

APPENDIX F

JET AIRCRAFT EMISSIONS

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APPENDIX F JET AIRCRAFT EMISSIONS

F-1.0 Introduction

The purpose of this Appendix is to set forth method(s) used in support of the HHRA for determining the potential for human exposure to chemicals in jet aircraft turbine exhaust at different locations in the study area. This Appendix describes a method to convert predicted annual average concentration for total hydrocarbons (THC) modelled by RWDI for Phase 1 into specified chemical concentrations. For the purpose of this human health risk assessment, 100% of the THC associated with these predicted isopleths of concentration (Phase 1) at any location off-site was assumed to represent jet turbine exhaust from operations at TPIA.

This Appendix establishes the data sources available, and identifies expected composition of VOC from jet turbines. It provides a rationale for interpolation of predicted concentrations of THC at receptor locations off-site into concentrations of chemicals of concern for use in the risk assessment. The conversion values ($\mu\text{g}/\text{m}^3 \text{ THC} \times \text{percent VOC in exhaust} = [\text{VOC } \mu\text{g}/\text{m}^3]$) were used directly to specify concentrations of benzene, toluene, 1,3-butadiene, formaldehyde, acetaldehyde, acrolein, *etc.* at chosen receptor locations at the location of maximum off-site concentration and at seven other locations in the surrounding community.

A sensitivity analysis was undertaken to compare monitored results with predicted results for several chemicals of concern including benzene and formaldehyde. Data from an on-site system (OPSIS) were evaluated and compared both with simultaneously collected monitoring results from Phase 4, and with off-site monitoring at Centennial Park and elsewhere in Toronto or Southern Ontario.

A detailed methodology describing aircraft operations and the associated emissions from each of those operations (idle, taxi, take-off and landing) is presented. The resulting composite emissions profile from Environment Canada data sources (ERMD) is compared with two less well characterized emission profiles from the U.S. EPA Speciate database.

Ultimately, results for predicted health risk were prepared from both the ERMD and the EPA #1098 profiles.

F-1.1 Speciation of Jet Aircraft Emissions Based On Emission Rates

Speciation profiles provide estimates of the chemical composition of emissions, and are used in the emission inventory and air quality models. Speciation profiles support air quality modeling and provide estimates of toxic air pollutants in modelled emissions.

An important step in modelling the health impacts from pollutant emissions is the speciation of chemical mixtures into specific compounds that can be assigned specific percentages or concentrations of total pollutant mass. The process of separating inventory pollutants into individual chemical components or groups of species provides a means for assessing ground level exposure to a particular pollutant found at a particular receptor location (EPA Speciate Memorandum, 2002). The profiles for chemical emission rates from jet aircraft that were supplied by the United States Environmental Protection Agency are found in the Technology Transfer Network (TTN) Clearinghouse for Inventories & Emission Factors Clearing House for Inventories and Emission Factors (CHIEF).

The EDMS model used by RWDI describes pollutant emissions associated with the TPIA. It predicts the total hydrocarbon emissions from activities of ground operations as well as take-off and landing cycles of aircraft during a given period (one hour maxima, 24 hour maxima or annual averages). Emissions of organic gases produced as a result of jet aircraft operations are typically reported in emission inventories only as aggregate organics (ICAO, 1995). The term VOC does not reflect the specific compounds included or excluded from an aggregate estimate. Inventories available to CEI were used to disaggregate this general term of VOC into specific compounds.

Two main sources of chemical profiles (the United States Environmental Protection Agency and Environment Canada) were identified for the purpose of speciation of the emissions non-methane hydrocarbons and oxygenated hydrocarbons as VOC at the TPIA. Three of these speciation profiles are discussed below. The choice of speciation profile applied to the total non-methane hydrocarbons generated from the EDMS model is important since this can affect the estimated contribution of hazardous air pollutants likely to be in inhaled air at ground level.

CHIEF's Emissions Modeling Clearinghouse (EMCH) at the U.S. EPA website for the collection of emissions factors (<http://www.epa.gov/ttn/chief/emch/speciation/index.html>) contains various resources such as software (Speciate 3.2), and emissions factor resource profiles for various mobile and industrial applications. These files have been developed to allow users to estimate the individual and/or "lumped" chemical species required by air quality models from the more aggregated emissions estimates that are usually reported in emissions inventories. Both organic gases and particulate matter emissions estimates, and to a lesser extent SO_x and NO_x estimates, must be split, or speciated, into more defined compounds in order to be properly modeled for chemical transformations and deposition.

F-1.2 *Speciation of Organic Gases*

Volatile Organic Compounds (VOC) or as Reactive Organic Gases (ROG) are terms that reflect specific inclusions or exclusions compounds from the aggregate estimate (Schwehr, 2000). While the U.S. EPA defines VOC to exclude both methane and ethane, and the California Air Resources Board (CARB) defines ROG exclude only methane, in practice it may be assumed that the VOC estimates reported to EPA's inventories largely represent non-methane organic compounds (methane, ethane and acetone are considered a low-reactive organic compounds, and have been excluded by the U.S. EPA from ROG). Thus, VOC and ROG inventories are essentially synonymous (EPA Speciate Memorandum, 2002). The speciation profiles used to split aggregate organic gas estimates into individual compounds are based on total organic gases (TOG), which includes methane and ethane. A general characterization of the speciation profiles available is described below.

F-1.2.1 Profile EPA #2572

Two of eleven samples collected in the Atlanta Airport study were collected near an aircraft with engines running, preparing for eventual departure (Conner *et al.*, 1995). No oxygenated hydrocarbons were determined for these emissions.

F-1.2.2 Profile EPA #1098

EPA #1098 is a composite profile developed from data for a CFM-36 jet engine fired with JP-5 fuel at idle, 30% thrust and 80% thrust. Data collected by GC/MS and DNPH analyses were combined according to average LTO cycle times obtained from AP-42. The source of the U.S. EPA HAPs emission factors and chemical species profiles for commercial aircraft are based largely on the work by Spicer (Spicer 1984, Spicer *et al.*, 1994).

While it is acknowledged that the work by Spicer was thorough and considered high quality (including the testing of engine emissions under varying power settings), the data is recognized as being appreciably limited as only two aircraft engines were tested (FAA, 2003). Nevertheless, in the absence of better data, these HAPs emission factors have subsequently been used in support of air quality analyses for some recent airport environmental impact assessments

As a practical matter, the EPA #1098 speciation profile was intended to be used for making estimates in support of macro-scale analyses of aviation-related emissions. They were not intended to provide exact estimates of emissions from any particular aircraft or airport facility. U.S. EPA indicates that due to unconfirmed assumptions, many uncertainties, and lack of data, these emission factors are imprecise and deficient (FAA, 2003).

F-1.2.3 ERMD Profile; Environment Canada Profile for Jet Aircraft Emissions

A composite emissions profile was developed from data supplied by the Mobile Sources Emissions Division of Environment Canada and the Airports Group of Transport Canada (ERMD). One study determined the emissions contribution of the various forms of mobile sources operating at the Macdonald-Cartier International Airport in Ottawa, Canada between September 1993 and December 1994. The study concentrated on airport service vehicles and aircraft engines from wide-bodied passenger aircraft (Boeing 727). Tests were performed during the fall, winter and summer seasons. Volatile organic compound concentrations in ambient air were highest the apron. Engine exhaust stream measurements were collected during simulated operational cycles for aircraft and service vehicles.

The ERMD profile considered jet aircraft emissions using Jet A1 fuel exclusively. Exhaust emission rates were predicted based on ground testing of various engine speeds representing different power settings. In-flight testing was completed for the purpose of the study, but is not included in the emissions profiles of VOC used in this HHRA. The ERMD-sponsored program employed an aircraft (Cessna Citation II) with two Pratt & Whitney JT15D-4 turbofan engines.

F-1.2.4 Characterization of Speciation Profiles Available for the HHRA

The purpose of developing speciation profiles was to have a means for apportioning the modelled total hydrocarbon emissions into individual VOC. This was the only means available to establish potential exposure levels and possible associated health outcomes off-site.

Oxygenated hydrocarbons or carbonyl compounds were not separately identified in the limited ambient sampling from the Atlanta Airport in 1990 (profile EPA #2572). The sampling profile EPA #1098 included carbonyl compounds, but is based on JP5 jet fuel not Jet A. Speciation profile EPA #1098 was prepared in 1984 with older model aircraft engines (Spicer *et al.*, 1994). The in-flight emissions analysis undertaken by ERMD (Graham and Ainslie, 1997-03) showed that depending on the operational stage of the landing and take-off (LTO) cycle, oxygenated hydrocarbons contributed between 57% and 88% of total VOC emissions. The carbonyl emissions for the U.S. EPA and Environment Canada profiles do not differ markedly with formaldehyde and acetaldehyde. The EPA #1098 profile shows these carbonyl compounds contributing nearly 20% of the total concentration of emissions in the 1984 study, and approximately a similar percent for the blended LTO derived from the 1997 Environment Canada study as revised in 2003 (Graham and Ainslie, 1997-03) (see Section F-2.0). On the other hand, the largest contributor to emissions of oxygenated hydrocarbon compounds in the Ottawa study was for acetone at nearly 64% of total concentration.

Table F-1 provides a side-by-side comparison of the chemicals determined in each of the profiles from the U.S. EPA Speciate database, and from the 1997 Environment Canada ERMD document (as revised 2003). The determinations for jet emissions EPA #2572 and EPA #1098 both have deficiencies when compared to the ERMD profile.

Benzene emission rates were much lower in the Ottawa profile, perhaps reflecting the greatly reduced aromatic content of jet fuel produced since the mid- to the latter 1990s. On the other hand, the predicted relative concentration of benzene among the non-methane hydrocarbons alone was 2% (Table F-6, column 5). Overall, the aromatic content of emissions in the ERMD Ottawa profile was lower (1%) than that of the profile EPA #1098 (5%), and considerably less than for the Atlanta profile (16.8%). The Atlanta profile lacked data for carbonyl compound contribution which ranged from 32 to 87% of the composition of the other two profiles. This explains the relatively higher percent of aromatics in Atlanta (EPA #2572). The Environment Canada profile (Ottawa) was clearly more comprehensive in terms of chemical species for which analytical data were available when compared to the 1984 study (EPA #1098), and provided a better approximation of the distribution of types of aromatic compounds that is found in either U.S. EPA speciation profile.

An important component of jet aircraft fuel, and exhaust emissions are the paraffins and long chain alkane or aliphatic molecules. These compounds produce the greatest heat of combustion of all the fuel components (see jet fuel composition, Appendix G) and comprise the largest group of petroleum compounds in Jet A, the current fuel supplied to virtually all commercial jet aircraft. The non-combusted alkanes represent 34, 16 and 2% of the emissions in the three speciation profiles, with the relative contribution observed in the Environment Canada profile showing the being the smallest, and the #1098 the intermediate in percent of total VOC recovered. In the blended Environment Canada/ERMD GTAA emission profile for aircraft jet exhaust, for all non-methane hydrocarbons, alkanes contributed ~17.5%, and aromatics 8%. The characteristic odour of these compounds (kerosene) is what is universally recognized by persons in the vicinity of operating aircraft.

Finally, similarities of chemical constituents of the olefin segment of the profiles are greater between the Atlanta (EPA #2572) and the Ottawa (ERMD) results. In recent years, concerns regarding benzene content in petroleum products has led to a general effort among aircraft fuel suppliers to employ hydro cracking techniques to reduce the aromatic and olefin content of Jet A in comparison to older fuels such as J5 (the fuel that characterizes the EPA #1098 profile). Although a relatively small component of total aircraft exhaust, when considered in the absence of carbonyl compounds in total emissions (non-methane hydrocarbons alone), alkynes or olefins contributed 74% of the compounds detected.

For use in this assessment, the Environment Canada ERMD profile was blended to reflect expected emissions during different operational phases of aircraft activity at the TPIA. This profile was selected for the purpose of speciation VOC emissions generated by the FAA EDMS model. This profile was

thought to be most representative of total hydrocarbons released from TPIA. For purposes of comparison we have also used the EPA #1098 speciation profile for a limited number of chemicals, focusing on the chemicals of greatest concern. These were evaluated and compared for both profiles using similar exposure scenarios (Section 2).

F-2.0 Rationale for Interpolation of Concentrations

The EDMS model used by RWDI to predict the aggregate pollutant emissions from the TPIA produces concentrations of potentially hazardous volatile organic gasses and other air pollutants expressed simply as Total Hydrocarbons (THC). The format of data presented by RWDI from which ground level concentrations of volatile organic compounds (VOC) (as well as criteria pollutants) is in the form of concentration isopleths. Detailed figures showing the VOC profiles as annual predicted average concentrations across the study area are presented in Appendix H. For VOC, the modelled annual average VOC concentrations predicted for a specified location for Phases 1, 2 or 3 can be identified and interpolated into individual chemical concentrations using the conservative assumption that all VOC emanating from the TPIA would be equivalent to jet aircraft emissions. A large number of activities that occur on TPIA property and contribute to overall pollutant concentrations potentially detectable off site (described in the RWDI Phase 1 to 3 Report). Among these, aircraft operations contribute 50% or more of the total hydrocarbons. Other forms of transport that are found at the Airport (cars, buses and trucks) contribute to off-site as well as on-site pollutants to the environment. The most notable difference between activities at the TPIA that do not occur off-site are aircraft operations. Therefore, for the purpose of this health assessment, a reasonable and conservative assumption that would most clearly distinguish the health impact of TPIA operations off-site was to assume that all predicted concentrations of hydrocarbons off-site would arise from jet exhaust.

Conversion of local concentrations of annually averaged THC predicted from isopleths described in the modelled results from RWDI for Phase 1 took place in a number of steps as described below.

F-2.1 Conversion of Total Hydrocarbons (THC) to Volatile Organic Compounds (VOC).

The emission factors for exhaust hydrocarbons (HC) referred to in the aircraft emissions documents on emission factors in the Federal Aviation Administration's EDMS model represent total hydrocarbons (THC). Conversion of THC to VOC was required in order to make quantitative and qualitative comparisons between data generated by the EDMS model. These estimated concentrations can be confirmed from comparisons with actual data available from the OPSIS system used at the TPIA and by comparison with data from Environment Canada's National Air Pollutant Surveillance Programme.

The commercial aircraft fleets are dominated by turbine engines. Therefore, a single correction factor can be used to convert THC to VOC emissions for each aircraft category as follows:

$$\text{VOC}_{\text{COMMERCIAL}} = \text{THC}_{\text{COMMERCIAL}} \times 1.0947$$

This is from "Procedures for Emissions Inventory Preparation Volume IV: Mobile Sources (EPA420-R-92-009) which was released in 1992.

F-2.2 Speciation of VOC

The source of emission profile or speciation method to characterize the chemical content of the THC (or VOC) modelled for aircraft emissions were identified through extensive scientific and technical literature review. Two profiles were found to be suitable for purposes of this risk assessment. EPA #1098 was based on analysis of samples from older jet engines (both commercial and military) that were evaluated in the 1980s. This speciation profile is used to convert an undetermined mixture of hydrocarbons characteristic of combustion emissions into a well defined mixture of chemicals that comprise the jet fuel combustion during the LTO cycle.

The second profile was prepared from speciation data produced by the Emissions Measurement and Research Division located at the Environmental Technology Centre of Environment Canada in Ottawa. This work contained a number of emission rate profiles based on a combination of direct measurements of emissions from aircraft engaged in ground and flight manoeuvres, and on sampling completed on the ground at the Macdonald-Cartier International Airport in Ottawa (Graham and Ainslie, 1997, revised 2003).

A detailed methodology that employed the ERMD results and determined the likely composition of aircraft exhaust was based on different emission rates experienced during selected operational phases. This methodology is described in section F-3.0.

F-2.3 On-Site Monitoring Data and the Choice of Speciation Profile

A number of comparisons were made to assist in the choice of speciation method to apply to turbine exhaust. Historical monitoring and analytical data were compared with modelled predicted concentrations of VOC. Monitoring data were available from two sources including the Environment Canada NAPS programme site at Centennial Park (a site adjacent to the airport), and the TPIA OPSIS routine monitoring systems. In this analysis same days were compared when both analytical chemical data and OPSIS data were available (complete summaries of OPSIS data are shown in Table F-7).

The methods used at the two sites (OPIS and NAPS) were different (See the RWDI Phase 4 Report for a discussion of the OPSIS system). The OPSIS system has many capabilities, but it is not recognized as an equivalent to accepted analytical technology and methods by the U.S. EPA for detection organic compounds. Results comparing standard technologies used by the U.S. EPA and optical systems similar to OPSIS were favourable only for the criteria pollutants (oxides of nitrogen or sulphur). Technologies like OPSIS have not been accepted for the purpose of analytical determination of VOC by regulatory authorities in North America.

F 2.3.1 Aromatic Hydrocarbons

OPSIS is an optically based monitoring system that determines air concentrations of specified VOC and criteria pollutants within a specified light path. During operation, the OPSIS system recorded readings at intervals of 2.5 minutes to produce an hourly average concentration. Mean hourly, daily or annual averages were provided for specified pollutants monitored by the system. Table F-2 (and Table F-7) summarizes the 24-hour average concentration for a limited number of pollutants by the OPSIS system and the NAPS system at Centennial Park in Etobicoke located nearby. These comparisons were made for benzene, toluene, 1,2,4- and 1,3,5-trimethylbenzenes. OPSIS also provided information for criteria pollutants and formaldehyde concentrations. No data for formaldehyde was available from the Centennial Park site.

A direct comparison between of simultaneous data from the analytical chemical method (NAPS) and monitoring method of OPSIS was not possible during the duration of the air quality (Phase 4) study period. The OPSIS system was unavailable when on-site monitoring that employed Environment Canada's approved methodology was scheduled in September, 2002.

The OPSIS data show that levels of VOC and some criteria pollutants are higher in proximity to the aircraft runways that were detected at the NAPS location (Centennial Park). OPSIS monitoring data were available for only a few of the more than 50 hydrocarbons and carbonyl compounds detailed in the aircraft exhaust speciation profiles prepared by ERMD. The direct comparison of the annual averages for benzene and toluene showed that the OPSIS system consistently reported much higher concentrations on the airport property than could be detected at the NAPS site located across Highway 401 at Centennial Park (Table F-2). The ratios for the relative concentrations of other organic compounds observed were variable, ranging from near unity for xylenes to fifty-fold for 1,3,5-trimethylbenzene.

Table F-1: Comparison of speciation profiles for jet aircraft emissions developed by U.S. EPA and Environment Canada

U.S. EPA Speciate 3.2				U.S. EPA Speciate 3.2				Speciation Profile: Environment Canada Mobile Sources Emissions Division, Environmental Technology Centre, Ottawa.			
Profile Name		Aircraft - Atlanta - August 27, 1990 # 2572		Profile Name		Aircraft Landing/Take-off (LTO) - Commercial # 1098		VOC Speciation for Jet Turbine Emission Rates Based on Descent, Taxi, Low Idle and Maximum Power Aircraft Operation Phases			
CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Percent
Carbonyl Compounds											
									Isobutyraldehyde & Butyraldehyde	0.14	
								110-62-3	Valeraldehyde & 3-Methyl-2-Butanone	0.16	
								620-23-5 & 100-87-0	m & p-Tolualdehyde	0.10	
								590-86-3	Isovaleraldehyde	0.07	
									Trimethylacetaldehyde	0.00	
								98-86-2 & 529-20-4	Acetophenone & o-Tolualdehyde	0.05	
								78-93-3	Methyl Ethyl Ketone	0.026	
								4170-30-3	Crotonaldehyde	0.28	
				50-00-0	Formaldehyde	15.01		50-00-0	Formaldehyde	16.55	
				75-07-0	Acetaldehyde	4.65		75-07-0	Acetaldehyde	3.68	
				107-22-2	Glyoxal	2.54					
				67-64-1	Acetone	2.45		67-64-1	Acetone	64.39	
				107-02-8	Acrolein	2.27		107-02-8	Acrolein	1.52	
				78-98-8	Methyl Glyoxal	1.97		78-85-3	Methacrolein	0.27	
				123-72-8	Butyraldehyde	1.2		123-72-8	Butyraldehyde	Nd	
				123-38-6	Propionaldehyde	0.95		123-38-6	Propionaldehyde	0.00	
				100-52-7	Benzaldehyde	0.55		100-52-7	Benzaldehyde	0.18	
				66-25-1	Hexanal	0.21	31.8%	66-25-1	Hexanaldehyde	0.04	87.6 %
				108-95-2	Phenol	0.24					
	Unidentified	41.0%	41.0%								
106-99-0	1,3-Butadiene	0.11		106-99-0	1,3-Butadiene	1.8		106-99-0	1,3-Butadiene	0.17	
									1,2-Butadiene	0.01	
			0.11%				1.8%		2-Methyl-1,3-Butadiene	0.12	0.17%
Aromatic Compounds											
100-42-5	Styrene	0.22		100-42-5	Styrene	0.39		100-42-5	Styrene	0.00	
71-43-2	Benzene	0.94		71-43-2	Benzene	1.94		71-43-2	Benzene	0.25	
108-88-3	Toluene	2.8		108-88-3	Toluene	0.52		108-88-3	Toluene	0.08	
526-73-8	1,2,3-Trimethylbenzene	0.96						56-73-8	1,2,3-Trimethylbenzene	0.00	
95-63-6	1,2,4-Trimethylbenzene	1.58						108-67-8	1,3,5-Trimethylbenzene	0.02	
108-67-8	1,3,5-Trimethylbenzene	0.78						95-63-6	1,2,4-Trimethylbenzene	0.09	
488-23-3	1,2,3,4 Tetramethylbenzene	1.65						488-23-3	1,2,3,4-Tetramethylbenzene	0.00	
527-53-7	1,2,3,5-Tetramethylbenzene	1.37									
95-93-2	1,2,4,5-Tetramethylbenzene	0.01									
620-14-4	m-Ethyltoluene	0.68						620-14-4	3-Ethyltoluene	0.06	
611-14-3	o-Ethyltoluene	0.37						611-14-3	2-Ethyltoluene	0.03	

Table F-1: Comparison of speciation profiles for jet aircraft emissions developed by U.S. EPA and Environment Canada

U.S. EPA Speciate 3.2				U.S. EPA Speciate 3.2				Speciation Profile: Environment Canada Mobile Sources Emissions Division, Environmental Technology Centre, Ottawa.			
Profile Name		Aircraft - Atlanta - August 27, 1990 # 2572		Profile Name		Aircraft Landing/Take-off (LTO) - Commercial # 1098		VOC Speciation for Jet Turbine Emission Rates Based on Descent, Taxi, Low Idle and Maximum Power Aircraft Operation Phases			
CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Percent
								622-96-8	4-Ethyltoluene	0.02	
								527-84-4	2-Isopropyltoluene (o-Cymene)	0.03	
								535-77-3	3- Isopropyltoluene (m-Cymene)	0.03	
								88-87-6	4- Isopropyltoluene (p-Cymene)	0.00	
									3-n-Propyltoluene	0.03	
									2-n-Propyltoluene	0.01	
100-41-4	Ethylbenzene	0.52		100-41-4	Ethylbenzene	0.17		100-41-4	Ethylbenzene	0.03	
								135-01-3	1,2-Diethylbenzene	0.02	
141-93-5	1,3-Diethylbenzene	0.26		538-68-1	Pentyl Benzene	0.19		141-93-5	1,3-Diethylbenzene	0.00	
								105-05-5	1,4-Diethylbenzene	0.00	
874-41-9	1,3-Dimethyl-4-Ethylbenzene	0.37						874-41-9	1,3-Dimethyl-4-Ethylbenzene	0.00	
									1,4-Dimethyl-2-Ethylbenzene	0.00	
									1,2,3,4-Trans-Tetramethylbenzene	0.00	
									1,3-Dimethyl-2-Ethylbenzene	0.00	
									Tert-Butyl-4-Ethylbenzene	0.00	
									Tertbutyl-3,5-Dimethylbenzene	0.03	
									1,2-Dimethyl-4ethyl-Benzene	0.02	
104-51-8	Butylbenzene	1.1		104-51-8	Butyl Benzene	0.24		104-51-8	n-Butylbenzene	0.04	
25321099	Diisopropylbenzene	0.63						98-06-6	Tert-Butylbenzene	0.00	
103-65-1	n-Propylbenzene	0.33						135-98-8	Sec-Butylbenzene	0.01	
								538-93-2	Iso-Butylbenzene	0.00	
									2-Methyl-Butylbenzene	0.02	
98-82-8	Isopropylbenzene (Cumene)	0.01						98-82-8	Isopropylbenzene (Cumene)	0.00	
									Tert-Butyl-2-Methylbenzene	0.00	
95-47-6	o-Xylene	0.65		95-47-6	o-Xylene	0.19		95-47-6	o-Xylene	0.04	
108-38-3 + 106-42-3	m-Xylene & p-Xylene	1.62		108-38-3 + 106-42-3	m-Xylene & p-Xylene	0.29		108-38-3 + 106-42-3	m-Xylene & p-Xylene	0.08	
				91-20-3	Napthalene	0.57		91-20-3	Napthalene	0.00	
					Methyl Naphthalenes	0.49					
			16.8%				5.0%				0.95 %
Paraffin and Alkane Compounds											
					C7-C16 Paraffins	0.3			N-C13	0.19	
									N-C14	0.33	
									N-C15	0.41	
									N-C16	0.30	
									N-C17	0.22	
									N-C18	0.15	
									N-C19	0.06	
				74-82-8	Methane	9.57		74-82-8	Methane	----	
74-84-0	Ethane	0.77		74-84-0	Ethane	0.88		74-84-0	Ethane	0.02	
74-98-6	Propane	0.65		74-98-6	Propane	0.18		74-98-6	Propane	0.00	
106-97-8	n-Butane	1.63						106-97-8	n-Butane	0.00	
109-66-0	n-Pentane	1.11		109-66-0	n-Pentane	0.21		109-66-0	n-Pentane	0.00	
110-54-3	n-Hexane	0.55						110-54-3	n-Hexane	0.00	
590-73-8	2,2 Dimethylhexane	0.11						591-76-4	2-Methylhexane	0.00	
58-494-1	2,3 Dimethylhexane	0.12						589-34-4	3-Methylhexane	0.00	

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Profile Name		Aircraft - Atlanta - August 27, 1990 # 2572		Profile Name		Aircraft Landing/Take-off (LTO) - Commercial # 1098		VOC Speciation for Jet Turbine Emission Rates Based on Descent, Taxi, Low Idle and Maximum Power Aircraft Operation Phases			
CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Percent
589-43-5	2,4-Dimethylhexane	0.20						590-73-8	2,2-Dimethylhexane	0.00	
592-13-2	2,5-Dimethylhexane	0.11						592-13-2	2,5-Dimethylhexane	0.00	
591-76-4	2-Methylhexane	0.4						589-43-5	2,4-Dimethylhexane	0.00	
589-34-4	3-Methylhexane	0.49						3522-94-9	2,2,5-Trimethylhexane	0.00	
142-82-5	n-Heptane	0.36		142-82-5	n-Heptane	0.06		142-82-5	n-Heptane	0.00	
111-65-9	n-Octane	0.41		111-65-9	n-Octane	0.05		111-65-9	n-Octane	0.00	
111-84-2	n-Nonane	0.90		111-84-2	n-Nonane	0.13		111-84-2	n-Nonane	0.00	
112-40-3	n-Dodecane	4.00		112-40-3	n-Dodecane	1.07		112-40-3	n-Dodecane	0.09	
629-50-5	n-Tridecane	2.43		629-50-5	n-Tridecane	0.66					
629-59-4	n-Tetradecane	0.77		629-59-4	n-Tetradecane	0.58					
112-02-14	n-Undecane	4.89		1120-21-4	n-Undecane	0.53		1120-21-4	n-Undecane	0.07	
124-18-5	n-Decane	3.30		124-18-5	n-Decane	0.42		124-18-5	n-Decane	0.05	
75-28-5	Isobutane	0.53			Isomers Of Tetradecane	0.19		75-28-5	Isobutane	0.00	
75-83-2	2,2-Dimethylbutane	0.17			Isomers Of Dodecane	0.18		75-83-2	2,2-Dimethylbutane	0.00	
79-29-8	2,3-Dimethylbutane	0.33			C16 Branched Alkane	0.14		79-29-8	2,3-Dimethylbutane	0.00	
2453-00-1	1,3-Dimethylcyclopentane	0.08		544-76-3	Hexadecane	0.12					
78-78-4	Isopentane	3.21		629-78-7	N-Heptadecane	0.01					
2216-30-0	2,5 Dimethylheptane	0.21						2216-30-0	2,5-Dimethylheptane	0.00	
7146-60-3	2,3 Dimethyloctane	0.58		629-62-9	N-Pentadecane	0.26		7146-60-3	2,3-Dimethyloctane	0.00	
565-59-3	2,3-Dimethylpentane	0.41			Isomers Of Pentadecane	0.17		565-59-3	2,3-Dimethylpentane	0.05	
108-08-7	2,4-Dimethylpentane	0.27						108-08-7	2,4-Dimethylpentane	0.00	
540-84-1	2,2,4-Trimethylpentane	0.79						540-84-1	2,2,4-Trimethylpentane	0.05	
565-75-3	2,3,4-Trimethylpentane	0.27						565-75-3	2,3,4-Trimethylpentane	0.00	
617-78-7	3-Ethylpentane	0.13						617-78-7	3-Ethylpentane	0.00	
287-92-3	Cyclopentane	0.11						287-92-3	Cyclopentane	0.00	
96-37-7	Methylcyclopentane	0.34						96-37-7	Methylcyclopentane	0.00	
592-27-8	2-Methylheptane	0.23						592-27-8	2-Methyl-Heptane	0.00	
589-81-1	3-Methylheptane	0.21						589-81-1	3-Methylheptane	0.00	
2216-33-3	3-Methyloctane	0.24						2216-33-3	3-Methyloctane	0.00	
2216-34-4	4-Methyloctane	0.27						2216-34-4	4-Methyloctane	0.00	
107-83-5	2-Methylpentane	1.21		107-83-5	2-Methylpentane	0.39		107-83-5	2-Methylpentane	0.00	
96-14-0	3-Methylpentane	0.55						96-14-0	3-Methylpentane	0.00	
110-82-7	Cyclohexane	0.11						110-82-7	Cyclohexane	0.00	
108-87-2	Methylcyclohexane	0.32						108-87-2	Methylcyclohexane	0.00	
1678-93-9	Butylcyclohexane	0.55						2234-75-5	Cis,Cis,Trans-1,2,4-Trimethylcyclohexane	0.00	
			34.3%				16.1%				2.00 %
Alkenes (Olefins)											
74-86-2	Acetylene	1.7		74-86-2	Acetylene	4.17		74-86-2	Acetylene	0.90	
78-79-5	Isoprene	0.39		106-98-9	1-Butene	1.97					
115-07-1	Propylene	0.64		115-07-1	Propylene	5.15		115-07-1	Propylene	1.31	
590-18-1	Cis-2-Butene	0.12		590-18-1	Cis-2-Butene	0.48					
624-64-6	Trans-2-Butene	0.08						624-64-6	Trans-2-Butene	0.09	
74-85-1	Ethylene	2.26		74-85-1	Ethylene	17.45		74-85-1	Ethylene	5.10	
115-11-7	Isobutylene	0.26						115-11-7	Isobutene	0.54	
563-46-2	2-Methyl-1-Butene	0.13		513-35-9	2-Methyl-2-Butene	0.2		513-35-9	2-Methyl-1-Butene	0.05	
563-45-1	3-Methyl-1-Butene	0.05						563-45-1	3-Methyl-1-Butene	0.05	

Table F-1: Comparison of speciation profiles for jet aircraft emissions developed by U.S. EPA and Environment Canada

U.S. EPA Speciate 3.2				U.S. EPA Speciate 3.2				Speciation Profile: Environment Canada Mobile Sources Emissions Division, Environmental Technology Centre, Ottawa.			
Profile Name		Aircraft - Atlanta - August 27, 1990 # 2572		Profile Name		Aircraft Landing/Take-off (LTO) - Commercial # 1098		VOC Speciation for Jet Turbine Emission Rates Based on Descent, Taxi, Low Idle and Maximum Power Aircraft Operation Phases			
CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Sum	CAS No.	Pollutant	Percent	Fraction Percent
513-35-9	2-Methyl-2-Butene	0.15									
594-56-9	2,3,3-Trimethyl-1-Butene	0.17									
109-67-1	1-Pentene	0.16		109-67-1	1-Pentene	0.84		109-67-1	1-Pentene	0.18	
763-29-1	2-Methyl-1-Pentene	0.03						763-29-1	2m1-Pentene	0.00	
691-37-2	4-Methyl-1-Pentene	0.15						691-37-2	4-Methyl-1pentene	0.07	
142-29-0	Cyclopentene	0.04			Isomers Of Pentene	0.73		142-29-0	Cyclopentene	0.00	
627-20-3	Cis-2-Pentene	0.1						627-20-3	Cis-2-Pentene	0.01	
646-04-8	Trans-2-Pentene	0.2						646-04-8	Trans-2-Pentene	0.02	
4050-45-7	Trans-2-Hexene	0.07						4050-45-7	Trans-2-Hexene	0.01	
592-41-6	1-Hexene	0.11		592-41-6	1-Hexene	0.82		592-41-6	1-Hexene	0.10	
7688-21-3	Cis-2-Hexene	0.03		25339-56-4	Heptene	0.54		7688-21-3	Cis-2-Hexene	0.00	
13269-52-8	Trans-3-Hexene	0.02		111-66-0	Octene	0.28		13269-52-8	Cis/Trans--3-Hexene	0.00	
112-41-4	Dodecene	0.82		872-05-9	1-Decene	0.17					
			7.7%				32.8%				8.43 %
					C ₆ H ₁₈ O ₃ Si ₃	9.11					
					C ₈ H ₂₄ O ₄ Si ₄	2.92					
TOTAL OF ASSIGNED FRACTION		100%				99.8%				99.1%	

Table F-2: Comparison of Mean Annual Average Concentrations of Aromatic Hydrocarbons

Compounds	OPSIS	Centennial Park	RATIO
	Annual Mean		
	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	
Benzene	11.9	1.56	7.7
Toluene	35.9	6.02	6.0
<i>p</i> -Xylene	3.4	3.16	1.1
1,2,4-Trimethylbenzene	14.8	1.04	14.3
1,3,5-Trimethylbenzene	17.5	0.35	50.8

The relative abundance of organic chemical compounds recorded by the OPSIS system in annual average values does not match the relative ratios in either of the profiles specified by standardized methodologies. Higher concentrations of these chemicals would be expected if these annual averages were accurate. Observations during the air quality monitoring study suggested that chemical concentrations on- and off-site were generally higher off-site for these compounds. (RWDI, 2003b)

F 2.3.2 Formaldehyde

No carbonyl compound monitoring data compatible with NAPS *routine* monitoring for non-methane hydrocarbon compounds are available for the reference station at Centennial Park. The NAPS program has routinely monitored carbonyl compounds at Junction Triangle in western Toronto for years. Data from a reference site located in Simcoe County in rural Southern Ontario and therefore presumably less affected by urban sources were available for comparison. Regular formaldehyde monitoring data are available from the OPSIS system on the TPIA property.

The annual average formaldehyde concentration measured by the OPSIS system on the days when the Centennial Park NAPS system took samples in the years 1995 to 2001 range from 4.4 to 6.8 $\mu\text{g}/\text{m}^3$.

The annual average formaldehyde concentrations monitored at Junction Triangle in Toronto (2.66 $\mu\text{g}/\text{m}^3$) or at the Simcoe Agricultural Station on Lake Erie (3.40 $\mu\text{g}/\text{m}^3$) in the year 2000 were available for purposes of comparison. On a long-term average (every sixth day sampling) OPSIS appears to overestimate the analytical chemical values from the NAPS data by just under 50%. Since the Junction Triangle is several km to the east of the OPSIS location, it is difficult to state whether this is a systematic difference or a genuine reflection of higher levels of formaldehyde experienced at the TPIA. During the Air Quality Study (RWDI, Phase 4), formaldehyde was monitored simultaneously at several locations. For the three occasions when data were available, the concentration of formaldehyde off-site was generally the same or lower than concentrations observed in the surrounding community. This

suggests that the OPSIS method when compared with the Referenced Environment Canada/EPA analytical chemical method overestimates formaldehyde concentration.

Table F-3 compares maximum and minimum values observed at OPSIS in comparison to the two NAPS locations. The *maximum* formaldehyde for a 24 H period recorded at OPSIS was 3.0 to 3.5 times higher than the NAPS values. OPSIS also overestimated the *minimum* value measured in Toronto by about four fold. This result was inconsistent with results of the air quality study for formaldehyde (RWDI, 2003b).

Table F-3 Maximum and Minimum Monitored Formaldehyde Concentrations

Year/Location	Maximum $\mu\text{g}/\text{m}^3$	Minimum $\mu\text{g}/\text{m}^3$
Toronto (NAPS): 2000	5.6 ^a	1.1
Simcoe (NAPS): 2000	16.7 ^a	0.56
TPIA OPSIS 2000	20.2 ^b	4.5
Toronto (NAPS): 2001	6.2 ^a	1.3
Simcoe (NAPS): 2001	35.5 ^a	1.0
TPIA OPSIS 2001	19.6 ^b	7
Phase 4 Air Quality (n = 5) ^c off-site only	48.0 ^a	5.8
Phase 4 Airside ^d	8.1 ^a	3.3

^a Standard EC/U.S. EPA detection method for carbonyl compounds

^b DOAS/OPIS optical method for detection

^c For complete summary of carbonyl compounds (aldehydes) detected over 5 days see RWDI Phase 4 Report

^d Airside measurements taken on TPIA property in 2001. Three of five days were monitored Airside.

The *predicted values* (modelled) for annual average concentration of formaldehyde at the location of maximum off-site concentration used in the HHRA were prepared from speciation profiles of jet exhaust. Predicted annual average formaldehyde for the year 2000 (Phase 1) at the location of maximum off-site concentration was $6.0 \mu\text{g}/\text{m}^3$. These were in the range of the annual average OPSIS values for the year 2000 and exceeded the maximum monitored concentrations for the Junction Triangle site in Toronto. Predicted maximum annual average off-site concentrations for formaldehyde for the years 2005, 2010 and 2015 increased to a predicted annual concentration of $8.7 \mu\text{g}/\text{m}^3$ in year 2015.

It was concluded that the concentrations of formaldehyde predicted by speciation profiles over estimate what is most likely to be the actual concentration of formaldehyde in the vicinity of the Airport.

F-3.0 Jet Exhaust Emission Profile

Table F-4 shows an example of time associated with specific aircraft operations for the purpose of evaluating emissions to the ambient environment. Different stages of the LTO cycle have been shown to have corresponding emission profiles (Graham and Ainslie, 1997).

Table F-4 Standard Thrust Settings For Estimating Aircraft Engine Emissions

Operating Mode	Thrust Setting	Time in Mode
Take-off	100%	0.7 minutes
Climb	85%	2.2 minutes
Approach (descent)	30%	4.0 minutes
Taxi/Idle	7%	26 minutes

^a ICAO, adapted from Romano *et al.*, 1999

Comparable thrust settings recorded by Graham and Ainslie (1997 revised 2003) and shown in Table F-4 are Taxi (31%), Idle 1 (31%), Idle 2 (descent = 60%) and Idle 4 (Take-off = 97%). The generally used thrust setting for Taxi/Idle currently used by pilots at the TPIA is comparable to the 30% power described in the ERMD report.

Time apportioned to each operational activity for aircraft described as a typical landing and take-off cycle (LTO) for the GTAA were estimated based on results of the EDMS model inputs for the majority of wide-bodied aircraft (personal communication from RWDI, 2003).

LTO cycle = 19.65 minutes

Taxi/Idle 1 = 14.7 minutes divided equally 7.4 min + 7.3 min (Taxi and Idle 1)

Take-off = 1.02 minutes to 3000 ft (Idle 4)

Descent = 3.93 minutes from 3000 ft (Idle 2)

“Climb” is omitted since it is assumed that this would be at altitudes above the ceiling used by EDMS (3000 ft)

The approximate composition chemical classes of compounds emitted in aircraft exhaust during each operation in an LTO is shown in Table F-5.

Table F-5 Percent (by Class) of Total Organic Emissions^a per LTO

Operation	CH ₄	Paraffins	Unsaturates (olefins)	Naphthenes	Aromatics	Total NMHC	Total Carbonyls
Taxi	0.1	5.7	1.1	0.2	4.6	11.7	88.2
Idle 1	0.2	3.9	4.3	0.2	2.5	10.9	88.9
Idle 2 Descent	0.6	4.9	27.0	1.2	8.5	41.7	57.7
Idle 4 Take-off	0.0	50.3	3.2	7.1	1.2	61.7	38.3

^a From Table 5.6 ERMD, 97-03

Conversion of emission rates (milligrams per minute) into average percent composition of emissions in a standard LTO cycle was accomplished in four steps. Emission rates for a jet aircraft fuelled with Jet A were supplied by Graham and Ainslie (1997 as revised in 2003). Chemical emissions were divided into chemical classes corresponding to those shown in Table F-5. The percent of a particular chemical species that should be “detected” in a composite exhaust sample from a typical LTO cycle is given by the formula below. Complete jet exhaust speciation results shown in Table F-7.

$$\sum_{\text{Taxi; Idle; Take-off; Descent}} (\text{emission rate [mg / min]}) \times \left(\frac{\%}{\text{mg}} \text{chemical class in emission} \right) \times (\text{min per cycle}) \cong \% \text{ chemical} \quad (1)$$

Equation (1) above produces the predicted percent of a chemical emissions in a composite sample of aircraft exhaust over an average landing and take-off cycle as described in the ERMD report (Graham and Ainslie, 1997-2003). Completed speciation profiles for jet aircraft exhaust at TPIA were prepared in several steps using time allocated to each operational phase based on outputs from the EDMS modelling of aircraft movements supplied by RWDI.

F-3.1 Chemical Speciation of Jet Aircraft Exhaust at the TPIA

Step 1: Compounds and their associated emission rates as reported in Graham and Ainslie (1997 revised 2003) were arranged by class as described in the Table F-5 above (mg/min). (see Table F-7, Column 1).

Step 2: Total emissions were estimated for each stage (Taxi, Idle 1, etc) and for a single LTO cycle (Table F-7, Column 2 gives the mg-percent/min for each operation of the LTO cycle). Column 2 in the spread sheet multiplies the emission rate for a specific chemical species by a factor (the fraction or percent that a chemical class contributes to an LTO cycle). For example, combined aromatics constitute 4.6 % of the emissions during Taxi. So each aromatic is multiplied by 0.046 to determine the total contribution of that chemical during the Taxi part of an LTO.

Step 3: Only a fraction of the total LTO cycle (19.65 minutes) was spent taxiing, taking off or descending from 3000 ft (e.g. the average LTO cycle includes 14.69 minutes standing or taxiing, 1.02 minutes for take-off to reach 3000 ft, and 3.93 minutes for descent respectively). A standardized chemical contribution (percent) for each chemical based modes and time of the LTO cycle is shown in Table F-7, Column 3.

Step 4: Add across the columns to find the total chemical emissions (as percentages) for each portion of the LTO cycle to determine the contributions from different operational stages. This weighted average is shown in the column 4 of Table F-7.

As shown in Column 4 of Table F-7 the blended speciation profile predicts that jet exhaust at the TPIA would contain 16.5% formaldehyde, 64.4 % acetone and only 0.25% benzene. The final column (Column 5) shows the predicted composition of jet exhaust for the LTO cycle if oxygenated hydrocarbons (mainly carbonyl compounds) were removed, and only non-methane hydrocarbons (NMHC) considered. As shown in the last column (5) of Table F-7, benzene in jet exhaust would be 2% of NMHC.

Estimates for Benzene in the NAPS VOC detected at Centennial Park (see Appendix B) show that the annual average from 1994 to 2001 for benzene was about 2% of all NMHC detected.

Comparisons between speciation profiles EPA #1098, EPA #2572 and the final ERMD profile are shown in Table F-1.

F-4.0 Particulate Matter Emissions from Jet Aircraft

Concern about the adverse impact of aviation on the environment has focused on exhaust emissions from aircraft engines (U.S. EPA, 1999). At a meeting in January 2001, the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) called for further examination of more stringent measures for controlling all gaseous engine emissions, especially the oxides of nitrogen (NO_x).

ICAO maintains an *Aircraft Engine Exhaust Emissions Data Bank* that describes emissions of criteria pollutants and total hydrocarbons, but contains no data for emission rates associated with PM₁₀. Standards applied to aircraft engines are concerned with limitation of smoke emissions, unburned hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) from turbojet and turbofan aircraft engines. Details of these emissions are contained in Volume II of Annex 16 to the Convention on International Civil Aviation, Second Edition, July 1993. The Annex also contains approved test and measurement procedures.

Standards for smoke apply to engines on all subsonic commercial aircraft manufactured after January, 1983. For the gaseous emissions, the Standards apply only to engines whose rated output is greater than 26.7 kN. For hydrocarbons and carbon monoxide, they apply to engines manufactured after January 1986. For oxides of nitrogen, the Standards have two levels of stringency depending on the date of manufacture of the engine (ICAO, 1995).

Much of the focus on aircraft emissions of particulate matter has had to do with effects on the upper atmosphere and contrail formation. Additional concerns have been associated with aircraft participation in the production of green house gases and the effect of operation at altitude, and under cruise conditions. These are largely not relevant to environmental concerns that are addressed in this study.

Romano *et al.*, (1999) cited emission factors for particulate matter based kilograms particulate produced during landing and takeoff (LTO) cycles of a variety of commercial jet aircraft. The source attributed was the U.S. EPA *Compilation of air pollutant emission factors, Vol. II, Mobile Sources*; however, the currently available version of this document does not contain this information. Engine operating conditions during a typical LTO are shown in Table F-5.

For purposes of estimating PM₁₀ loadings to ground-based operations, only the taxi time and take-off time would be considered as likely to contribute significant PM₁₀ to the surrounding environment. As shown in Table F-6, the manufacturer of a particular aircraft and/or engine combination can affect the emission rate for PM₁₀.

Table F-6 PM₁₀ Emission Factors and Fuel Consumption for LTO per Aircraft Type^a.

Boeing 737	0.4 kg PM ₁₀ /LTO
Boeing 727, 757	0.5 kg PM ₁₀ /LTO
Boeing 747	2.1 kg PM ₁₀ /LTO
Boeing 767	2.1 kg PM ₁₀ /LTO
Airbus A300, 310	2.1 kg PM ₁₀ /LTO
Airbus A320	0.4 kgPM /LTO
DC10	0.1 kg PM ₁₀ /LTO

^a Adapted from Romano *et al.*, 1999

The crude estimates of emissions (Table F-6), and the wide variability associated with fuel type and manufacturer show how difficult it is to produce reasonable and defensible estimates for aircraft particulate emissions over time and multiple LTOs.

Very few detailed measurements have been reported in the open scientific literature for particulate matter (PM₁₀) emissions from aircraft engines. For most turbine engines there is a regulated limit for the amount of smoke that may be emitted. This limit is specified as a smoke number. Attempts have been made to derive a correlation between smoke and particulate matter, but such prediction does not generally match experimental results. The U.S. EPA has not established an emission factor for PM₁₀ from turbine aircraft engines (U.S. EPA, 2003).

Ions formed in the combustion process of jet fuel participate in chemical radical reactions to produce chemiions (CI) that may be important in the formation of aerosols (Eichkorn *et al.* 2002). CI are composed of oxygenated compounds as well as hydrocarbons present in exhaust gases (Kiendler *et al.*, 2002). Recombination of positive and negative ions generated during combustion provides a nucleation element that can initiate particle formation and grow through condensation reactions. The massive chemiions present in hot exhaust gases are likely to participate in particle formation independent of sulphur concentration (Kiendler *et al.*, 2002).

Taken together, it appears that the composition of exhaust gases from jet turbine operation are primarily precursors of particles that eventually develop in the ambient environment. Data for direct PM₁₀ emission are scanty. Since aircraft move at such a high rate of speed, especially during takeoff, it is difficult to attribute the presence of a particulate level at one location to a specific source. Modelling the production of PM₁₀ from jet emissions requires some means of characterizing post-emission chemical reactions in the environment. Algorithms that describe atmospheric transformation of chemical mixtures of this type into PM₁₀ are not generally available at the time that this report was prepared.

Sulphur in fuel contributes to aerosol formation. Sulphur content of fuels and its effect on particulate size was examined by Schröder *et al.*, (1998). Low sulphur fuels (20 ppm) reduce the mass of particles in the 5 nm range by as much as ten fold. The emission index for SO₂ which can lead to sulphuric acid aerosols is approximately 1.0 g/kg fuel burnt. Aerosols released from aircraft participate in contrail formation (Brasseur *et al.*, 1998), but the relation between acid aerosol and particulate formation at ground level is unclear for jet aircraft emissions. Most of the recent scientific literature in this area has been focussed on contrail production and green house gas contribution and effects. Soot emitted by engines can interact with HNO₃, H₂SO₄ and H₂O to promote aerosol formation. Preliminary studies of aerosol formation at cruising altitude suggest that air corridors used by commercial aircraft contain 10 to 30 % higher levels of condensed nuclei capable of forming particulate matter.

Measured emission indices for soot produced by a jet engine at a power setting of 30% have been recorded at 130 mg/kg fuel burnt (Eichkorn *et al.* 2002). Date of engine manufacture, fuel composition and operating conditions strongly influence reported emission rates for PM₁₀. An emission index for soot of 200 mg/kg fuel has been reported, without reference to operating conditions (thrust level) (Brasseur *et al.*, 1998). Fuel additives for JP-8 have been investigated by the military in order to reduce particulate emissions. Fuel additives have been offered as an alternative approach for engine redesign, and to prolong the operational capability of current in-use designs. Key findings of such programmes show that lowering the aromatic content of fuels reduces particulate formation. Proprietary additives also work to reduce particulate formation, but generally these need to be over the 100 ppm level in fuel, making their use expensive. Recently the U.S. Military has identified a need to reduce particulate < PM_{2.5} in aircraft and ground equipment by 70% (McNesby and Litzinger, 2003). Currently interest has been expressed in the addition of ethanol to fuel, but other additive substances are being pursued.

The considerable visible and noise impact of large jet aircraft has presented an obvious target for public and community concern around major airports (Colvile *et al.*, 2001). Several studies have demonstrated that the emissions from aircraft themselves contribute little by comparison with the great volumes of traffic, as well as the associated ground services that large airports generate. It has been argued that the emissions from aircraft are efficiently dispersed before aircraft reach the ground analogous to the process applied to single source (stack) modelling for emissions (Colvile *et al.*, 2001). The recent development of the Federal Aviation Administration's EDMS model has simplified estimation of pollution impact from landing, taxi and take-off cycles for specific airport operating scenarios.

Poor air quality in urban environments has a well demonstrated effect on respiratory and circulatory (cardiovascular) health. Ground level pollutants from aircraft operations that have received attention include carbon monoxide, hydrocarbons, and to a lesser degree oxides of nitrogen (Colvile *et al.*, 2001).

Some of the characteristics of black carbon emitted from jet aircraft include aerosols with a size distribution (at ground level) that peaks at a modal diameter of 0.05 µm, and shows a second mode

diameter of approximately 0.2 μm (Petzold *et al.*, 1999). Recent design improvement has markedly reduced black smoke emissions from commercial aircraft. Atmospheric particulate black carbon (soot) in the upper atmosphere has been identified with the formation of cirrus clouds, and has been assigned a possible role when reacting with HNO_3 and NO_2 as an agent of ozone depletion.

F-5.0 References:

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Table F-7 Aircraft Speciation Profile Based on Emission Rate and Aircraft Operations per LTO Cycle

Compound	COLUMN 1: Basic Emission Rates				FACTOR	COLUMN 2: Factor % by chemical class				COLUMN 3: Duration of each stage				COLUMN 4	Compound	COLUMN 5
	Taxi	IDLE 1 (Low Idle)	IDLE 2 (Descent)	IDLE 4 Max Power		Taxi	IDLE 1 Low Idle	IDLE 2 Descent Idle	IDLE 4 Max Power	Emissions Taxi (7.4 min)	Emissions Idle 1 (7.3 min)	Emissions Descent (3.93 min)	Emissions Take off (1.02 min)	% VOC emissions per LTO cycle		% NMHC emissions per LTO cycle
	mg/MIN	mg/MIN	mg/MIN	mg/MIN		mg-%	mg-%	mg-%	mg-%	mg-% per cycle	mg-% per cycle	mg-% per cycle	mg-% per cycle	PERCENT		
					AROMATIC	0.046	0.025	0.085	0.012							
A benzene	0.32	1.68	279.98	3.52	AROMATIC	0.01	0.04	23.80	0.04	0.11	0.31	93.53	0.04	0.25	benzene	2.05
A toluene	9.48	5.07	77.41	12.63		0.44	0.13	6.58	0.15	3.23	0.93	25.86	0.15	0.08	toluene	0.66
A ethyl-benzene	0.29	0.22	35.08	0.25		0.01	0.01	2.98	0.00	0.10	0.04	11.72	0.00	0.03	ethyl-benzene	0.26
A m & p-xylene	6.58	5.81	83.68	0.71		0.30	0.15	7.11	0.01	2.24	1.06	27.95	0.01	0.08	m & p-xylene	0.68
A o-xylene	0.62	0.46	41.74	0.35		0.03	0.01	3.55	0.00	0.21	0.08	13.94	0.00	0.04	o-xylene	0.31
A isopropyl-benzene	0.09	0.00	1.17	0.00		0.00	0.00	0.10	0.00	0.03	0.00	0.39	0.00	0.00	isopropyl-benzene	0.01
A n-propylbenzene	0.44	0.26	29.21	0.33		0.02	0.01	2.48	0.00	0.15	0.05	9.76	0.00	0.03	n-propylbenzene	0.22
A 3-ethyl-toluene	10.04	0.83	53.74	0.25		0.46	0.02	4.57	0.00	3.42	0.15	17.95	0.00	0.06	3-ethyl-toluene	0.47
A 4-ethyl-toluene	0.72	0.56	22.72	0.00		0.03	0.01	1.93	0.00	0.25	0.10	7.59	0.00	0.02	4-ethyl-toluene	0.17
A 1,3,5-trimethyl-benzene	0.99	0.58	21.97	0.23		0.05	0.01	1.87	0.00	0.34	0.11	7.34	0.00	0.02	1,3,5-trimethyl-benzene	0.17
A 2-ethyl-toluene	0.94	0.77	27.86	0.00		0.04	0.02	2.37	0.00	0.32	0.14	9.31	0.00	0.03	2-ethyl-toluene	0.21
A 1,2,4-trimethyl-benzene	20.39	9.75	76.37	0.54		0.94	0.24	6.49	0.01	6.94	1.78	25.51	0.01	0.09	1,2,4-trimethyl-benzene	0.75
A iso-butylbenzene	0.15	0.00	2.50	0.00		0.01	0.00	0.21	0.00	0.05	0.00	0.84	0.00	0.00	iso-butylbenzene	0.02
A sec-butylbenzene	0.25	0.00	10.97	0.00		0.01	0.00	0.93	0.00	0.09	0.00	3.66	0.00	0.01	Sec-butylbenzene	0.08
A 3-isopropyl-toluene	0.61	0.00	27.84	2.78		0.03	0.00	2.37	0.03	0.21	0.00	9.30	0.03	0.03	3-isopropyl-toluene	0.21
A 1,2,3-trimethyl-benzene	1.12	1.70	2.38	0.15		0.05	0.04	0.20	0.00	0.38	0.31	0.80	0.00	0.00	1,2,3-trimethyl-benzene	0.03
A 4-isopropyl-toluene	0.00	0.00	3.79	1.03		0.00	0.00	0.32	0.01	0.00	0.00	1.27	0.01	0.00	4-isopropyl-toluene	0.03
A Indan	0.70	0.47	1.11	0.30		0.03	0.01	0.09	0.00	0.24	0.09	0.37	0.00	0.00	indan	0.02
A 2-isopropyl-toluene	1.10	0.73	0.98	0.00		0.05	0.02	0.08	0.00	0.37	0.13	0.33	0.00	0.00	2-isopropyl-toluene	0.02
A 1,3-diethyl-benzene	0.15	0.08	0.59	0.33		0.01	0.00	0.05	0.00	0.05	0.01	0.20	0.00	0.00	1,3-diethyl-benzene	0.01
A 1,4-diethyl-benzene	0.52	0.17	1.99	0.00		0.02	0.00	0.17	0.00	0.18	0.03	0.66	0.00	0.00	1,4-diethyl-benzene	0.02
A 3-npropyl-toluene	0.92	0.47	27.98	0.28		0.04	0.01	2.38	0.00	0.31	0.09	9.35	0.00	0.03	3-npropyl-toluene	0.21
A n-butylbenzene	1.65	0.93	46.72	0.52		0.08	0.02	3.97	0.01	0.56	0.17	15.61	0.01	0.04	n-butylbenzene	0.36
A 1,2-diethyl-benzene	0.55	0.11	19.93	0.12		0.03	0.00	1.69	0.00	0.19	0.02	6.66	0.00	0.02	1,2-diethyl-benzene	0.15
A 2-n-propyl-toluene	0.28	0.42	13.53	0.38		0.01	0.01	1.15	0.00	0.10	0.08	4.52	0.00	0.01	2-n-propyl-toluene	0.10
A 1,4-dimethyl-2ethyl-benzene	0.88	0.46	11.01	0.21		0.04	0.01	0.94	0.00	0.30	0.08	3.68	0.00	0.01	1,4-dimethyl-2ethyl-benzene	0.09
A 1,3-dimethyl-4ethyl-benzene	0.60	0.24	0.43	0.47		0.03	0.01	0.04	0.01	0.20	0.04	0.14	0.01	0.00	1,3-dimethyl-4ethyl-benzene	0.01
A 1,2-dimethyl-4ethyl-benzene	7.56	0.49	11.67	0.39		0.35	0.01	0.99	0.00	2.57	0.09	3.90	0.00	0.02	1,2-dimethyl-4ethyl-benzene	0.14
A 1,3-dimethyl-2ethyl-benzene	0.16	0.55	0.54	0.00		0.01	0.01	0.05	0.00	0.05	0.10	0.18	0.00	0.00	1,3-dimethyl-2ethyl-benzene	0.01
A 2-methylbutylbenzene	0.70	0.77	19.04	0.50		0.03	0.02	1.62	0.01	0.24	0.14	6.36	0.01	0.02	2-methyl-butylbenzene	0.15
A tert-butyl-2-methyl-benzene	0.17	0.15	0.00	0.18		0.01	0.00	0.00	0.00	0.06	0.03	0.00	0.00	0.00	tert-butyl-2-methylbenzene	0.00
A 1,2,3,4-tert-tetramethyl-benzene	0.23	0.32	0.25	0.18		0.01	0.01	0.02	0.00	0.08	0.06	0.08	0.00	0.00	1,2,3,4-tert-tetramethyl-benzene	0.00
A n-pentyl-benzene	0.42	1.11	21.20	0.62		0.02	0.03	1.80	0.01	0.14	0.20	7.08	0.01	0.02	n-pentyl-benzene	0.16
A tert-butyl-3,5-dimethyl-benzene	0.38	0.24	28.88	0.22		0.02	0.01	2.45	0.00	0.13	0.04	9.65	0.00	0.03	tert-butylb-3,5-dimethyl-benzene	0.21
A tert-butylb-4-ethyl-benzene	0.09	0.51	1.01	1.01		0.00	0.01	0.09	0.01	0.03	0.09	0.34	0.01	0.00	tert-butyl-4-ethyl-benzene	0.01
A 1,3,5-triethyl-benzene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,3,5-triethyl-benzene	0.00
A 1,2,4-triethyl-benzene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,2,4-triethyl-benzene	0.00
A n-hexylbenzene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n-hexylbenzene	0.00
					FACTOR	0.882	0.889	0.577	0.383							
C formaldehyde	6.00	2.00	2693.00	74.00	CARBONYL	5.29	1.78	1553.86	28.34	39.16	12.98	6106.67	28.91	16.55	formaldehyde	
C acetaldehyde	0.00	0.00	602.00	27.00		0.00	0.00	347.35	10.34	0.00	0.00	1365.10	10.55	3.68	acetaldehyde	
C 2-3 butandione	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2-3 butandione	
C acrolein	0.00	0.00	249.00	7.00		0.00	0.00	143.67	2.68	0.00	0.00	564.63	2.73	1.52	acrolein	
C acetone	1320.00	1276.00	3021.00	831.00		1164.24	1134.36	1743.12	318.27	8615.38	8280.86	6850.45	324.64	64.39	acetone	
C propionaldehyde	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	propionaldehyde	
C methoxyacetone	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	methoxyacetone	

Table F-7 Aircraft Speciation Profile Based on Emission Rate and Aircraft Operations per LTO Cycle

Compound	COLUMN 1: Basic Emission Rates					COLUMN 2: Factor % by chemical class				COLUMN 3: Duration of each stage				COLUMN 4	Compound	COLUMN 5
	Taxi	IDLE 1 (Low Idle)	IDLE 2 (Descent)	IDLE 4 Max Power		Taxi	IDLE 1 Low Idle	IDLE 2 Descent Idle	IDLE 4 Max Power	Emissions Taxi (7.4 min)	Emissions Idle 1 (7.3 min)	Emissions Descent (3.93 min)	Emissions Take off (1.02 min)	% VOC emissions per LTO cycle		% NMHC emissions per LTO cycle
	mg/MIN	mg/MIN	mg/MIN	mg/MIN		mg-%	mg-%	mg-%	mg-%	mg-% per cycle	mg-% per cycle	mg-% per cycle	mg-% per cycle	PERCENT		
C crotonaldehyde	0.00	0.00	46.00	0.00		0.00	0.00	26.54	0.00	0.00	0.00	104.31	0.00	0.28	crotonaldehyde	
C methacrolein	3.00	0.00	36.00	0.00		2.65	0.00	20.77	0.00	19.58	0.00	81.63	0.00	0.27	methacrolein	
C isobutyraldehyde & butyraldehyde	0.00	0.00	23.00	0.00		0.00	0.00	13.27	0.00	0.00	0.00	52.16	0.00	0.14	isobutyraldehyde & butyraldehyde	
C methyl ethyl ketone	7.00	3.00	14.00	0.00		6.17	2.67	8.08	0.00	45.69	19.47	31.75	0.00	0.26	methyl ethyl ketone	
C benzaldehyde	0.00	0.00	30.00	0.00		0.00	0.00	17.31	0.00	0.00	0.00	68.03	0.00	0.18	benzaldehyde	
C isovaleraldehyde	0.00	0.00	11.00	0.00		0.00	0.00	6.35	0.00	0.00	0.00	24.94	0.00	0.07	isovaleraldehyde	
C trimethylacetaldehyde	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	trimethylacetaldehyde	
C valeraldehyde & 3-methyl-2-butanone	0.00	0.00	26.00	0.00		0.00	0.00	15.00	0.00	0.00	0.00	58.96	0.00	0.16	valeraldehyde & 3-methyl-2-butanone	
C acetophenone & o-tolualdehyde	0.00	0.00	9.00	0.00		0.00	0.00	5.19	0.00	0.00	0.00	20.41	0.00	0.05	acetophenone & o-tolualdehyde	
C m & p-tolualdehyde	0.00	0.00	17.00	0.00		0.00	0.00	9.81	0.00	0.00	0.00	38.55	0.00	0.10	m & p-tolualdehyde	
C methyl isobutyl ketone	0.00	0.00	7.00	0.00		0.00	0.00	4.04	0.00	0.00	0.00	15.87	0.00	0.04	methyl isobutyl ketone	
C pinacolone	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	pinacolone	
C hexanaldehyde	0.00	0.00	7.00	0.00		0.00	0.00	4.04	0.00	0.00	0.00	15.87	0.00	0.04	hexanaldehyde	
					FACTOR	0.002	0.002	0.012	0.071							
N cyclopentene	0.04	0.21	14.25	0.17	NAPHTHENE	0.00	0.00	0.17	0.01	0.00	0.00	0.67	0.01	0.00	cyclopentene	0.02
N cyclopentane	0.00	0.00	2.97	0.29		0.00	0.00	0.04	0.02	0.00	0.00	0.14	0.02	0.00	cyclopentane	0.00
N m-cyclopentane	0.00	0.00	0.59	0.00		0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	m-cyclopentane	0.00
N 1-methyl-cyclopentene	0.04	0.00	2.67	0.17		0.00	0.00	0.03	0.01	0.00	0.00	0.13	0.01	0.00	1-methyl-cyclopentene	0.00
N cyclohexane	0.00	0.00	3.94	0.37		0.00	0.00	0.05	0.03	0.00	0.00	0.19	0.03	0.00	cyclohexane	0.00
N 1,1-dimethyl-cyclopentane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,1-dimethyl-cyclopentane	0.00
N cyclohexene	0.00	0.00	1.76	0.70		0.00	0.00	0.02	0.05	0.00	0.00	0.08	0.05	0.00	cyclohexene	0.00
N c-1,3-dimethyl-cyclopentane	0.00	0.00	0.51	0.00		0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.00	c-1,3-dimethyl-cyclopentane	0.00
N t-1,2-dimethyl-cyclopentane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	t-1,2-dimethyl-cyclopentane	0.00
N m-cyclohexane	0.11	0.00	1.71	0.00		0.00	0.00	0.02	0.00	0.00	0.00	0.08	0.00	0.00	m-cyclohexane	0.00
N 1,2-dimethyl-cyclohexane	0.20	0.39	1.76	0.77		0.00	0.00	0.02	0.05	0.00	0.01	0.08	0.06	0.00	1,2-dimethyl-cyclohexane	0.00
N ctc1,2,3-trimethyl-cyclopentane	0.06	0.11	3.91	0.87		0.00	0.00	0.05	0.06	0.00	0.00	0.18	0.06	0.00	ctc1,2,3-trimethyl-cyclopentane	0.01
N t-1,4-dimethyl-cyclohexane	0.05	0.00	0.97	0.18		0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.01	0.00	t-1,4-dimethyl-cyclohexane	0.00
N 1,1-dimethyl-cyclohexane	0.00	0.38	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	1,1-dimethyl-cyclohexane	0.00
N ccc-1,2,3-trimethyl-cyclopentane	0.04	0.00	2.59	0.15		0.00	0.00	0.03	0.01	0.00	0.00	0.12	0.01	0.00	ccc-1,2,3-trimethyl-cyclopentane	0.00
N ccc-1,3,5-trimethyl-cyclohexane	0.10	0.00	4.97	0.00		0.00	0.00	0.06	0.00	0.00	0.00	0.23	0.00	0.00	ccc-1,3,5-trimethyl-cyclohexane	0.01
N 1,1,4-trimethyl-cyclohexane	0.05	0.23	10.52	0.20		0.00	0.00	0.13	0.01	0.00	0.00	0.50	0.01	0.00	1,1,4-trimethyl-cyclohexane	0.01
N cct1,2,4-trimethyl-cyclohexane	2.46	0.99	58.18	161.53		0.00	0.00	0.70	11.47	0.04	0.01	2.74	11.70	0.04	cct1,2,4-trimethyl-cyclohexane	0.32
N ctc-1,2,4-trimethyl-cyclohexane	0.09	0.14	3.29	0.00		0.00	0.00	0.04	0.00	0.00	0.00	0.16	0.00	0.00	ctc-1,2,4-trimethyl-cyclohexane	0.00
N isobutyl-cyclopentane	0.00	0.00	0.00	0.46		0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03	0.00	isobutyl-cyclopentane	0.00
N isopropyl-cyclohexane	0.14	0.00	9.63	0.00		0.00	0.00	0.12	0.00	0.00	0.00	0.45	0.00	0.00	isopropyl-cyclohexane	0.01
N n-butyl-cyclopentane	0.19	0.43	6.56	1.32		0.00	0.00	0.08	0.09	0.00	0.01	0.31	0.10	0.00	n-butyl-cyclopentane	0.01
N 1-butyl-cyclohexane	0.17	0.23	5.48	6.26		0.00	0.00	0.07	0.44	0.00	0.00	0.26	0.45	0.00	1-butyl-cyclohexane	0.02
					FACTOR	0.06	0.04	0.05	0.50							
P ethane	0.00	1.01	36.87	1.98	PARAFFIN	0.00	0.04	1.81	1.00	0.00	0.29	7.10	1.02	0.02	ethane	0.18
P propane	0.93	1.01	4.68	0.00		0.05	0.04	0.23	0.00	0.39	0.29	0.90	0.00	0.00	propane	0.03
P isobutane	0.22	0.00	0.54	0.00		0.01	0.00	0.03	0.00	0.09	0.00	0.10	0.00	0.00	isobutane	0.00
P n-butane	0.53	0.52	1.47	0.00		0.03	0.02	0.07	0.00	0.22	0.15	0.28	0.00	0.00	n-butane	0.01
P 2,2-dimethyl-propane	0.00	0.00	2.80	0.00		0.00	0.00	0.14	0.00	0.00	0.00	0.54	0.00	0.00	2,2-dimethyl-propane	0.01
P 2-methyl-butane	0.00	2.09	2.78	0.00		0.00	0.08	0.14	0.00	0.00	0.60	0.54	0.00	0.00	2-methyl-butane	0.02
P n-pentane	0.24	0.20	0.77	0.00		0.01	0.01	0.04	0.00	0.10	0.06	0.15	0.00	0.00	n-pentane	0.01
P 2,2-dimethyl-butane	0.07	0.16	1.77	0.00		0.00	0.01	0.09	0.00	0.03	0.05	0.34	0.00	0.00	2,2-dimethyl-butane	0.01
P 2,3-dimethyl-butane	0.17	0.00	0.00	0.00		0.01	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	2,3-dimethyl-butane	0.00

Table F-7 Aircraft Speciation Profile Based on Emission Rate and Aircraft Operations per LTO Cycle

Compound	COLUMN 1: Basic Emission Rates					COLUMN 2: Factor % by chemical class				COLUMN 3: Duration of each stage				COLUMN 4	Compound	COLUMN 5
	Taxi	IDLE 1 (Low Idle)	IDLE 2 (Descent)	IDLE 4 Max Power		Taxi	IDLE 1 Low Idle	IDLE 2 Descent Idle	IDLE 4 Max Power	Emissions Taxi (7.4 min)	Emissions Idle 1 (7.3 min)	Emissions Descent (3.93 min)	Emissions Take off (1.02 min)	% VOC emissions per LTO cycle		% NMHC emissions per LTO cycle
	mg/MIN	mg/MIN	mg/MIN	mg/MIN		mg-%	mg-%	mg-%	mg-%	mg-% per cycle	mg-% per cycle	mg-% per cycle	mg-% per cycle	PERCENT		
P 2-methyl-pentane	0.21	0.31	0.70	0.00		0.01	0.01	0.03	0.00	0.09	0.09	0.13	0.00	0.00	2-methyl-pentane	0.01
P 3-methyl-pentane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3-methyl-pentane	0.00
P n-hexane	0.26	0.35	1.84	0.76		0.01	0.01	0.09	0.38	0.11	0.10	0.35	0.39	0.00	n-hexane	0.02
P 2,2-dimethyl-pentane	0.17	0.00	0.00	0.00		0.01	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	2,2-dimethyl-pentane	0.00
P 2,4-dimethyl-pentane	0.16	0.00	3.74	0.96		0.01	0.00	0.18	0.48	0.07	0.00	0.72	0.49	0.00	2,4-dimethyl-pentane	0.03
P 2,2,3-trimethyl-butane	0.09	0.00	2.98	0.00		0.01	0.00	0.15	0.00	0.04	0.00	0.57	0.00	0.00	2,2,3-trimethyl-butane	0.01
P 3,3-dimethyl-pentane	0.00	0.00	4.37	0.00		0.00	0.00	0.21	0.00	0.00	0.00	0.84	0.00	0.00	3,3-dimethyl-pentane	0.02
P 2-methyl-hexane	0.10	0.00	1.49	0.00		0.01	0.00	0.07	0.00	0.04	0.00	0.29	0.00	0.00	2-methyl-hexane	0.01
P 2,3-dimethyl-pentane	0.06	0.00	18.67	31.84		0.00	0.00	0.91	16.02	0.03	0.00	3.60	16.34	0.05	2,3-dimethyl-pentane	0.44
P 3-methyl-hexane	0.11	0.22	12.79	1.64		0.01	0.01	0.63	0.82	0.05	0.06	2.46	0.84	0.01	3-methyl-hexane	0.07
P 3-ethyl-pentane	0.00	0.00	2.97	0.00		0.00	0.00	0.15	0.00	0.00	0.00	0.57	0.00	0.00	3-ethyl-pentane	0.01
P 2,2,4-trimethyl-pentane	0.11	0.20	61.55	13.96		0.01	0.01	3.02	7.02	0.05	0.06	11.85	7.16	0.05	2,2,4-trimethyl-pentane	0.42
P n-heptane	0.12	0.00	1.97	0.27		0.01	0.00	0.10	0.14	0.05	0.00	0.38	0.14	0.00	n-heptane	0.01
P 2,2-dimethyl-hexane	0.00	0.00	1.76	0.13		0.00	0.00	0.09	0.07	0.00	0.00	0.34	0.07	0.00	2,2-dimethyl-hexane	0.01
P 2,5-dimethyl-hexane	0.00	0.00	0.77	0.21		0.00	0.00	0.04	0.11	0.00	0.00	0.15	0.11	0.00	2,5-dimethyl-hexane	0.01
P 2,4-dimethyl-hexane	0.00	0.00	7.26	0.21		0.00	0.00	0.36	0.11	0.00	0.00	1.40	0.11	0.00	2,4-dimethyl-hexane	0.03
P 3,3-dimethyl-hexane	0.00	0.00	0.65	0.12		0.00	0.00	0.03	0.06	0.00	0.00	0.13	0.06	0.00	3,3-dimethyl-hexane	0.00
P 2,3,4-trimethyl-pentane	0.03	0.00	2.14	0.24		0.00	0.00	0.10	0.12	0.01	0.00	0.41	0.12	0.00	2,3,4-trimethyl-pentane	0.01
P 2,3-dimethyl-hexane	0.00	0.00	3.45	0.45		0.00	0.00	0.17	0.23	0.00	0.00	0.66	0.23	0.00	2,3-dimethyl-hexane	0.02
P 2-methyl -heptane	0.07	0.00	2.59	0.00		0.00	0.00	0.13	0.00	0.03	0.00	0.50	0.00	0.00	2-methyl -heptane	0.01
P 4-methyl -heptane	0.04	0.00	1.53	0.22		0.00	0.00	0.07	0.11	0.02	0.00	0.29	0.11	0.00	4-methyl -heptane	0.01
P 3-methyl -heptane	0.08	0.00	2.66	0.00		0.00	0.00	0.13	0.00	0.03	0.00	0.51	0.00	0.00	3-methyl -heptane	0.01
P 3-ethyl-hexane	0.80	0.86	6.17	1.98		0.05	0.03	0.30	1.00	0.34	0.24	1.19	1.02	0.01	3-ethyl-hexane	0.06
P 2,2,5-trimethyl-hexane	0.00	0.00	2.36	0.00		0.00	0.00	0.12	0.00	0.00	0.00	0.45	0.00	0.00	2,2,5-trimethyl-hexane	0.01
P 2,2,4-trimethyl-hexane	0.00	0.00	1.10	0.21		0.00	0.00	0.05	0.11	0.00	0.00	0.21	0.11	0.00	2,2,4-trimethyl-hexane	0.01
P n-octane	0.16	0.49	5.89	0.26		0.01	0.02	0.29	0.13	0.07	0.14	1.13	0.13	0.00	n-octane	0.03
P 2,4,4-trimethyl-hexane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,4,4-trimethyl-hexane	0.00
P 2,3,5-trimethyl-hexane	0.00	0.00	0.72	0.00		0.00	0.00	0.04	0.00	0.00	0.00	0.14	0.00	0.00	2,3,5-trimethyl-hexane	0.00
P 4,4- & 2,2- & 2,6-dimethyl-heptane	0.16	0.20	12.01	4.21		0.01	0.01	0.59	2.12	0.07	0.06	2.31	2.16	0.01	4,4- & 2,2- & 2,6-dimethyl-heptane	0.10
P 2,4-dimethyl-heptane	0.00	0.00	1.50	0.00		0.00	0.00	0.07	0.00	0.00	0.00	0.29	0.00	0.00	2,4-dimethyl-heptane	0.01
P 2,5-dimethyl-heptane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,5-dimethyl-heptane	0.00
P 3,3-dimethyl-heptane	0.00	0.00	0.72	0.00		0.00	0.00	0.04	0.00	0.00	0.00	0.14	0.00	0.00	3,3-dimethyl-heptane	0.00
P 3,5-dimethyl-heptane	0.03	0.00	2.64	0.28		0.00	0.00	0.13	0.14	0.01	0.00	0.51	0.14	0.00	3,5-dimethyl-heptane	0.01
P 3,4-dimethyl-heptane	0.05	0.00	3.71	0.00		0.00	0.00	0.18	0.00	0.02	0.00	0.71	0.00	0.00	3,4-dimethyl-heptane	0.02
P 4-ethyl-heptane	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4-ethyl-heptane	0.00
P 2,4,6-trimethyl-hexane	0.11	0.37	5.44	0.62		0.01	0.01	0.27	0.31	0.05	0.11	1.05	0.32	0.00	2,4,6-trimethyl-hexane	0.03
P 3-methyl-octane	0.28	0.68	0.00	0.65		0.02	0.03	0.00	0.33	0.12	0.19	0.00	0.33	0.00	3-methyl-octane	0.01
P n-nonane	0.48	0.64	41.87	0.31		0.03	0.02	2.05	0.16	0.20	0.18	8.06	0.16	0.02	n-nonane	0.19
P 2,2-dimethyl-octane	0.07	0.00	2.32	0.00		0.00	0.00	0.11	0.00	0.03	0.00	0.45	0.00	0.00	2,2-dimethyl-octane	0.01
P 3,3-dimethyl-octane	0.94	1.47	2.33	0.27		0.05	0.06	0.11	0.14	0.40	0.42	0.45	0.14	0.00	3,3-dimethyl-octane	0.03
P 2,3-dimethyl-octane	0.00	0.00	0.00	0.18		0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.09	0.00	2,3-dimethyl-octane	0.00
P 2-methyl -nonane	0.55	0.87	19.89	0.87		0.03	0.03	0.97	0.44	0.23	0.25	3.83	0.45	0.01	2-methyl -nonane	0.10
P 3-ethyl-octane	0.00	0.00	1.83	0.00		0.00	0.00	0.09	0.00	0.00	0.00	0.35	0.00	0.00	3-ethyl-octane	0.01
P 3m-nonane	0.00	0.00	29.06	0.33		0.00	0.00	1.42	0.17	0.00	0.00	5.60	0.17	0.02	3m-nonane	0.13
P n-decane	12.04	6.95	60.68	0.00		0.69	0.27	2.97	0.00	5.08	1.98	11.69	0.00	0.05	n-decane	0.41
P n-undecane	20.52	12.02	74.10	0.78		1.17	0.47	3.63	0.39	8.66	3.42	14.27	0.40	0.07	n-undecane	0.58
P n-dodecane	15.26	8.77	39.22	30.17		0.87	0.34	1.92	15.18	6.44	2.50	7.55	15.48	0.09	n-dodecane	0.70

Table F-7 Aircraft Speciation Profile Based on Emission Rate and Aircraft Operations per LTO Cycle

Compound	COLUMN 1: Basic Emission Rates					COLUMN 2: Factor % by chemical class				COLUMN 3: Duration of each stage				COLUMN 4	Compound	COLUMN 5
	Taxi	IDLE 1 (Low Idle)	IDLE 2 (Descent)	IDLE 4 Max Power		Taxi	IDLE 1 Low Idle	IDLE 2 Descent Idle	IDLE 4 Max Power	Emissions Taxi (7.4 min)	Emissions Idle 1 (7.3 min)	Emissions Descent (3.93 min)	Emissions Take off (1.02 min)	% VOC emissions per LTO cycle		% NMHC emissions per LTO cycle
	mg/MIN	mg/MIN	mg/MIN	mg/MIN		mg-%	mg-%	mg-%	mg-%	mg-% per cycle	mg-% per cycle	mg-% per cycle	mg-% per cycle	PERCENT		
P N-C13	17.00	8.48	36.72	102.90		0.97	0.33	1.80	51.76	7.17	2.41	7.07	52.79	0.19	N-C13	1.52
P N-C14	14.53	8.62	28.38	216.13		0.83	0.34	1.39	108.71	6.13	2.45	5.47	110.89	0.33	N-C14	2.73
P N-C15	0.00	0.00	15.91	293.10		0.00	0.00	0.78	147.43	0.00	0.00	3.06	150.38	0.41	N-C15	3.35
P N-C16	0.00	0.00	0.00	215.01		0.00	0.00	0.00	108.15	0.00	0.00	0.00	110.31	0.30	N-C16	2.41
P N-C17	0.00	0.00	0.00	157.33		0.00	0.00	0.00	79.14	0.00	0.00	0.00	80.72	0.22	N-C17	1.76
P N-C18	0.00	0.00	0.00	111.04		0.00	0.00	0.00	55.85	0.00	0.00	0.00	56.97	0.15	N-C18	1.24
P N-C19	0.00	0.00	0.00	44.45		0.00	0.00	0.00	22.36	0.00	0.00	0.00	22.81	0.06	N-C19	0.50
P N-C20	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C20	0.00
P N-C21	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C21	0.00
P N-C22	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C22	0.00
P N-C23	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C23	0.00
P N-C24	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C24	0.00
P N-C25	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C25	0.00
P N-C26	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N-C26	0.00
					FACTOR	0.011	0.043	0.270	0.032							
U ethylene	0.94	33.09	1786.11	43.27	ALKENES	0.01	1.42	482.25	1.38	0.08	10.39	1895.24	1.41	5.10	ethylene	41.60
U acetylene	0.28	6.58	314.14	24.05		0.00	0.28	84.82	0.77	0.02	2.07	333.33	0.78	0.90	acetylene	7.33
U propylene	0.00	8.77	458.02	0.00		0.00	0.38	123.67	0.00	0.00	2.75	486.01	0.00	1.31	propylene	10.66
U propyne	0.00	1.02	48.47	0.00		0.00	0.04	13.09	0.00	0.00	0.32	51.43	0.00	0.14	propyne	1.13
U isobutene/1-butene	0.32	3.16	158.99	2.46		0.00	0.14	42.93	0.08	0.03	0.99	168.70	0.08	0.45	isobutene/1-butene	3.70
U 1,3-butadiene	0.12	0.43	58.18	0.00		0.00	0.02	15.71	0.00	0.01	0.13	61.73	0.00	0.17	1,3-butadiene	1.35
U t2-butene	0.00	0.00	30.45	0.00		0.00	0.00	8.22	0.00	0.00	0.00	32.31	0.00	0.09	t2-butene	0.70
U 1-butyne	0.00	0.14	6.51	0.00		0.00	0.01	1.76	0.00	0.00	0.04	6.91	0.00	0.02	1-butyne	0.15
U c2-butene	0.00	0.23	12.08	0.00		0.00	0.01	3.26	0.00	0.00	0.07	12.82	0.00	0.03	c2-butene	0.28
U 1,2-butadiene	0.00	0.00	3.00	0.00		0.00	0.00	0.81	0.00	0.00	0.00	3.18	0.00	0.01	1,2-butadiene	0.07
U 3-methyl-1-butene	0.00	0.34	18.74	0.16		0.00	0.01	5.06	0.01	0.00	0.11	19.89	0.01	0.05	3-methyl-1-butene	0.44
U 1,4-pentadiene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,4-pentadiene	0.00
U 2-butyne	0.09	1.41	3.42	0.00		0.00	0.06	0.92	0.00	0.01	0.44	3.63	0.00	0.01	2-butyne	0.09
U 1-pentene	0.14	1.55	62.15	0.00		0.00	0.07	16.78	0.00	0.01	0.49	65.95	0.00	0.18	1-pentene	1.45
U 2-methyl-1-butene	0.04	0.34	18.87	0.68		0.00	0.01	5.09	0.02	0.00	0.11	20.02	0.02	0.05	2-methyl-1-butene	0.44
U 2-methyl-1,3-butadiene	2.70	1.51	40.41	0.99		0.03	0.06	10.91	0.03	0.22	0.47	42.88	0.03	0.12	2-methyl-1,3-butadiene	0.95
U t2-pentene	0.00	0.13	8.02	0.00		0.00	0.01	2.17	0.00	0.00	0.04	8.51	0.00	0.02	t2-pentene	0.19
U c2-pentene	0.00	0.00	4.85	0.00		0.00	0.00	1.31	0.00	0.00	0.00	5.15	0.00	0.01	c2-pentene	0.11
U 2-methyl-2-butene	0.10	0.00	3.91	0.79		0.00	0.00	1.06	0.03	0.01	0.00	4.15	0.03	0.01	2-methyl-2-butene	0.09
U 4-methyl-1- & 3-methyl-1-pentene	0.08	0.80	23.55	0.92		0.00	0.03	6.36	0.03	0.01	0.25	24.99	0.03	0.07	4-methyl-1- & 3-methyl-1-pentene	0.55
U c/t-4-methyl-2-pentene	0.00	0.66	2.74	2.87		0.00	0.03	0.74	0.09	0.00	0.21	2.91	0.09	0.01	c/t-4-methyl-2-pentene	0.07
U 2-methyl-1-pentene	0.10	0.00	0.00	0.17		0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	2-methyl-1-pentene	0.00
U 1-hexene	0.00	0.79	36.27	0.65		0.00	0.03	9.79	0.02	0.00	0.25	38.49	0.02	0.10	1-hexene	0.85
U c/t-3-hexene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	c/t-3-hexene	0.00
U t2-hexene	0.00	0.00	2.86	0.27		0.00	0.00	0.77	0.01	0.00	0.00	3.03	0.01	0.01	t2-hexene	0.07
U 2-methyl-2-pentene	0.09	0.00	6.13	0.00		0.00	0.00	1.66	0.00	0.01	0.00	6.50	0.00	0.02	2-methyl-2-pentene	0.14
U t-3-methyl-2-pentene	0.00	0.00	3.79	1.03		0.00	0.00	1.02	0.03	0.00	0.00	4.02	0.03	0.01	t-3-methyl-2-pentene	0.09
U c2-hexene	0.00	0.81	1.75	0.00		0.00	0.03	0.47	0.00	0.00	0.25	1.86	0.00	0.01	c2-hexene	0.05
U c-3-methyl-2-pentene	0.00	0.00	2.13	0.26		0.00	0.00	0.58	0.01	0.00	0.00	2.26	0.01	0.01	c-3-methyl-2-pentene	0.05
U t3-heptene	0.00	0.00	1.20	0.00		0.00	0.00	0.32	0.00	0.00	0.00	1.27	0.00	0.00	t3-heptene	0.03
U t2-heptene	0.00	0.00	1.41	0.00		0.00	0.00	0.38	0.00	0.00	0.00	1.50	0.00	0.00	t2-heptene	0.03
U c2-heptene	0.07	0.19	1.97	0.57		0.00	0.01	0.53	0.02	0.01	0.06	2.09	0.02	0.01	c2-heptene	0.05

Table F-7 Aircraft Speciation Profile Based on Emission Rate and Aircraft Operations per LTO Cycle

Compound	COLUMN 1: Basic Emission Rates					COLUMN 2: Factor % by chemical class				COLUMN 3: Duration of each stage				COLUMN 4	Compound	COLUMN 5
	Taxi	IDLE 1 (Low Idle)	IDLE 2 (Descent)	IDLE 4 Max Power		Taxi	IDLE 1 Low Idle	IDLE 2 Descent Idle	IDLE 4 Max Power	Emissions Taxi (7.4 min)	Emissions Idle 1 (7.3 min)	Emissions Descent (3.93 min)	Emissions Take off (1.02 min)	% VOC emissions per LTO cycle		% NMHC emissions per LTO cycle
	mg/MIN	mg/MIN	mg/MIN	mg/MIN		mg-%	mg-%	mg-%	mg-%	mg-% per cycle	mg-% per cycle	mg-% per cycle	mg-% per cycle	PERCENT		
U 1-octene	0.07	0.00	33.20	0.29		0.00	0.00	8.96	0.01	0.01	0.00	35.23	0.01	0.09	1-octene	0.77
U t2-octene	0.10	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	t2-octene	0.00
U c2-octene	0.00	0.00	1.79	0.00		0.00	0.00	0.48	0.00	0.00	0.00	1.90	0.00	0.01	c2-octene	0.04
U 1-nonene	10.93	0.00	25.31	0.00		0.12	0.00	6.83	0.00	0.89	0.00	26.86	0.00	0.07	1-nonene	0.61
U t3-nonene	0.74	0.00	0.00	0.00		0.01	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	t3-nonene	0.00
U c3-nonene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	c3-nonene	0.00
U t2-nonene	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	t2-nonene	0.00
U c2-nonene	0.00	0.00	2.01	0.30		0.00	0.00	0.54	0.01	0.00	0.00	2.13	0.01	0.01	c2-nonene	0.05

A=AROMATICS; C=CARBONYLS; N=NAPHTHENES; P=PARAFFINS; A=ALKENES
FINAL 10/24/03; Derived by Lisa Graham ERMD 97 (03)

Table F-8: OPSIS Summary Data For the Same Days During a Year that NAPS Monitoring Took Place

Compound Concentration in µg/m³		1998					1999					2000					2001				
		Count	Annual Average	Percent OPSIS/NAPS ^A	Maximum	Minimum	Count	Annual Average	Percent OPSIS/NAPS	Maximum	Minimum	Count	Annual Average	Percent OPSIS/NAPS	Maximum	Minimum	Count	Annual Average	Percent OPSIS/NAPS	Maximum	Minimum
Benzene	Mean 24 hr	31	9.5	50%	101.3	0.9	25	8.7	93%	19.4	4.1	60	12.2	100%	22.2	4.3	46	11.3	96%	46	4.9
	Max one hr	31	21.7	50%	194	1.9	25	14.7	93%	52.7	6.3		18.2		54.8	6.3		17.5		37.2	7
Toluene	Mean 24 hr	30	25.5	48%	47.5	5.8	25	41.8	93%	65.1	18.3	60	30.8	100%	74.3	9.6	46	20.1	96%	46.4	4.4
	Max one hr	30	49.2	48%	119.6	10.8	25	68.0	93%	137.1	28.4		59.6		246.7	15.3		39.4		103.6	9.7
p-Xylene	Mean 24 hr	18	1.2	29%	3.5	0	2	4.0	7%	6.9	1.1	60	4.7	100%	31.7	1.6	46	5.7	96%	46	2.8
	Max one hr	18	2.2	29%	5.1	0.1	2	4.7	7%	8.2	1.1		6.5		36.0	3.3		7.5		12.6	3.8
1,2,4-Trimethylbenzene	Mean 24 hr	29	11.2	47%	21.3	4.7	25	18.8	93%	28.1	9.5	60	14.4	100%	25.4	4.4	46	10.5	96%	46	5.4
	Max one hr	29	16.8	47%	57.9	11.1	25	21.4	93%	30.2	13.7		22.3		37.0	9.0		16.2		32.3	7.9
1,3,5-Trimethylbenzene	Mean 24 hr	27	6.0	44%	21	0.6	25	2.3	93%	15.9	0.6	60	32.1	100%	86.0	6.6	46	32.3	96%	60.9	7
	Max one hr	27	11.5	44%	64.5	1.3	25	3.6	93%	27	0.9		72.8		224.1	22.2		66.7		223.7	13.1
Formaldehyde	Mean 24 hr	27	7.1	44%	12.4	0.8	25	6.8	89%	8.9	5.1	60	5.4	100%	8.3	2.3	46	6.8	96%	46	4.3
	Max one hr	27	11.1	44%	30.4	1.4	25	10.4	93%	22.7	7		8.6		20.2	4.5		10.0		19.6	7

^A Percent OPSIS/NAPS Only days when NAPS data were collected were evaluated. The Percent OPSIS/NAPS refers to the percentage of days when both the OPSIS system and the NAPS data were simultaneously collected.