	NM
Copper	NM		NM		NM	NM
Zinc	NM		NM		NM	NM
Gallium	NM		NM		NM	NM
Germanium	NM		NM		NM	NM
Arsenic	NM		NM		NM	NM
Selenium	NM		NM		NM	NM
Rbidium	NM		NM		NM	NM
Strontium	NM		NM		NM	NM
Ytrium	NM		NM		NM	NM
Niobium	NM		NM		NM	NM
Molybdenum	NM		NM		NM	NM
Palladium	NM		NM		NM	NM
Silver	NM		NM		NM	NM
Cadmium	NM		NM		NM	NM
Indium	NM		NM		NM	NM
Tin	NM		NM		NM	NM
Antimony	NM		NM		NM	NM
Cesium	NM		NM		NM	NM
Barium	NM		NM		NM	NM
Lanthanum	NM		NM		NM	NM
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	NM		NM		NM	NM
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8					
	Nitrate	7697-37-2					

NM - no measurement was made

BDL - Below detection limit

EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.

LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.

These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.

Analytical uncertainty for all measurement methods was provided in the original text.

Table I.3: PM data and speciation profiles for N353SW Port Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.16	0.892	6.09	7.04	9.36	NM
NO2	2.51	2.18	1.00	0.885	0.88	NM
NOX	2.67	3.08	7.09	7.92	10.2	NM
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O						
CO	22.2	16.9	3.11	1.85	0.786	NM
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	NM	NM	NM	NM	NM	NM
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.4: PM data and speciation profiles for N353SW Starboard Engine

Aircraft Tail Number:	N353SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
	Mass				X		
EC					X		
OC					X		
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	13.25 ± 0.12	11.76 ± 0.10	15.11 ± 0.43	17.01 ± 0.43	20.39 ± 0.24	28.65 ± 0.29
Sigma	1.52 ± 0.01	1.56 ± 0.002	1.60 ± 0.013	1.61 ± 0.012	1.83 ± 0.008	1.93 ± 0.01
DgeomM (nm)	28.28 ± 0.71	26.51 ± 0.19	31.67 ± 0.53	33.45 ± 0.13	51.03 ± 0.23	73.17 ± 0.61
	Emission Indices (g/kg fuel)					
Number	1.13 ± 0.05	0.76 ± 0.02	0.74 ± 0.10	0.66 ± 0.05	2.92 ± 0.06	4.13 ± 0.145
Mass	0.005 ± 0.0002	0.003 ± 0.0001	0.004 ± 0.0004	0.006 ± 0.0002	0.058 ± 0.0013	0.254 ± 0.014
Mass	0.0092		0.0058		NM	0.1820
	0.0044		0.0035		NM	0.1540
	0.0065		0.0035		NM	0.0221
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.712	0.138	BDL	0.00289	BDL	BDL
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1998 ± .0952	0.0375 ± .0044	0.0019 ± .0004	0.0012 ± .0003	0.0012 ± .0003	0.0012 ± 0
Toluene	0.0940 ± .0565	0.0127 ± .0014	0.0027 ± .0027	0.0009 ± .0002	0.0009 ± .0002	0.0007 ± 0
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0375 ± .0204	0.0056 ± .0012	0.0011 ± .0007	0.0004 ± .0001	0.0004 ± .0001	0.0005 ± 0

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		XAD-PUF/Quartz sampling	X		
	Acenaphthene	83-32-9		XAD-PUF/Quartz sampling	X		
	Fluorene	86-73-7		XAD-PUF/Quartz sampling	X		
	Phenanthrene	85-01-8		XAD-PUF/Quartz sampling	X		
	Anthracene	120-12-7		XAD-PUF/Quartz sampling	X		
	Fluoranthene	206-44-0		XAD-PUF/Quartz sampling	X		
	Pyrene	129-00-0		XAD-PUF/Quartz sampling	X		
	Benzo(a)pyrene	50-32-8		XAD-PUF/Quartz sampling	X		
	Indeno[1,2,3-cd]pyrene	193-39-5		XAD-PUF/Quartz sampling	X		
	Dibenz[a,h]anthracene	53-70-3		XAD-PUF/Quartz sampling	X		
	Benzo[ghi]perylene	191-24-2		XAD-PUF/Quartz sampling	X		
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6		XAD-PUF/Quartz sampling	X		
	Octacosane	630-02-4		XAD-PUF/Quartz sampling	X		
	Hexacosane	630-01-3		XAD-PUF/Quartz sampling	X		
	Tetracosane	646-31-1		XAD-PUF/Quartz sampling	X		
	Docosane	629-92-0		XAD-PUF/Quartz sampling	X		
	Eicosane	112-95-8		XAD-PUF/Quartz sampling	X		
	Nonadecane	629-92-5		XAD-PUF/Quartz sampling	X		
	Octadecane	593-46-3		XAD-PUF/Quartz sampling	X		
	Hexadecane	544-76-3		XAD-PUF/Quartz sampling	X		
	Tetradecane	629-59-4		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-2		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3		XAD-PUF/Quartz sampling	X		
	Chrysene	218-01-9		XAD-PUF/Quartz sampling	X		
	Benzo(b)fluoranthene	205-99-2		XAD-PUF/Quartz sampling	X		
	Benzo(k)fluoranthene	207-08-9		XAD-PUF/Quartz sampling	X		
	Dodecane	112-40-3		XAD-PUF/Quartz sampling	X		
Carbonyls							
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	0.021377042		1.91247E-03		0.000669928	2.72632E-05
Acenaphthene	0.038970077		1.60742E-02		0.004724923	8.414E-05
Fluorene	0.003237607		5.54317E-05		2.24589E-05	1.33099E-05
Phenanthrene	0.004059081		2.63478E-04		3.05338E-05	0.000357917
Anthracene	0.004678825		3.30689E-04		0.000258091	0.000425889
Fluoranthene	0.000315034		0.000102087		2.97E-06	0.001133975
Pyrene	0.000752021		1.81276E-04		0.000437521	0.001819716
Benzo(a)pyrene	BDL		BDL		1.44753E-05	2.38615E-05
Indeno[1,2,3-cd]pyrene	BDL		BDL		1.15698E-05	BDL
Dibenz[a,h]anthracene	BDL		BDL		1.93E-05	BDL
Benzo[ghi]perylene	BDL		BDL		BDL	BDL
Hexatriacontane	NM		NM		NM	NM
Triacontane	2.33E-06		1.80E-06		2.73E-06	9.02E-06
Octacosane	6.93E-06		2.20E-06		2.39E-06	3.39E-05
Hexacosane	1.67E-05		4.46E-05		2.59E-05	5.53E-04
Tetracosane	4.34E-06		2.99E-06		3.55E-06	1.14E-05
Docosane	2.58E-06		2.49E-06		4.38E-06	1.51E-05
Eicosane	2.87E-06		3.12E-06		4.38E-06	2.23E-05
Nonadecane	5.39E-06		5.85E-06		7.45E-06	3.13E-05
Octadecane	1.87E-05		1.86E-05		2.13E-05	9.21E-05
Hexadecane	6.46E-06		9.87E-06		1.15E-05	5.23E-05
Tetradecane	2.94E-05		2.97E-05		4.52E-05	2.32E-04
Naphthalene	9.69E-03		1.25564E+00		5.52E+00	6.68E-02
Naphthalene	0.0317 ± .0183	0.0072 ± .0018	0.0020 ± .0004	0.0011 ± .0003	0.0011 ± .0003	0.0010 ± 0
Benz(a)anthracene	2.74547E-05		1.00377E-05		5.22E-05	2.05E-04
Chrysene	2.78242E-05		1.01728E-05		5.49E-05	2.91E-04
Benzo(b)fluoranthene	BDL		BDL		1.69E-05	BDL
Benzo(k)fluorantene	BDL		BDL		3.73E-05	6.35E-05
Dodecane	1.59E-03		2.68E-04		9.81E-05	1.23E-03
Formaldehyde	0.80 ± 0.34	0.16 ± 0.06	0.0018 ± 0.004	0.002 ± 0.0009	0.002 ± 0.0009	0.002 ± 0
Acetaldehyde	0.36 ± 0.14	0.08 ± 0.007	0.005 ± 0.0005	0.002 ± 0.0008	0.002 ± 0.0008	0.002 ± 0
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0.3604 ± .0364	0.1031 ± .0218	0.0233 ± 0	0.0461 ± 0	0.0130 ± 0	0.0066 ± 0
mz59	0.1521 ± .0585	0.0354 ± .0042	0.0027 ± .0011	0.0014 ± .0002	0.0014 ± .0002	0.0014 ± 0
mz107	0.1455 ± .0844	0.0250 ± .0045	0.0023 ± .0010	0.0017 ± .0004	0.0017 ± .0004	0.0021 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200		X		
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000		X		
	Silicon	7440-21-3	1.200		X		
	Phosphorous	7723-14-0	0.204		X		
	Sulfur	63705-05-5	0.204		X		
	Chlorine	7782-50-5	0.068		X		
	Potassium	744-09-5	0.017		X		
	Calcium	7440-70-2	0.017		X		
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007		X		
	Titanium	7440-32-6	0.051		X		
	Vanadium	7440-62-2	0.020		X		
	Chromium	7440-47-3	0.017		X		
	Manganese	7439-96-5	0.009		X		
	Cobalt	7440-48-4	0.007		X		
	Nickel	7440-2-0	0.003		X		
	Copper	7440-50-8	0.003		X		
	Zinc	7440-66-6	0.003		X		
	Gallium	7440-55-3	0.425		X		
	Germanium	7440-38-2	0.017		X		
	Arsenic	7440-38-2	0.003		X		
	Selenium	7782-49-2	0.017		X		
	Rbidium		0.007		X		
	Strontium	7440-24-6	0.017		X		
	Ytrium		0.003		X		
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017		X		
	Palladium	7440-05-3	0.026		X		
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017		X		
	Indium	7440-74-6	0.017		X		
	Tin	7440-31-6	0.026		X		
	Antimony	7440-36-0	0.024		X		
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170		X		
	Lanthanum	4639-91-0	0.425		X		
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051		X		
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	4.69E-05		BDL		8.97E-05	BDL
Beryllium	NM		NM		NM	NM
Aluminum	6.32E-05		BDL		1.18E-04	3.40E-04
Silicon	7.45E-05		8.30E-05		NM	NM
Phosphorous	BDL		BDL		NM	NM
Sulfur	2.47E-05		2.29E-05		1.48E-04	5.58E-04
Chlorine	BDL		BDL		7.68E-05	BDL
Potassium	BDL		BDL		BDL	BDL
Calcium	4.19E-07		3.75E-06		2.28E-06	5.15E-05
Scandium	NM		NM		NM	NM
Iron	2.09E-06		2.29E-05		BDL	3.43E-05
Titanium	2.09E-06		2.50E-06		4.56E-06	8.58E-06
Vanadium	BDL		BDL		7.61E-07	BDL
Chromium	8.37E-07		1.00E-05		5.32E-06	3.14E-05
Manganese	4.19E-07		2.09E-06		2.28E-06	1.72E-05
Cobalt	BDL		BDL		1.52E-06	8.58E-06
Nickel	BDL		1.67E-06		BDL	1.14E-05
Copper	BDL		4.17E-07		1.52E-06	2.86E-06
Zinc	4.19E-06		4.59E-06		6.08E-06	2.57E-05
Gallium	BDL		0.00E+00		1.52E-06	0.00E+00
Germanium	8.37E-07		1.25E-06		0.00E+00	3.14E-05
Arsenic	BDL		BDL		BDL	BDL
Selenium	BDL		BDL		BDL	BDL
Rbidium	BDL		BDL		NM	NM
Strontium	BDL		BDL		NM	NM
Ytrium	BDL		4.17E-07		1.52E-06	5.72E-06
Niobium	NM		NM		NM	NM
Molybdenum	1.26E-06		4.17E-07		1.52E-06	2.86E-06
Palladium	BDL		BDL		6.08E-06	BDL
Silver	NM		NM		NM	NM
Cadmium	3.35E-06		BDL		2.28E-06	5.72E-06
Indium	1.67E-06		2.09E-06		9.13E-06	1.43E-05
Tin	1.67E-06		BDL		BDL	1.43E-05
Antimony	BDL		BDL		BDL	BDL
Cesium	NM		NM		NM	NM
Barium	5.02E-06		2.50E-06		3.04E-06	0.00E+00
Lanthanum	BDL		BDL		NM	NM
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	BDL		BDL		NM	NM
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8			X		
	Nitrate	7697-37-2					

NM - no measurement was made

BDL - Below detection limit

EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.

LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.

These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.

Analytical uncertainty for all measurement methods was provided in the original text.

Table I.4: PM data and speciation profiles for N353SW Starboard Engine (continued)

Aircraft Tail Number:	N353SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.204	1.21	5.70	6.89	9.41	14.6
NO2	2.21	1.91	0.984	0.887	0.902	1.22
NOX	2.41	3.12	6.69	7.78	10.3	15.8
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O						
CO	19.3	12.3	3.05	1.92	0.935	1.068
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	0.000210879		0.00024978		0.00077622	0.003275906
Nitrate	NM		NM		NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.5: PM data and speciation profiles for N695SW Port Engine

Aircraft Tail Number:	N695SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			
	Sigma		1.05	DMS500			
	DgeomM (nm)		5	DMS500			
	Number(10e15/kg fuel)		0.02	DMS500			
	Mass		1.0E-06	DMS500			
EC	Mass						
OC							
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	NM	NM	NM	NM	NM	NM
Sigma	NM	NM	NM	NM	NM	NM
DgeomM (nm)	NM	NM	NM	NM	NM	NM
	Emission Indices (g/kg fuel)					
Number	NM	NM	NM	NM	NM	NM
Mass	NM	NM	NM	NM	NM	NM
	NM		NM		NM	NM
	NM		NM		NM	NM
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.571	0.360	BDL	BDL	BDL	NM
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1228 ± .0012	0.0739 ± .0057	0.0041 ± .0018	0.0009 ± .0009	0.0015 ± .0008	NM
Toluene	0.0582 ± .0033	0.0376 ± .0065	0.0026 ± .0009	0.0045 ± .0006	0.0033 ± .0023	NM
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0270 ± .0002	0.0159 ± .0007	0.0028 ± .0018	0.0018 ± .0004	0.0019 ± .0004	NM

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		**XAD-PUF/Quartz sampling**			
	Acenaphthene	83-32-9					
	Fluorene	86-73-7					
	Phenanthrene	85-01-8					
	Anthracene	120-12-7					
	Fluoranthene	206-44-0					
	Pyrene	129-00-0					
	Benzo(a)pyrene	50-32-8					
	Indeno[1,2,3-cd]pyrene	193-39-5					
	Dibenz[a,h]anthracene	53-70-3					
	Benzo[ghi]perylene	191-24-2					
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6					
	Octacosane	630-02-4					
	Hexacosane	630-01-3					
	Tetracosane	646-31-1					
	Docosane	629-92-0					
	Eicosane	112-95-8					
	Nonadecane	629-92-5					
	Octadecane	593-46-3					
	Hexadecane	544-76-3					
	Tetradecane	629-59-4					
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3					
	Chrysene	218-01-9					
	Benzo(b)fluoranthene	205-99-2					
	Benzo(k)fluoranthene	207-08-9					
	Dodecane	112-40-3					
Carbonyls				(DNPH Sampling)			
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	NM		NM		NM	NM
Acenaphthene	NM		NM		NM	NM
Fluorene	NM		NM		NM	NM
Phenanthrene	NM		NM		NM	NM
Anthracene	NM		NM		NM	NM
Fluoranthene	NM		NM		NM	NM
Pyrene	NM		NM		NM	NM
Benzo(a)pyrene	NM		NM		NM	NM
Indeno[1,2,3-cd]pyrene	NM		NM		NM	NM
Dibenz[a,h]anthracene	NM		NM		NM	NM
Benzo[ghi]perylene	NM		NM		NM	NM
Hexatriacontane	NM		NM		NM	NM
Triacontane	NM		NM		NM	NM
Octacosane	NM		NM		NM	NM
Hexacosane	NM		NM		NM	NM
Tetracosane	NM		NM		NM	NM
Docosane	NM		NM		NM	NM
Eicosane	NM		NM		NM	NM
Nonadecane	NM		NM		NM	NM
Octadecane	NM		NM		NM	NM
Hexadecane	NM		NM		NM	NM
Tetradecane	NM		NM		NM	NM
Naphthalene	0.0298 ± .0020	0.0179 ± .0014	0.0053 ± .0025	0.0033 ± .0005	0.0034 ± .0014	NM
Benz(a)anthracene	NM		NM		NM	NM
Chrysene	NM		NM		NM	NM
Benzo(b)fluoranthene	NM		NM		NM	NM
Benzo(k)fluorantene	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Formaldehyde	0.62 ± 0.03	0.41 ± 0.03	0.008 ± 0.005	0.005 ± 0.002	0.005 ± 0.003	NM
Acetaldehyde	0.30 ± 0.004	0.20 ± 0.017	0.01 ± 0.0005	0.009 ± 0.0004	0.008 ± 0.0005	NM
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0.3454 ± 0	0.2085 ± .0270	0.0325 ± 0	0 ± 0	0.0190 ± 0	0 ± 0
mz59	0.1267 ± .0054	0.0862 ± .0064	0.0053 ± 0	0.0067 ± .0014	0.0042 ± .0007	0 ± 0
mz107	0.1140 ± .0097	0.0718 ± .0042	0.0075 ± .0046	0.0034 ± .0002	0.0043 ± .0003	0 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200				
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000				
	Silicon	7440-21-3	1.200				
	Phosphorous	7723-14-0	0.204				
	Sulfur	63705-05-5	0.204				
	Chlorine	7782-50-5	0.068				
	Potassium	744-09-5	0.017				
	Calcium	7440-70-2	0.017				
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007				
	Titanium	7440-32-6	0.051				
	Vanadium	7440-62-2	0.020				
	Chromium	7440-47-3	0.017				
	Manganese	7439-96-5	0.009				
	Cobalt	7440-48-4	0.007				
	Nickel	7440-2-0	0.003				
	Copper	7440-50-8	0.003				
	Zinc	7440-66-6	0.003				
	Gallium	7440-55-3	0.425				
	Germanium	7440-38-2	0.017				
	Arsenic	7440-38-2	0.003				
	Selenium	7782-49-2	0.017				
	Rbidium		0.007				
	Strontium	7440-24-6	0.017				
	Ytrium		0.003				
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017				
	Palladium	7440-05-3	0.026				
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017				
	Indium	7440-74-6	0.017				
	Tin	7440-31-6	0.026				
	Antimony	7440-36-0	0.024				
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170				
	Lanthanum	4639-91-0	0.425				
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051				
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	NM		NM		NM	NM
Beryllium	NM		NM		NM	NM
Aluminum	NM		NM		NM	NM
Silicon	NM		NM		NM	NM
Phosphorous	NM		NM		NM	NM
Sulfur	NM		NM		NM	NM
Chlorine	NM		NM		NM	NM
Potassium	NM		NM		NM	NM
Calcium	NM		NM		NM	NM
Scandium	NM		NM		NM	NM
Iron	NM		NM		NM	NM
Titanium	NM		NM		NM	NM
Vanadium	NM		NM		NM	NM
Chromium	NM		NM		NM	NM
Manganese	NM		NM		NM	NM
Cobalt	NM		NM		NM	NM
Nickel	NM		NM		NM	NM
Copper	NM		NM		NM	NM
Zinc	NM		NM		NM	NM
Gallium	NM		NM		NM	NM
Germanium	NM		NM		NM	NM
Arsenic	NM		NM		NM	NM
Selenium	NM		NM		NM	NM
Rbidium	NM		NM		NM	NM
Strontium	NM		NM		NM	NM
Ytrium	NM		NM		NM	NM
Niobium	NM		NM		NM	NM
Molybdenum	NM		NM		NM	NM
Palladium	NM		NM		NM	NM
Silver	NM		NM		NM	NM
Cadmium	NM		NM		NM	NM
Indium	NM		NM		NM	NM
Tin	NM		NM		NM	NM
Antimony	NM		NM		NM	NM
Cesium	NM		NM		NM	NM
Barium	NM		NM		NM	NM
Lanthanum	NM		NM		NM	NM
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	NM		NM		NM	NM
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8					
	Nitrate	7697-37-2					

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.5: PM data and speciation profiles for N695SW Port Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.23	0.69	5.54	7.22	10.2	NM
NO2	2.30	2.21	0.979	0.905	0.999	NM
NOX	2.53	2.90	6.52	8.12	11.2	NM
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	NM	NM	NM	NM	NM	NM
CO	19.6	16.8	3.26	1.80	1.04	NM
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	NM	NM	NM	NM	NM	NM
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made

BDL - Below detection limit

EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.

LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.

These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty

UCR only made one measurement so uncertainty cannot be calculated.

Analytical uncertainty for all measurement methods was provided in the original text.

Table I.6: PM data and speciation profiles for N695SW Starboard Engine

Aircraft Tail Number:	N695SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
	Mass			DMS500	X		
EC					X		
OC					X		
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	11.38 ± 0.14	12.98 ± 0.08	16.98 ± 0.20	19.07 ± 0.18	31.05 ± 0.23	38.54 ± 0.24
Sigma	1.54 ± 0.007	1.52 ± 0.005	1.71 ± 0.004	1.73 ± 0.005	1.63 ± 0.009	1.69 ± 0.01
DgeomM (nm)	29.9 ± 2.02	28.77 ± 0.24	39.94 ± 0.33	46.86 ± 0.16	61.67 ± 0.22	81.16 ± 0.43
	Emission Indices (g/kg fuel)					
Number	2.70 ± 0.16	0.28 ± 0.01	1.53 ± 0.05	2.07 ± 0.04	2.00 ± 0.05	2.51 ± 0.049
Mass	0.007 ± 0.0003	0.003 ± 0.0002	0.014 ± 0.0004	0.04 ± 0.0005	0.092 ± 0.002	0.25 ± 0.0072
Mass	0.0102		0.0196		0.0804	0.2160
	0.0056		0.0135		0.0595	0.1708
	0.0080		0.0064		0.0157	0.0406
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS			
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.998	0.505	0.00509	BDL	BDL	BDL
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*						
Benzene	0.1984 ± .0008	0.1031 ± .0083	0.0035 ± .0003	0.0016 ± 0	0.0006 ± .0004	0.0009 ± 0
Toluene	0.1025 ± 0	0.0478 ± .0035	0.0027 ± .0005	0.0021 ± .0003	0.0019 ± 0	0.0010 ± 0
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0496 ± 0	0.0215 ± .0033	0.0021 ± .0020	0.0015 ± .0005	0.0013 ± .0002	0.0004 ± 0

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		XAD-PUF/Quartz sampling	X		
	Acenaphthene	83-32-9		XAD-PUF/Quartz sampling	X		
	Fluorene	86-73-7		XAD-PUF/Quartz sampling	X		
	Phenanthrene	85-01-8		XAD-PUF/Quartz sampling	X		
	Anthracene	120-12-7		XAD-PUF/Quartz sampling	X		
	Fluoranthene	206-44-0		XAD-PUF/Quartz sampling	X		
	Pyrene	129-00-0		XAD-PUF/Quartz sampling	X		
	Benzo(a)pyrene	50-32-8		XAD-PUF/Quartz sampling	X		
	Indeno[1,2,3-cd]pyrene	193-39-5		XAD-PUF/Quartz sampling	X		
	Dibenz[a,h]anthracene	53-70-3		XAD-PUF/Quartz sampling	X		
	Benzo[ghi]perylene	191-24-2		XAD-PUF/Quartz sampling	X		
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6		XAD-PUF/Quartz sampling	X		
	Octacosane	630-02-4		XAD-PUF/Quartz sampling	X		
	Hexacosane	630-01-3		XAD-PUF/Quartz sampling	X		
	Tetracosane	646-31-1		XAD-PUF/Quartz sampling	X		
	Docosane	629-92-0		XAD-PUF/Quartz sampling	X		
	Eicosane	112-95-8		XAD-PUF/Quartz sampling	X		
	Nonadecane	629-92-5		XAD-PUF/Quartz sampling	X		
	Octadecane	593-46-3		XAD-PUF/Quartz sampling	X		
	Hexadecane	544-76-3		XAD-PUF/Quartz sampling	X		
	Tetradecane	629-59-4		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-2		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3					
	Chrysene	218-01-9					
	Benzo(b)fluoranthene	205-99-2					
	Benzo(k)fluoranthene	207-08-9					
	Dodecane	112-40-3					
Carbonyls							
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	4.12E-02		1.24E-03		2.59E-03	7.68E-04
Acenaphthene	3.74E-02		8.60E-03		2.02E-02	4.51E-03
Fluorene	1.11E-03		8.07E-06		4.74E-05	3.21E-05
Phenanthrene	8.58E-04		5.56E-05		1.44E-04	9.57E-05
Anthracene	1.22E-03		9.07E-06		2.29E-04	4.73E-04
Fluoranthene	1.31E-04		7.27E-05		5.10E-06	1.23E-03
Pyrene	1.52E-04		1.73E-04		1.64E-04	7.35E-04
Benzo(a)pyrene	2.26E-05		3.35E-06		5.34E-06	2.43E-05
Indeno[1,2,3-cd]pyrene	4.98547E-06		BDL		BDL	1.96E-05
Dibenz[a,h]anthracene	BDL		BDL		BDL	1.65E-05
Benzo[ghi]perylene	5.24029E-06		BDL		BDL	BDL
Hexatriacontane	NM		NM		NM	NM
Triacontane	4.89E-06		3.80E-06		4.92E-06	1.50E-05
Octacosane	7.96E-06		4.21E-06		1.11E-05	3.94E-05
Hexacosane	2.08E-05		3.55E-05		1.07E-04	3.77E-04
Tetracosane	3.09E-06		4.07E-06		4.32E-06	9.49E-06
Docosane	3.81E-06		4.60E-06		7.23E-06	1.89E-05
Eicosane	5.61E-06		4.86E-06		6.08E-06	2.16E-05
Nonadecane	4.64E-05		1.07E-05		1.21E-05	3.07E-05
Octadecane	2.69E-04		1.34E-05		7.09E-05	1.06E-04
Hexadecane	3.75E-04		1.54E-05		2.30E-05	5.43E-05
Tetradecane	3.89E-05		6.07E-05		1.22E-04	2.34E-01
Naphthalene	2.16E-02		2.18E-01		2.25E+00	1.06E+00
Naphthalene	0.0427 ± .0015	0.0222 ± .0031	0.0046 ± .0040	0.0027 ± .0005	0.0024 ± .0002	
Benz(a)anthracene	6.17E-06		3.71E-05		3.91E-05	9.35E-05
Chrysene	7.88E-05		3.76E-05		3.96E-05	1.63E-04
Benzo(b)fluoranthene	9.85E-06		8.62E-06		BDL	BDL
Benzo(k)fluorantene	2.05E-05		1.42E-05		9.85E-06	5.83E-05
Dodecane	1.55E-03		2.71E-04		5.71E-04	1.76E-03
Formaldehyde	0.98 ± 0.014	0.53 ± 0.039	0.012 ± 0.0008	0.002 ± 0.0032	(-)0.0003 ± 0.003	0.0005 ± 0
Acetaldehyde	0.45 ± 0.018	0.26 ± 0.018	0.009 ± 0.004	0.0038 ± 0.0016	0.003 ± 0.0004	0.004 ± 0
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0.6500 ± 0	0.3004 ± .0133	0.0158 ± 0	0.0153 ± 0	0.0142 ± 0	0.0045 ± 0
mz59	0.1854 ± .0024	0.1105 ± .0073	0.0050 ± .0019	0.0029 ± .0005	0.0023 ± .0006	0.0015 ± 0
mz107	0.1731 ± .0059	0.0853 ± .0102	0.0069 ± .0047	0.0028 ± .0004	0.0026 ± .0001	0.0015 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200		X		
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000		X		
	Silicon	7440-21-3	1.200		X		
	Phosphorous	7723-14-0	0.204		X		
	Sulfur	63705-05-5	0.204		X		
	Chlorine	7782-50-5	0.068		X		
	Potassium	744-09-5	0.017		X		
	Calcium	7440-70-2	0.017		X		
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007		X		
	Titanium	7440-32-6	0.051		X		
	Vanadium	7440-62-2	0.020		X		
	Chromium	7440-47-3	0.017		X		
	Manganese	7439-96-5	0.009		X		
	Cobalt	7440-48-4	0.007		X		
	Nickel	7440-2-0	0.003		X		
	Copper	7440-50-8	0.003		X		
	Zinc	7440-66-6	0.003		X		
	Gallium	7440-55-3	0.425		X		
	Germanium	7440-38-2	0.017		X		
	Arsenic	7440-38-2	0.003		X		
	Selenium	7782-49-2	0.017		X		
	Rbidium		0.007		X		
	Strontium	7440-24-6	0.017		X		
	Ytrium		0.003		X		
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017		X		
	Palladium	7440-05-3	0.026		X		
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017		X		
	Indium	7440-74-6	0.017		X		
	Tin	7440-31-6	0.026		X		
	Antimony	7440-36-0	0.024		X		
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170		X		
	Lanthanum	4639-91-0	0.425				
	Platinum	7440-06-4			X		
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051				
	Bismuth	7440-69-9			X		
	Uranium	7440-61-1					

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM	NM	NM	NM	NM	NM
Magnesium	5.56E-05		1.07E-04		BDL	6.18E-04
Beryllium	NM		NM		NM	NM
Aluminum	BDL		1.35E-04		2.79E-04	BDL
Silicon	BDL		1.94E-04		BDL	BDL
Phosphorous	BDL		BDL		BDL	BDL
Sulfur	7.30E-05		1.89E-04		4.89E-04	8.01E-04
Chlorine	BDL		BDL		BDL	BDL
Potassium	BDL		BDL		BDL	BDL
Calcium	2.58E-06		1.41E-05		2.51E-05	4.41E-05
Scandium	NM		NM		NM	NM
Iron	8.40E-06		3.39E-05		3.39E-05	2.57E-05
Titanium	BDL		4.94E-06		BDL	BDL
Vanadium	6.46E-07		BDL		1.25E-06	BDL
Chromium	5.81E-06		3.24E-05		1.42E-04	1.43E-04
Manganese	2.58E-06		8.46E-06		2.38E-05	4.04E-05
Cobalt	BDL		7.05E-07		8.78E-06	3.68E-06
Nickel	6.46E-07		2.82E-06		1.76E-05	2.21E-05
Copper	BDL		2.12E-06		BDL	BDL
Zinc	6.46E-07		2.47E-05		1.25E-06	4.41E-05
Gallium	1.23E-05		4.94E-06		0.00E+00	2.57E-05
Germanium	6.46E-07		4.23E-06		6.27E-06	1.84E-05
Arsenic	BDL		BDL		BDL	BDL
Selenium	BDL		BDL		BDL	BDL
Rbidium	BDL		7.05E-07		BDL	BDL
Strontium	BDL		BDL		BDL	BDL
Ytrium	BDL		BDL		BDL	3.68E-06
Niobium	NM		NM		NM	NM
Molybdenum	1.29E-06		2.12E-06		6.27E-06	1.47E-05
Palladium	BDL		7.05E-07		2.51E-06	1.10E-05
Silver	NM		NM		NM	NM
Cadmium	3.23E-06		BDL		3.76E-06	1.10E-05
Indium	5.17E-06		9.17E-06		1.51E-05	2.94E-05
Tin	1.94E-06		BDL		1.00E-05	3.68E-06
Antimony	BDL		BDL		BDL	BDL
Cesium	NM		NM		NM	NM
Barium	7.11E-06		1.13E-05		2.26E-05	3.68E-06
Lanthanum	NM		NM		NM	NM
Platinum	BDL		BDL		BDL	BDL
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	NM		NM		NM	NM
Bismuth	BDL		BDL		BDL	BDL
Uranium	NM		NM		NM	NM

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC						X	
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX						
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2				X	
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9					
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8			X		
	Nitrate	7697-37-2					

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.6: PM data and speciation profiles for N695SW Starboard Engine (continued)

Aircraft Tail Number:	N695SW					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	0.135	0.518	5.48	6.88	9.86	15.8
NO	2.45	2.48	1.08	1.02	0.984	1.20
NO2	2.58	2.99	6.56	7.90	10.8	17.0
NOX	NM	NM	NM	NM	NM	NM
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	23.8	21.3	4.00	2.58	1.15	1.07
CO	3160	3160	3160	3160	3160	3160
CO2	NM	NM	NM	NM	NM	NM
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	0.000450947		0.000723414		0.0013216	0.003651705
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made

BDL - Below detection limit

EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.

LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.

These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.

Analytical uncertainty for all measurement methods was provided in the original text.

Table I.7: PM data and speciation profiles for N429WN Port Engine

Aircraft Tail Number:	N429WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			
	Sigma		1.05	DMS500			
	DgeomM (nm)		5	DMS500			
	Number(10e15/kg fuel)		0.02	DMS500			
	Mass		1.0E-06	DMS500			
EC	Mass						
OC							
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	NM	NM	NM	NM	NM	NM
Sigma	NM	NM	NM	NM	NM	NM
DgeomM (nm)	NM	NM	NM	NM	NM	NM
	Emission Indices (g/kg fuel)					
Number	NM	NM	NM	NM	NM	NM
Mass	NM	NM	NM	NM	NM	NM
	NM		NM		NM	NM
	NM		NM		NM	NM
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.590	0.0143	BDL	NM	NM	NM
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1098 ± 0	0.0454 ± 0	0.0044 ± 0	NM	NM	NM
Toluene	0.0578 ± 0	0.0334 ± 0	0.0030 ± 0	NM	NM	NM
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0290 ± 0	0.0124 ± 0	0.0016 ± 0	NM	NM	NM

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		**XAD-PUF/Quartz sampling**			
	Acenaphthene	83-32-9					
	Fluorene	86-73-7					
	Phenanthrene	85-01-8					
	Anthracene	120-12-7					
	Fluoranthene	206-44-0					
	Pyrene	129-00-0					
	Benzo(a)pyrene	50-32-8					
	Indeno[1,2,3-cd]pyrene	193-39-5					
	Dibenz[a,h]anthracene	53-70-3					
	Benzo[ghi]perylene	191-24-2					
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6					
	Octacosane	630-02-4					
	Hexacosane	630-01-3					
	Tetracosane	646-31-1					
	Docosane	629-92-0					
	Eicosane	112-95-8					
	Nonadecane	629-92-5					
	Octadecane	593-46-3					
	Hexadecane	544-76-3					
	Tetradecane	629-59-4					
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3					
	Chrysene	218-01-9					
	Benzo(b)fluoranthene	205-99-2					
	Benzo(k)fluoranthene	207-08-9					
	Dodecane	112-40-3					
Carbonyls				(DNPH Sampling)			
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	NM		NM		NM	NM
Acenaphthene	NM		NM		NM	NM
Fluorene	NM		NM		NM	NM
Phenanthrene	NM		NM		NM	NM
Anthracene	NM		NM		NM	NM
Fluoranthene	NM		NM		NM	NM
Pyrene	NM		NM		NM	NM
Benzo(a)pyrene	NM		NM		NM	NM
Indeno[1,2,3-cd]pyrene	NM		NM		NM	NM
Dibenz[a,h]anthracene	NM		NM		NM	NM
Benzo[ghi]perylene	NM		NM		NM	NM
Hexatriacontane	NM		NM		NM	NM
Triacontane	NM		NM		NM	NM
Octacosane	NM		NM		NM	NM
Hexacosane	NM		NM		NM	NM
Tetracosane	NM		NM		NM	NM
Docosane	NM		NM		NM	NM
Eicosane	NM		NM		NM	NM
Nonadecane	NM		NM		NM	NM
Octadecane	NM		NM		NM	NM
Hexadecane	NM		NM		NM	NM
Tetradecane	NM		NM		NM	NM
Naphthalene	0.0479 ± 0	0.0193 ± 0	0.0040 ± 0	NM	NM	NM
Benz(a)anthracene	NM		NM		NM	NM
Chrysene	NM		NM		NM	NM
Benzo(b)fluoranthene	NM		NM		NM	NM
Benzo(k)fluorantene	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Formaldehyde	0.68 ± 0	0.24 ± 0	0.004 ± 0	NM	NM	NM
Acetaldehyde	0.33 ± 0	0.13 ± 0	0.009 ± 0	NM	NM	NM
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
	NM	NM	NM	NM	NM	NM
mz57	0 ± 0	0 ± 0	0.0906 ± 0	0 ± 0	0 ± 0	0 ± 0
mz59	0.1587 ± 0	0.0554 ± 0	0.0044 ± 0	0 ± 0	0 ±0	0 ± 0
mz107	0.1128 ± 0	0.0527 ± 0	0.0040 ± 0	0 ± 0	0 ± 0	0 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200				
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000				
	Silicon	7440-21-3	1.200				
	Phosphorous	7723-14-0	0.204				
	Sulfur	63705-05-5	0.204				
	Chlorine	7782-50-5	0.068				
	Potassium	744-09-5	0.017				
	Calcium	7440-70-2	0.017				
	Scandium	7440-20-2					
	Iron	7439-89-5	0.007				
	Titanium	7440-32-6	0.051				
	Vanadium	7440-62-2	0.020				
	Chromium	7440-47-3	0.017				
	Manganese	7439-96-5	0.009				
	Cobalt	7440-48-4	0.007				
	Nickel	7440-2-0	0.003				
	Copper	7440-50-8	0.003				
	Zinc	7440-66-6	0.003				
	Gallium	7440-55-3	0.425				
	Germanium	7440-38-2	0.017				
	Arsenic	7440-38-2	0.003				
	Selenium	7782-49-2	0.017				
	Rbidium		0.007				
	Strontium	7440-24-6	0.017				
	Ytrium		0.003				
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017				
	Palladium	7440-05-3	0.026				
	Silver	7440-22-4					
	Cadmium	7440-43-9	0.017				
	Indium	7440-74-6	0.017				
	Tin	7440-31-6	0.026				
	Antimony	7440-36-0	0.024				
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170				
	Lanthanum	4639-91-0	0.425				
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051				
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	NM		NM		NM	NM
Beryllium	NM		NM		NM	NM
Aluminum	NM		NM		NM	NM
Silicon	NM		NM		NM	NM
Phosphorous	NM		NM		NM	NM
Sulfur	NM		NM		NM	NM
Chlorine	NM		NM		NM	NM
Potassium	NM		NM		NM	NM
Calcium	NM		NM		NM	NM
Scandium	NM		NM		NM	NM
Iron	NM		NM		NM	NM
Titanium	NM		NM		NM	NM
Vanadium	NM		NM		NM	NM
Chromium	NM		NM		NM	NM
Manganese	NM		NM		NM	NM
Cobalt	NM		NM		NM	NM
Nickel	NM		NM		NM	NM
Copper	NM		NM		NM	NM
Zinc	NM		NM		NM	NM
Gallium	NM		NM		NM	NM
Germanium	NM		NM		NM	NM
Arsenic	NM		NM		NM	NM
Selenium	NM		NM		NM	NM
Rbidium	NM		NM		NM	NM
Strontium	NM		NM		NM	NM
Ytrium	NM		NM		NM	NM
Niobium	NM		NM		NM	NM
Molybdenum	NM		NM		NM	NM
Palladium	NM		NM		NM	NM
Silver	NM		NM		NM	NM
Cadmium	NM		NM		NM	NM
Indium	NM		NM		NM	NM
Tin	NM		NM		NM	NM
Antimony	NM		NM		NM	NM
Cesium	NM		NM		NM	NM
Barium	NM		NM		NM	NM
Lanthanum	NM		NM		NM	NM
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	NM		NM		NM	NM
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Port						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8					
	Nitrate	7697-37-2					

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.7: PM data and speciation profiles for N429WN Port Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Port					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.144	1.68	7.54	NM	NM	NM
NO2	2.64	1.83	0.751	NM	NM	NM
NOX	2.78	3.51	8.29	NM	NM	NM
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	NM	NM	NM	NM	NM	NM
CO	25.3	15.8	1.35	NM	NM	NM
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	NM	NM	NM	NM	NM	NM
Nitrate	NM	NM	NM	NM	NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.

Table I.8: PM data and speciation profiles for N429WN Starboard Engine

Aircraft Tail Number:	N429WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
PM							
	Dgeom (nm)		5	DMS500			X
	Sigma		1.05	DMS500			X
	DgeomM (nm)		5	DMS500			X
	Number(10e15/kg fuel)		0.02	DMS500			X
	Mass		1.0E-06	DMS500			X
	Mass			DMS500	X		
EC					X		
OC					X		
Normal Alkanes							
	Methane*	74-82-8					
	Ethane*	74-84-0					
	Propane*	74-98-6					
	Butane	106-97-8					
	Pentane	109-66-0					
	Hexane	110-54-3					
	Heptane	142-82-5					
	Octane	111-65-9					
	Nonane	111-84-2					
	Decane	124-18-5					
	Undecane	1120-21-4					
	Dodecane	112-40-3					
	Tridecane	629-50-5					
Branched Alkanes							
	2-Methylbutane	78-78-4					
	2,3-Dimethylbutane	79-29-8					
	2-Methylpentane	107-83-5					
	3-Methylpentane	96-14-0					
	2,3-Dimethylpentane	565-59-3					
	2,4-Dimethylpentane	108-08-7					
	3,3-Dimethylpentane	562-49-2					
	2-Methylhexane	598-76-4					
	3-Methylhexane	589-34-4					
	3-Ethylpentane	617-78-7					
	3,5-Dimethylheptane	926-82-9					
	2-Methyloctane	3221-61-2					
	3-Methyloctane	2216-33-3					
	2,4-Dimethyloctane						
Cycloalkanes							
	Cyclopentane	287-923					
	Methylcyclopentane	96-37-7					
	Cyclohexane	110-82-7					
	t-1,2-Dimethylcyclopentane	2452-99-5					
	c-1,3-Dimethylcyclopentane	2453-00-1					
	Methylcyclohexane	108-87-2					
	1c,2t,3-Trimethylcyclopentane						
	Ethylcyclohexane	1678-91-7					

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
	Size Distribution Shape Parameters					
Dgeom (nm)	13.65 ± 0.12	11.80 ± 0.18	18.72 ± 0.17	19.06 ± 0.08	27.12 ± 0.06	32.26 ± 0.25
Sigma	1.44 ± 0.01	1.25 ± 0.02	1.53 ± 0.01	1.62 ± 0.003	1.81 ± 0.002	1.87 ± 0.01
DgeomM (nm)	33.15 ± 0.43	33.71 ± 1.28	36.66 ± 0.38	37.83 ± 0.25	66.36 ± 0.19	81.0 ± 1.03
	Emission Indices (g/kg fuel)					
Number	0.15 ± 0.01	0.01 ± 0.001	0.06 ± 0.003	0.16 ± 0.004	0.87 ± 0.009	0.88 ± 0.024
Mass	0.0007 ± 0.0001	DL	0.0008 ± 0.0001	0.0017 ± 0.0001	0.038 ± 0.0006	0.073 ± 0.004
Mass	0.0017		0.0022		0.0395	0.0700
	0.0008		0.0016		0.0338	0.0475
	0.0032		0.0028		0.0059	0.0243
Methane*	NM		NM		NM	NM
Ethane*	NM		NM		NM	NM
Propane*	NM		NM		NM	NM
Butane	NM		NM		NM	NM
Pentane	NM		NM		NM	NM
Hexane	NM		NM		NM	NM
Heptane	NM		NM		NM	NM
Octane	NM		NM		NM	NM
Nonane	NM		NM		NM	NM
Decane	NM		NM		NM	NM
Undecane	NM		NM		NM	NM
Dodecane	NM		NM		NM	NM
Tridecane	NM		NM		NM	NM
2-Methylbutane	NM		NM		NM	NM
2,3-Dimethylbutane	NM		NM		NM	NM
2-Methylpentane	NM		NM		NM	NM
3-Methylpentane	NM		NM		NM	NM
2,3-Dimethylpentane	NM		NM		NM	NM
2,4-Dimethylpentane	NM		NM		NM	NM
3,3-Dimethylpentane	NM		NM		NM	NM
2-Methylhexane	NM		NM		NM	NM
3-Methylhexane	NM		NM		NM	NM
3-Ethylpentane	NM		NM		NM	NM
3,5-Dimethylheptane	NM		NM		NM	NM
2-Methyloctane	NM		NM		NM	NM
3-Methyloctane	NM		NM		NM	NM
2,4-Dimethyloctane	NM		NM		NM	NM
Cyclopentane	NM		NM		NM	NM
Methylcyclopentane	NM		NM		NM	NM
Cyclohexane	NM		NM		NM	NM
t-1,2-Dimethylcyclopentane	NM		NM		NM	NM
c-1,3-Dimethylcyclopentane	NM		NM		NM	NM
Methylcyclohexane	NM		NM		NM	NM
1c,2t,3-Trimethylcyclopentane	NM		NM		NM	NM
Ethylcyclohexane	NM		NM		NM	NM

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Alkenes							
	Ethene*	74-85-1		TILDAS		X	
	Propene*	115-07-1					
	1-Butene	106-98-9					
	c-2-Butene						
	t-2-Butene						
	2-Methylpropene	115-11-7					
	Pentene	25377-72-4					
	1-Hexene	592-41-6					
	3-Methyl-c-2-Pentene						
	3-Methyl-t-2-Pentene						
	4-Methyl-c-2-Pentene						
	4-Methyl-t-2-Pentene						
	1-Nonene	124-11-8					
	Propadiene	463-49-0					
	1,3-Butadiene	106-99-0					
	2-Methyl-1,3-Butadiene	78-79-5					
	Cyclopentadiene	542-92-7					
	Cyclohexene	110-83-8					
Alkynes							
	Ethyne*	74-86-2					
Aromatic Hydrocarbons							
	Benzene	71-43-2		PTR-MS		X	
	Toluene	108-88-3		PTR-MS		X	
	Ethylbenzene	100-41-4					
	o-Xylene	95-47-6					
	m&p-Xylene	63-68-3					
	1-Methyl-2-ethylbenzene	611-14-3					
	1-Methyl-3-ethylbenzene	620-14-4					
	1-Methyl-4-ethylbenzene	622-96-8					
	1,4-Dimethyl-2-ethylbenzene	1758-88-9					
	1,2,3-Trimethylbenzene	526-73-8					
	1,2,4-Trimethylbenzene	95-63-6					
	1,3,5-Trimethylbenzene	95-63-6					
	Indan	496-11-7					
	1,2-Diethylbenzene	135-01-3					
	1,3-Diethylbenzene	141-93-5					
	1,4-Diethylbenzene	105-05-5					
	1-Methyl-2-n-Propylbenzene						
	1-Methyl-3-n-Propylbenzene						
	1-Methyl-4-n-Propylbenzene						
	1-Methyl-2-i-Propylbenzene						
	1-Methyl-3-i-Propylbenzene						
	1,2,4,5-Tetramethylbenzene	95-93-2					
	n-Pent-Benzene						
	Styrene	100-42-5		PTR-MS		X	

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Ethene*	0.636	0.145	BDL	BDL	BDL	BDL
Propene*	NM	NM	NM	NM	NM	NM
1-Butene	NM	NM	NM	NM	NM	NM
c-2-Butene	NM	NM	NM	NM	NM	NM
t-2-Butene	NM	NM	NM	NM	NM	NM
2-Methylpropene	NM	NM	NM	NM	NM	NM
Pentene	NM	NM	NM	NM	NM	NM
1-Hexene	NM	NM	NM	NM	NM	NM
3-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
3-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-c-2-Pentene	NM	NM	NM	NM	NM	NM
4-Methyl-t-2-Pentene	NM	NM	NM	NM	NM	NM
1-Nonene	NM	NM	NM	NM	NM	NM
Propadiene	NM	NM	NM	NM	NM	NM
1,3-Butadiene	NM	NM	NM	NM	NM	NM
2-Methyl-1,3-Butadiene	NM	NM	NM	NM	NM	NM
Cyclopentadiene	NM	NM	NM	NM	NM	NM
Cyclohexene	NM	NM	NM	NM	NM	NM
Ethyne*	NM	NM	NM	NM	NM	NM
Benzene	0.1282 ± .0029	0.048 ± .0093	0.0012 ± .0005	0.0008 ± .0002	0.0013 ± .0008	0.0011 ± 0
Toluene	0.0620 ± .0063	0.0228 ± .0057	0.0008 ± .0004	0.0012 ± .0007	0.0012 ± .0005	0.0006 ± 0
Ethylbenzene	NM	NM	NM	NM	NM	NM
o-Xylene	NM	NM	NM	NM	NM	NM
m&p-Xylene	NM	NM	NM	NM	NM	NM
1-Methyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-ethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-ethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Dimethyl-2-ethylbenzene	NM	NM	NM	NM	NM	NM
1,2,3-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,2,4-Trimethylbenzene	NM	NM	NM	NM	NM	NM
1,3,5-Trimethylbenzene	NM	NM	NM	NM	NM	NM
Indan	NM	NM	NM	NM	NM	NM
1,2-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,3-Diethylbenzene	NM	NM	NM	NM	NM	NM
1,4-Diethylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-4-n-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-2-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1-Methyl-3-i-Propylbenzene	NM	NM	NM	NM	NM	NM
1,2,4,5-Tetramethylbenzene	NM	NM	NM	NM	NM	NM
n-Pent-Benzene	NM	NM	NM	NM	NM	NM
Styrene	0.0278 ± .0033	0.0105 ± .0027	0.0005 ± .0004	0.0006 ± .0003	0.0005 ± .0001	0.0006 ± 0

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Semivolatiles							
(alkanes and PAHs)	Acenaphthylene	208-96-8		XAD-PUF/Quartz sampling	X		
	Acenaphthene	83-32-9		XAD-PUF/Quartz sampling	X		
	Fluorene	86-73-7		XAD-PUF/Quartz sampling	X		
	Phenanthrene	85-01-8		XAD-PUF/Quartz sampling	X		
	Anthracene	120-12-7		XAD-PUF/Quartz sampling	X		
	Fluoranthene	206-44-0		XAD-PUF/Quartz sampling	X		
	Pyrene	129-00-0		XAD-PUF/Quartz sampling	X		
	Benzo(a)pyrene	50-32-8		XAD-PUF/Quartz sampling	X		
	Indeno[1,2,3-cd]pyrene	193-39-5		XAD-PUF/Quartz sampling	X		
	Dibenz[a,h]anthracene	53-70-3		XAD-PUF/Quartz sampling	X		
	Benzo[ghi]perylene	191-24-2		XAD-PUF/Quartz sampling	X		
	Hexatriacontane	630-06-8					
	Triacontane	638-68-6		XAD-PUF/Quartz sampling	X		
	Octacosane	630-02-4		XAD-PUF/Quartz sampling	X		
	Hexacosane	630-01-3		XAD-PUF/Quartz sampling	X		
	Tetracosane	646-31-1		XAD-PUF/Quartz sampling	X		
	Docosane	629-92-0		XAD-PUF/Quartz sampling	X		
	Eicosane	112-95-8		XAD-PUF/Quartz sampling	X		
	Nonadecane	629-92-5		XAD-PUF/Quartz sampling	X		
	Octadecane	593-46-3		XAD-PUF/Quartz sampling	X		
	Hexadecane	544-76-3		XAD-PUF/Quartz sampling	X		
	Tetradecane	629-59-4		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-2		XAD-PUF/Quartz sampling	X		
	Naphthalene	91-20-3		PTR-MS		X	
	Benz(a)anthracene	56-55-3		XAD-PUF/Quartz sampling	X		
	Chrysene	218-01-9		XAD-PUF/Quartz sampling	X		
	Benzo(b)fluoranthene	205-99-2		XAD-PUF/Quartz sampling	X		
	Benzo(k)fluoranthene	207-08-9		XAD-PUF/Quartz sampling	X		
	Dodecane	112-40-3		XAD-PUF/Quartz sampling	X		
Carbonyls							
	Formaldehyde			TILDAS		X	
	Acetaldehyde			PTR-MS		X	
	Acetone	67-64-1					
	Acrolein	107-02-8		TILDAS			
	Propion-aldehyde	123-38-6					
	Crotonaldehyde	4170-30-3					
	MEK	78-93-3					
	Methacrolein	78-85-3					
	Butyraldehyde	123-72-8					
	Benzaldehyde	100-52-7					
	Valeraldehyde	110-62-3					
	Tolualdehyde						
	Hexaldehyde	66-25-1					
Other Organics							
	mz57			PTR-MS		X	
	mz59			PTR-MS		X	
	mz107			PTR-MS		X	
	MTBE	1634-04-4					

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Acenaphthylene	1.56E-03		3.83E-02		3.73E-05	6.90E-04
Acenaphthene	2.38E-03		3.87E-01		2.64E-04	5.30E-03
Fluorene	6.68E-03		6.55E-05		2.78E-05	2.03E-05
Phenanthrene	7.80E-03		2.31E-04		8.68E-05	6.38E-05
Anthracene	1.07E-02		2.21E-04		1.51E-04	3.22E-04
Fluoranthene	6.34E-05		4.70E-05		2.92E-06	8.43E-04
Pyrene	7.37E-05		1.12E-04		9.38E-05	5.03E-04
Benzo(a)pyrene	1.10E-05		2.16E-06		3.06E-06	1.66E-05
Indeno[1,2,3-cd]pyrene	2.42E-06		BDL		BDL	1.34E-05
Dibenz[a,h]anthracene	BDL		BDL		BDL	1.13E-05
Benzo[ghi]perylene	2.55E-06		BDL		BDL	BDL
Hexatriacontane	NM		NM		NM	NM
Triacontane	2.26E-06		1.47E-06		2.11E-06	1.21E-05
Octacosane	4.36E-06		1.59E-06		2.55E-06	1.07E-05
Hexacosane	1.31E-05		1.45E-05		6.14E-05	2.64E-04
Tetracosane	1.84E-06		1.86E-06		2.66E-06	5.96E-06
Docosane	1.52E-06		2.07E-06		4.20E-06	7.36E-06
Eicosane	2.35E-06		1.92E-06		4.34E-06	1.12E-05
Nonadecane	1.53E-04		6.87E-06		7.79E-06	1.78E-05
Octadecane	7.21E-06		3.31E-05		3.50E-05	7.65E-05
Hexadecane	1.19E-04		7.40E-06		1.09E-05	3.02E-05
Tetradecane	3.14E-06		3.41E-05		5.27E-05	1.78E-04
Naphthalene	7.53E-03		1.90E+00		6.26E-01	6.85E-01
Naphthalene	0.0369 ± .0028	0.012 ± .0008	0.0018 ± .0006	0.0016 ± .0006	0.0015 ± .0006	0.0014 ± 0
Benz(a)anthracene	3.00E-06		2.40E-05		2.24E-05	6.40E-05
Chrysene	3.83E-05		2.43E-05		2.27E-05	1.12E-04
Benzo(b)fluoranthene	4.78E-06		5.57E-06		BDL	BDL
Benzo(k)fluorantene	9.97E-06		9.15E-06		5.64E-06	3.99E-05
Dodecane	3.95E-04		1.82E-04		3.34E-04	1.20E-04
Formaldehyde	0.74 ± 0.017	0.28 ± 0.05	0.003 ± 0.0008	0.0017 ± 0.002	0.0007 ± 0.001	0.002 ± 0
Acetaldehyde	0.35 ± 0.012	0.13 ± 0.02	0.003 ± 0.0008	0.003 ± 0.0004	0.003 ± 0.0004	0.004 ± 0
Acetone	NM	NM	NM	NM	NM	NM
Acrolein	NM	NM	NM	NM	NM	NM
Propion-aldehyde	NM	NM	NM	NM	NM	NM
Crotonaldehyde	NM	NM	NM	NM	NM	NM
MEK	NM	NM	NM	NM	NM	NM
Methacrolein	NM	NM	NM	NM	NM	NM
Butyraldehyde	NM	NM	NM	NM	NM	NM
Benzaldehyde	NM	NM	NM	NM	NM	NM
Valeraldehyde	NM	NM	NM	NM	NM	NM
Tolualdehyde	NM	NM	NM	NM	NM	NM
Hexaldehyde	NM	NM	NM	NM	NM	NM
mz57	0.4015 ± .0104	0.1433 ± .0455	0.010 ± .0058	0.0094 ± .0025	0.011 ± .0027	0.0092 ± 0
mz59	0.1596 ± .0083	0.053 ± .0077	0.0017 ± .0004	0.0014 ± .0005	0.0017 ± .0005	0.0016 ± 0
mz107	0.1191 ± .0087	0.0440 ± .0103	0.0016 ± .0006	0.0014 ± .0009	0.0018 ± .0009	0.0015 ± 0
MTBE	NM	NM	NM	NM	NM	NM

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Elemental Analysis							
	Hexavalent Chromium	18540-29-9		(IC-CCD, XRF or ICP-MS)			
	Magnesium	7639-95-4	1.200		X		
	Beryllium	7440-41-7					
	Aluminum	7429-90-5	1.000		X		
	Silicon	7440-21-3	1.200		X		
	Phosphorous	7723-14-0	0.204		X		
	Sulfur	63705-05-5	0.204		X		
	Chlorine	7782-50-5	0.068		X		
	Potassium	744-09-5	0.017		X		
	Calcium	7440-70-2	0.017		X		
	Scandium	7440-20-2			X		
	Iron	7439-89-5	0.007		X		
	Titanium	7440-32-6	0.051		X		
	Vanadium	7440-62-2	0.020		X		
	Chromium	7440-47-3	0.017		X		
	Manganese	7439-96-5	0.009		X		
	Cobalt	7440-48-4	0.007		X		
	Nickel	7440-2-0	0.003		X		
	Copper	7440-50-8	0.003		X		
	Zinc	7440-66-6	0.003		X		
	Gallium	7440-55-3	0.425		X		
	Germanium	7440-38-2	0.017		X		
	Arsenic	7440-38-2	0.003		X		
	Selenium	7782-49-2	0.017		X		
	Rbidium		0.007		X		
	Strontium	7440-24-6	0.017		X		
	Ytrium		0.003		X		
	Niobium	7440-03-1					
	Molybdenum	7439-98-7	0.017		X		
	Palladium	7440-05-3	0.026		X		
	Silver	7440-22-4			X		
	Cadmium	7440-43-9	0.017		X		
	Indium	7440-74-6	0.017		X		
	Tin	7440-31-6	0.026		X		
	Antimony	7440-36-0	0.024		X		
	Cesium	7440-46-2					
	Barium	7440-39-3	0.170		X		
	Lanthanum	4639-91-0	0.425		X		
	Platinum	7440-06-4					
	Gold	7440-57-5					
	Mercury	7439-97-6					
	Lead	7439-92-1	0.051		X		
	Bismuth	7440-69-9					
	Uranium	7440-61-1					

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
Hexavalent Chromium	NM		NM		NM	NM
Magnesium	5.20E-05		BDL		1.11E-04	4.38E-04
Beryllium	NM		NM		NM	NM
Aluminum	3.45E-05		8.05E-05		8.26E-05	BDL
Silicon	BDL		BDL		BDL	
Phosphorous	BDL		BDL		BDL	
Sulfur	BDL		BDL		1.56E-04	9.01E-05
Chlorine	BDL		BDL		BDL	
Potassium	BDL		BDL		BDL	
Calcium	1.53E-06		BDL		BDL	BDL
Scandium	BDL		BDL		BDL	BDL
Iron	9.17E-06		3.87E-06		BDL	4.87E-06
Titanium	1.53E-06		1.29E-06		BDL	BDL
Vanadium	BDL		BDL		BDL	BDL
Chromium	9.17E-07		BDL		BDL	7.30E-06
Manganese	BDL		BDL		BDL	9.74E-06
Cobalt	BDL		8.61E-07		6.83E-07	2.43E-06
Nickel	3.06E-07		8.61E-07		BDL	2.43E-06
Copper	BDL		4.31E-07		BDL	BDL
Zinc	9.17E-07		4.31E-07		6.83E-07	2.43E-06
Gallium	BDL		BDL		BDL	4.87E-06
Germanium	BDL		1.72E-06		BDL	1.22E-05
Arsenic	BDL		4.31E-07		6.83E-07	4.87E-06
Selenium	BDL		BDL		BDL	BDL
Rbidium	BDL		BDL		BDL	BDL
Strontium	BDL		BDL		BDL	BDL
Ytrium	BDL		BDL		BDL	BDL
Niobium	NM		NM		NM	NM
Molybdenum	BDL		8.61E-07		6.83E-07	BDL
Palladium	BDL		8.61E-07		6.83E-07	7.30E-06
Silver	NM		NM		NM	NM
Cadmium	1.53E-06		BDL		2.05E-06	1.46E-05
Indium	2.44E-06		2.15E-06		6.83E-07	1.70E-05
Tin	BDL		1.29E-06		BDL	9.74E-06
Antimony	BDL		BDL		BDL	BDL
Cesium	NM		NM		NM	NM
Barium	BDL		BDL		1.09E-05	BDL
Lanthanum	BDL		BDL		BDL	BDL
Platinum	NM		NM		NM	NM
Gold	NM		NM		NM	NM
Mercury	NM		NM		NM	NM
Lead	BDL		BDL		BDL	BDL
Bismuth	NM		NM		NM	NM
Uranium	NM		NM		NM	NM

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN						
Engine Location:	Starboard						
Category	Species				Group		
					UCR	ARI	UMR
		CAS	LOD	Method			
Non-HC							
Combustion Gases	NO	10102-43-9		Chemiluminescence		X	
	NO2	10102-44-0		TILDAS		X	
	NOX					X	
	HNO3	7697-37-2					
	HONO	7782-77-6					
	N2O	10024-97-2					
	CO	630-08-0		TILDAS		X	
	CO2	124-38-9				X	
	SO2	7446-09-5					
	SOX						
Inorganic ions	Sulfate	14808-79-8			X		
	Nitrate	7697-37-2					

NM - no measurement was made

BDL - Below detection limit

EI for CO2 determined by elemental analysis of fuel

Notes:

UCR comments:

In the original text LODs were provided for all compounds and species measured on the high-flow side.

LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.

These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.

Analytical uncertainty for all measurement methods was provided in the original text.

Table I.8: PM data and speciation profiles for N429WN Starboard Engine (continued)

Aircraft Tail Number:	N429WN					
Engine Location:	Starboard					
Species	Power					
	4%	7%	30%	40%	65%	85%
	Mode 1		Mode 2		Mode 3	Mode 4
NO	0.182	1.91	8.48	10.1	14.8	16.7
NO2	2.61	2.11	0.876	0.814	0.998	1.52
NOX	2.79	4.02	9.36	10.9	15.8	18.2
HNO3	NM	NM	NM	NM	NM	NM
HONO	NM	NM	NM	NM	NM	NM
N2O	NM	NM	NM	NM	NM	NM
CO	18.5	12.6	1.38	0.838	0.443	0.607
CO2	3160	3160	3160	3160	3160	3160
SO2	NM	NM	NM	NM	NM	NM
SOX	NM	NM	NM	NM	NM	NM
Sulfate	0.00019248		0.000207342		0.000301223	0.004671114
Nitrate	NM		NM		NM	NM

NM - no measurement was made
BDL - Below detection limit
EI for CO2 determined by elemental analysis of fuel

Notes:
UCR comments:
In the original text LODs were provided for all compounds and species measured on the high-flow side.
LODs were not provided for C_1 to C_{12} compounds where we know there are sampling issues.
These issues were fully discussed in the test. Analytical uncertainties are different and will not reflect the sampling uncertainty.

UCR only made one measurement so uncertainty cannot be calculated.
Analytical uncertainty for all measurement methods was provided in the original text.