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RAPID MEASUREMENT OF EMISSIONS FROM MILITARY AIRCRAFT TURBINE ENGINES BY DOWNSTREAM EXTRACTIVE SAMPLING OF AIRCRAFT ON THE GROUND: RESULTS FOR C-130 AND F-15 AIRCRAFT

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14. ABSTRACT

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Rapid measurement of emissions from military aircraft turbine engines by downstream extractive sampling of aircraft on the ground: Results for C-130 and F-15 aircraft

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Aircraft emissions affect air quality on scales from local to global. More than 20% of the jet fuel used in the U.S. is consumed by military aircraft, and emissions from this source are facing increasingly stringent environmental regulations, so improved methods for quickly and accurately determining emissions from existing and new engines are needed. This paper reports results of a study to advance the methods used for detailed characterization of military aircraft emissions, and provides emission factors for two aircraft: the F-15 fighter and the C-130 cargo plane. The measurements involved outdoor ground-level sampling downstream behind operational military aircraft. This permits rapid change-out of the aircraft so that engines can be tested quickly on operational aircraft. Measurements were made at throttle settings from idle to afterburner using a simple extractive probe in the dilute exhaust. Emission factors determined using this approach agree very well with those from the traditional method of extractive sampling at the exhaust exit. Emission factors are reported for CO_2, CO, NO, NO_x, and more than 60 hazardous and/or reactive organic gases. Particle size, mass and composition also were measured and are being reported separately. Comparison of the emissions of nine hazardous air pollutants from these two engines with emissions from nine other aircraft engines is discussed.

1. Introduction

Aircraft emissions affect air quality on scales from local to global. On the local scale, emissions of reactive and toxic gases and particles can affect the health of flight line workers and people living near airports. Primary and secondary particle emissions can degrade visibility, and reactive organic gases and nitrogen oxides can contribute to urban and regional ozone and other photochemical pollutants (e.g. Naugle and Fox, 1981; Pison and Menut, 2004; Unal et al., 2005). On the larger scale, numerous studies have examined the impact of nitrogen oxides and particles emitted by aircraft on the stratosphere and upper troposphere (e.g. Derwent, 1982; Prather et al., 1992; Meijer et al., 2000; GAO, 2000), and aviation emissions of carbon dioxide and fine particles may be contributing to global climate change (EPA, 2006). Indeed, EPA (2006) estimates that subsonic aviation accounts for 9% of U.S. transportation greenhouse gas emissions (primarily CO_2) and 2–3% of all U.S. greenhouse emissions. Detailed emissions' inventories have been developed for use in assessing environmental effects and compliance with environmental regulations (ICAO, 2007).

Emissions generated by military aircraft are a special component of total aviation emissions, and are facing increasingly stringent environmental regulations in the U.S. and elsewhere. The U.S. Energy Information Administration estimates that military aircraft consumed about 22% of jet fuel in the U.S. in 2008 (EIA, 2008). Early studies of aircraft emissions focused on a very limited set of gases,

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but in the 1980s and 1990s' investigators began to examine the detailed chemical composition of the exhaust gases as well as the chemical and physical characteristics of particles emitted by aircraft turbine engines (e.g. see Spicer et al., 1987, 1990, 1992, 1994; Gerstle and Wade, 2002a,b, and references therein). Until very recently, nearly all aircraft emissions' measurements were made on engines mounted indoors in a test cell or outdoors on a test stand, rather than "on wing". However, in the interest of measuring emissions from many different types of aircraft engines and multiple engines of each type to obtain robust emissions' estimates, new sampling approaches have been explored. A recent report by Whitefield et al. (2008) and references therein, summarize the results of a number of commercial aircraft engine emissions measurement campaigns supported by NASA and the FAA. Many of these studies included gas and particle measurements from wing-mounted engines on stationary commercial aircraft. In some studies, emissions were measured at the exit plane and also at a downstream location. Also as part of that series of studies, Herndon et al. have measured nitrogen oxides (Herndon et al., 2004), selected organic species (Herndon et al., 2006) and PM emissions (Herndon et al., 2005) in the taxi and takeoff plumes of numerous commercial aircraft by sampling downwind of aircraft operations at airports.

This project is focused on determining emission factors for several important parameters including nitrogen oxides, PM, and a number of toxic air contaminants. The approach normally used to measure contaminants in aircraft engine exhaust is extractive sampling at the exhaust exit. In this approach, sample is withdrawn from the exhaust stream using a probe located just behind the engine exhaust nozzle, and transferred to the measurement systems for analysis. Until recently nearly all aircraft engine exhaust measurements were made by extractive sampling at the exhaust exit. However there are some concerns with this and other approaches that need to be considered. These concerns include

1. Potential reactions in a hot sample probe such as hydrocarbon cracking, NO_2 reduction or other reactions that could affect the integrity of the sample. This is relevant to sampling methods that do not employ cooled sampling probes.
2. Collection of representative samples of the exhaust to assure accurate emission factor estimates.
3. Potential loss of particles and low volatility gases in the probe or sampling system.

Other processes that can influence aircraft engine exhaust composition include chemical quenching reactions, particle formation and particle agglomeration that occur as the exhaust plume is diluted with ambient air. Under afterburner conditions, these processes generally are not complete at the exhaust exit nozzle, and may not be complete at maximum non-afterburner power.

With a few recent exceptions (see Whitefield et al., 2008), essentially all prior exhaust composition measurements were made by extractive sampling at the engine exhaust exit plane. However, the exhaust at the exit plane is so non-uniform, both radially and circumferentially, that samples must be taken from a large number of positions to assure representative sampling, and pressure and probe position must be carefully measured at each sampling point in order to determine weighting factors for the individual measurements. The design of the probe also is extremely critical, not only to withstand the severe environment, but also to maintain the integrity of the sample in the probe. At this location chemical and physical processes are still occurring in the exhaust stream, at least under afterburning conditions, so that measurements made at this location may not represent the final form of emissions to the atmosphere.

The present study has employed a strategy of outdoor sampling at ground level, downstream behind operational military aircraft. This permits rapid change-out of the aircraft so that different types of engines can be tested quickly, and multiple engines of the same type can be sampled in a short period of time to assess engine-to-engine variability. This approach allows for extended sampling intervals at known engine power settings, so that emissions can be related to the engine power. It also eliminates many of the difficulties of sampling just behind the exhaust nozzle by making the measurements far enough downstream of the engine that chemical reaction and particle formation are largely complete (Cheng et al., 2008; Cowen et al., in press). The downstream distance at which processes are essentially complete is 20–25 nozzle exit diameters behind the engine (Lyon et al., 1975). Sampling at this location greatly simplifies probe requirements due to reduced temperature, and data analysis is simplified because a carbon mass balance approach (described later) can be used to determine emission factors for trace chemicals without the need for detailed mapping of the exhaust plume area. When continuous, highly sensitive, rapid-response instruments are used for analysis, a test at a given engine operating condition can be completed in just a few minutes. This is especially important at high power settings (e.g. afterburner) where the strain on the engine and the fuel consumption are very high.

This paper reports on the first two studies in a series that has been designed to develop emissions data for military aircraft engines. The two aircraft are the C-130 cargo plane and the F-15 fighter. The C-130 testing was carried out in collaboration with a team led by Oak Ridge National Laboratory (ORNL), and an overview of that study is available (Cheng et al., 2008). During the studies reported here, extensive measurements were carried out to characterize particle size, composition and mass in the emissions. These results are reported separately (Cheng et al., 2008; Corporan et al., 2008; Cowen et al., in preparation). The present report is focused on emissions of gaseous species from these two types of aircraft.

2. Experimental methods

2.1. Aircraft/engines and power settings

The first aircraft examined in this study is a C-130H cargo plane designed to transport troops and equipment. The C-130H is configured with four Allison T56-A-15 turboprop engines which can generate in excess of 4500 horsepower at maximum power. This engine type uses a single entry, 14-stage axial-flow compressor with 6 combustion chambers and a 4-stage turbine. At throttle settings of high speed ground idle and above, the engines operate at maximum speed, and the thrust of the engine is varied by changing propeller torque. Two engines are mounted on each wing. Exhaust was sampled from the outboard and the inboard engines on the right side of the aircraft. Multiple tests were carried out on each engine in turn. During testing of the outboard engine, the inboard engine was not operated, but the outboard engine on the opposite wing was run to balance forces on the airframe. The same strategy was employed for the inboard engine tests. The operating engines on the opposing wings were separated by the aircraft fuselage and a considerable distance, so that sampling from the desired engine was not accidently contaminated by exhaust from the engine on the other wing.

Emissions from the C-130H were sampled at 5 power settings: low speed ground idle (LSG idle) at 4% maximum torque, high speed ground idle (HSG idle) at 7% maximum torque, flight idle at 20% maximum torque, cruise at 41% maximum torque, and maximum power at 100% maximum torque. All C-130 tests were carried out using JP-8 fuel. Fuel samples were collected and

analyzed to verify that the fuel met military specifications and to obtain the fuel hydrogen/carbon ratio needed for emission factor calculations.

The F-15 Eagle fighter aircraft is equipped with two Pratt & Whitney F100-PW-100 axial-flow, high pressure ratio, turbofan engines. These engines have a normal dry thrust of 12,420 pounds, with a maximum of 14,670 pounds at full military power. Maximum afterburning thrust is 23,830 pounds. The engines were tested as mounted on F-15 fighters, with the aircraft anchored to the ground during testing. The test matrix called for multiple test cycles at the following engine throttle settings (nominal percentage of maximum rotational speed in parentheses): ground idle (65–70%), low intermediate (80%), high intermediate (85%), military (91–93%) and afterburner. In order to assess engine-to-engine variability of emissions, 8 different engines were tested. The fuel used for the F-15 tests was JP-8 + 100. Fuel samples were collected and analyzed as noted for the C-130 tests.

For testing at power settings other than afterburner, only one of the F100 engines was operated at a time. Operation at afterburner power was limited to 3 min at ground level due to aircraft safety considerations. For afterburner testing, it was necessary for both engines to be operated simultaneously but only one could be operated at afterburner power. Therefore, for all F-15 afterburner tests, one engine was operated at afterburner power and the other was run at idle. This situation is not ideal for determining afterburner emissions because some emissions from the idle engine could have been entrained in the afterburner plume. However this protocol was the best available option for afterburner testing. Because the total fuel usage during these tests was dominated (~97%) by the engine in afterburner mode, we believe that the contribution of emissions from the idle engine to the afterburner engine plume was negligible. Nevertheless, caution should be exercised in using the afterburner emissions data due to the small possibility of contamination from the idle engine exhaust.

2.2. Test venues and schedules

The C-130 tests were conducted at the Kentucky Air National Guard facility in Louisville, KY in October 2005. At each of the 5 power settings the engine was run for a few minutes to assure stable conditions, and the exhaust was then sampled for 20 min. The goal was to carry out several replicate test cycles of 5 power settings per cycle for each engine. Altogether, data were collected for portions of 9 test cycles, with 39 separate test runs at the individual engine power settings described previously.

The F-15 tests were carried out at the trim pad facility at Tyndall Air Force Base in Panama City, FL in November 2006. The tests were designed to collect data on each engine for two power cycles (4 power settings excluding afterburner). In the first cycle sampling was carried out for 10 min at each power setting after the engine reached stable operation at the target power setting. For the second cycle, 10 min sampling was performed at low and high intermediate power, while 30 min samples were collected at ground idle and military power. The purpose of the extended test intervals was to allow longer time for filter sampling of PM. Altogether, 41 engine tests were carried out. Thirty-seven tests were conducted on single engines at the 4 non-afterburner power settings and 4 tests were carried out at afterburner power.

2.3. Exhaust sampling

Both extractive sampling and optical remote sensing measurements were made during the C-130 and F-15 testing programs. The emissions' results reported here are based on the extractive measurements. A detailed description of both the extractive and the remote sensing systems employed during C-130 testing is provided in Cheng et al. (2008), and comparisons of the extractive and remotely sensed measurements from the F-15 tests are given in Cowen et al. (in press). The approach used for F-15 exhaust sampling was similar to the C-130 approach (Cheng et al., 2008) but with some modifications. Due to the higher flows and temperatures expected for fighter engine exhaust, especially at afterburner power, a new probe stand was designed. Thermocouples were mounted at the top and bottom of the probe stand. The height of the sampling probes was adjustable, and for the F-15 tests the probes were 3 m above ground level. Both gas and aerosol probes were 1.27 cm diameter stainless steel tubes that extended to the base of the probe stand. From that point the gas sampling system employed a 46 m long, 1.27 cm diameter Teflon tube heated to 125 C to transfer sample to the instruments in the mobile laboratory. This length of tubing was necessary to accommodate the extra distance when the probe stand was moved further downstream for afterburner tests. Typical flow rates through the sample line were approximately 100 Lpm, yielding a residence time in the sampling system of approximately 2 s. The probe stand was positioned 23 m behind the exhaust exit plane for tests at idle through military power, and at 38 m for afterburner tests.

For both the C-130 and the F-15 tests, the sampling tubing and probe were back-flushed with clean filtered air during engine start-up, to avoid contamination from raw fuel and particulate matter.

2.4. Measurement methods

The measurement methods employed for emissions testing are shown in Table 1, and are described in Cheng et al. (2008) for the C-130 tests. A brief description is provided for methods that differed for the C-130 and F-15 tests. Air samples for VOCs were collected in 1 L passivated canisters (Entech, Inc.). A flow orifice installed on each sampling canister provided time-integrated samples (10 min for C-130 tests and 5 min for F-15 tests). Sampling was initiated 5 min into the C-130 tests and 2 min into the F-15 tests. For F-15 afterburner tests, the canister samples were collected without a flow orifice starting approximately 1 min into the 3 min test. A quadrupole proton transfer reaction mass spectrometer (PTR-MS; Ionicon Analytik) was used during F-15 testing for real-time monitoring of a number of VOCs from the engine exhaust. These were sampled through a heated gas manifold inside the mobile laboratory. Air samples were collected for carbonyl compounds using dinitrophenyl hydrazine (DNPH) coated cartridges. Acrolein was quantified by

Table 1
Gas measurement methods used for military aircraft emissions characterization.

Instrument, model no.	Measurement parameter
Nondispersive IR, LI-COR Model 820	CO_2 in gas manifold; C-130 and F-15 tests
Nondispersive IR, LI-COR Model 820	CO_2 in aerosol manifold; F-15 tests
Nondispersive IR, Fuji Model 3300	CO_2 in aerosol manifold; C-130 and F-15 tests
Cross–filter correlation spectroscopy, Thermo Environ. 48C	CO
Chemiluminescence, API Model 252 (2)	NO/NO_x, C-130 tests
Chemiluminescence, Thermo Environmental 42 CL	NO/NO_x, F-15 tests
Flame ionization, VIG Model 20 (sample heated to 50 °C)	Total hydrocarbons
Proton transfer reaction mass spectrometer, Ionicon	Selected organic gases, F-15 tests
SUMMA canister sampling with GC/MSD analysis	Individual organic gases
Dinitrophenyl hydrazine cartridge sampling and HPLC analysis	Carbonyl compounds

GC/MS analysis of the canister samples described above, rather than the DNPH cartridge samples, due to problems with the stability of the acrolein–DNPH derivative (Goelen et al., 1997).

2.5. Emission factor calculations

Emission factors for the individual gaseous species were calculated from the data based on a carbon mass balance approach. Essentially, this is a chemical tracer approach which makes use of the combustion products of carbon in the fuel. The assumptions underlying this approach are

1. All of the carbon in the fuel is converted to gaseous CO_2, CO, and hydrocarbons (for these calculations, soot was not included as a carbonaceous product).
2. The carbon in the fuel is conserved, i.e. the carbon may change chemical form during the combustion, but the total mass of carbon is unchanged.
3. The carbon combustion products are distributed in the plume similarly to the other emitted chemicals whose emission factors are to be measured. That is, while the absolute concentrations may vary dramatically within the plume, the relative concentration of target chemical to the sum of carbon combustion products is assumed constant.

The equations for determining emission factors in g kg^{-1} fuel are

$$(\text{Emission factor})_x = \frac{b_x M_x \times 10^3}{(M_C + nM_H)(1 + b_{CO} + b_{THC})}$$

where b_x = background corrected volume ratio of pollutant, x, to CO_2

$$\left(\text{e.g. } b_{CO} = \frac{[CO]_p - [CO]_{back}}{[CO_2]_p - [CO_2]_{back}}\right)$$

and M_C = atomic weight of carbon, M_H = atomic weight of hydrogen, n = hydrogen/carbon molar ratio of fuel.

3. Results

Fuel samples were collected from the batches of fuel used during the engine tests. The averaged results of the analyses for composition, sulfur content and carbon/hydrogen ratio are given in Table 2. Although the fuels met all specifications for military grade fuel, there are differences in the composition that could influence emissions.

3.1. Emission factors

Analysis of results from the C-130 tests validated our downstream extractive sampling approach by demonstrating good agreement between gaseous species measured at the exhaust exit plane and at a point 15 m downstream, once dilution was accounted for (Cheng et al., 2008). Cowen et al. (in press) have reported good agreement between downstream extractive sampling and optical remote sensing during these F-15 tests for species that were measured by both methods, and Schäfer et al. (2000) also demonstrated agreement between extractive and remote sensing measurements at the exhaust exit plane of turbine engines.

We have used the emissions' measurements obtained by downstream extractive sampling and the carbon mass balance method described earlier, to calculate emission factors for all measured inorganic and organic gases. Table 3 shows the average emission factors for the carbon and nitrogen oxides emitted by the C-130H and F-15 aircraft engines. The averages include emissions from all engines tested and all replicate tests for each engine.

The emission factors for selected organic gases are reported in Table 4 for C-130 aircraft engines, and Table 5 for F-15 engines. Results for all measured chemicals are provided as Supplemental data. Many of the chemicals in Tables 4 and 5 are considered to be potentially toxic or are ozone precursors, so knowledge of their emissions from military aircraft is important. Even for those chemicals not observed above the detection limits of our instrumentation, knowledge of the upper limits to their emissions could be useful. Therefore we used detection limits to calculate emission factors for non-detects and report the resulting values as upper limits in Tables 4 and 5. For cases where a chemical was not detected in one test in a set of replicate tests, we used 1/2 the detection limit to calculate an emission factor for that test, and averaged that value with the other emission factors for that test condition. Tables 4 and 5 include an emission factor for the sum of the three-carbon organic species. These data are derived from a summation of the partially resolved peaks from the gas chromatography–mass spectrometry analysis. Propylene and propyne are not resolved in the C_2–C_4 hydrocarbon chromatographic analysis, so they are listed together in Tables 4 and 5. Table 5 also lists emission factors for the mass homologs methanol/hydrazine and acetic acid/propanol because these species cannot be distinguished by the continuous real-time PTR-MS instrument.

4. Discussion

Emissions of CO_2, CO, NO and NO_x in turbine engine exhaust have been measured for many years, and the emission factors for the C-130 and F-15 aircraft engines in Table 3 exhibit the expected trends. Carbon monoxide emissions are greatest at low power, when combustion is least efficient, and decrease rapidly at higher power. The exception is at afterburner power. The higher power developed by the afterburner is achieved by addition of raw fuel to the hot

Table 2
Characteristics of fuel used for C-130 and F-15 emissions testing.

Fuel	JP-8	JP-8 + 100
Aircraft	C-130H	F-15
Engine	Allison T56	P & W F100-PE-100
Composition (Vol %)		
Aromatics	16.3	12.4
Alkenes	1.6	2.5
Alkanes	82.1	85.1
Sulfur content (wt %)	0.0814	0.0354
Carbon/hydrogen ratio	0.52	0.51

Table 3
Average emission factors for inorganic gases (g kg^{-1} fuel).

Engine power	CO_2	CO	NO[a]	NO_x
C-130H				
Low speed ground idle	3074	27.4	0.3	4.2
High speed ground idle	3149	5.4	4.0	6.3
Flight idle	3149	4.5	4.3	6.2
Cruise	3156	1.9	6.4	7.9
Maximum power	3156	1.5	7.4	8.8
F-15				
Idle	3132	10.4	2.7	4.3
Low intermediate	3150	1.20	11.4	11.7
High intermediate	3151	0.67	21.4	21.6
Military	3151	0.42	32.2	32.2
Afterburner	3136	9.7	6.7	7.7

[a] NO emission factors calculated as NO_2 by convention.

Table 4
Average organic emission factors for selected chemicals from C-130 aircraft engines. (Results for additional chemicals are provided in Supplemental data).

Species	Units	Engine power				
		Lo speed ground idle	Hi speed ground idle	Flight idle	Cruise	Max power
Acetaldehyde	mg kg^{-1} fuel	436	17.8	11.0	1.99	1.64
Acetone	mg kg^{-1} fuel	196	45.9	81.9	9.88	36.3
Acetylene	mg kg^{-1} fuel	155	[a]	[a]	[a]	[a]
Acrolein	mg kg^{-1} fuel	216	10.4	9.47	1.37	2.30
Benzene	mg kg^{-1} fuel	152	9.25	7.36	2.89	2.16
Benzyl chloride	mg kg^{-1} fuel	1.00	1.40	1.95	1.29	1.19
Bromodichloromethane	mg kg^{-1} fuel	1.24	1.45	2.13	1.47	1.39
1,3-Butadiene	mg kg^{-1} fuel	241	8.12	5.48	<0.97	0.74
2-Butanone	mg kg^{-1} fuel	29.4	10.7	5.44	4.27	4.80
C3 hydrocarbons	mg kg^{-1} fuel	767	26.7	20.0	5.31	4.55
Carbon disulfide	mg kg^{-1} fuel	1.31	2.78	1.26	1.09	0.58
Carbon tetrachloride	mg kg^{-1} fuel	0.74	0.62	1.16	0.55	1.05
Chlorobenzene	mg kg^{-1} fuel	0.71	1.25	<2.84	0.94	<1.92
Chloroform	mg kg^{-1} fuel	0.90	1.07	1.55	1.16	1.01
Cyclohexane	mg kg^{-1} fuel	1.32	0.94	1.42	1.09	0.92
1,2-Dichlorobenzene	mg kg^{-1} fuel	0.97	1.76	<3.7	1.42	<2.49
1,3-Dichlorobenzene	mg kg^{-1} fuel	0.88	1.69	1.55	0.89	0.80
1,4-Dichlorobenzene	mg kg^{-1} fuel	0.85	2.22	1.45	0.77	0.76
Dichlorodifluoromethane	mg kg^{-1} fuel	1.64	1.28	1.58	1.45	1.06
Ethylbenzene	mg kg^{-1} fuel	13.1	2.87	2.98	1.71	3.34
Ethylene	mg kg^{-1} fuel	1843	[a]	[a]	[a]	[a]
4-Ethyl toluene	mg kg^{-1} fuel	5.66	1.06	1.91	1.06	1.22
Formaldehyde	mg kg^{-1} fuel	1317	60.9	45.2	3.30	4.10
Heptane	mg kg^{-1} fuel	3.28	1.78	2.76	2.34	1.91
Hexane	mg kg^{-1} fuel	5.22	3.24	4.77	6.13	3.39
2-Hexanone	mg kg^{-1} fuel	7.39	1.59	<2.52	<1.8	<1.7
Isopropyl alcohol	mg kg^{-1} fuel	3.55	2.37	2.61	2.36	5.24
Methane	mg kg^{-1} fuel	1260	830	1450	470	700
Methyl chloride	mg kg^{-1} fuel	0.53	0.79	0.67	0.31	0.39
Methyl isobutyl ketone	mg kg^{-1} fuel	1.52	1.17	<2.52	<1.8	1.07
Methyl *tert*-butyl ether	mg kg^{-1} fuel	0.59	<1.54	<2.22	0.87	0.75
Methylene chloride	mg kg^{-1} fuel	1.55	1.43	1.98	4.80	2.02
Propylene/propyne	mg kg^{-1} fuel	510	[a]	[a]	[a]	[a]
Styrene	mg kg^{-1} fuel	29.1	1.36	1.41	0.96	0.85
1,1,2,2-Tetrachloroethane	mg kg^{-1} fuel	1.05	1.44	<4.23	<3.02	<2.85
Tetrachloroethene	mg kg^{-1} fuel	1.81	2.05	2.43	2.90	1.68
Tetrahydrofuran	mg kg^{-1} fuel	4.98	0.73	<1.81	2.35	<1.22
Toluene	mg kg^{-1} fuel	69.5	8.73	11.5	8.76	6.59
Total nonmethane hydrocarbons	gC kg^{-1} fuel	1.34	[a]	[a]	[a]	[a]
1,2,4-Trichlorobenzene	mg kg^{-1} fuel	1.43	3.30	2.13	<3.25	<3.07
1,1,1-Trichloroethane	mg kg^{-1} fuel	0.92	1.17	1.80	1.16	1.90
Trichloroethene	mg kg^{-1} fuel	1.13	1.56	2.16	1.53	1.37
Trichlorofluoromethane	mg kg^{-1} fuel	1.44	1.10	1.66	0.75	0.72
1,1,2-Trichloro-1,2,2-trifluoroethane	mg kg^{-1} fuel	0.93	1.05	1.19	0.76	0.87
1,2,4-Trimethylbenzene	mg kg^{-1} fuel	24.3	3.62	4.75	2.23	3.13
1,3,5-Trimethylbenzene	mg kg^{-1} fuel	6.38	0.86	1.48	0.76	1.05
Vinyl acetate	mg kg^{-1} fuel	18.7	4.23	4.80	2.71	2.91
m&*p*-Xylene	mg kg^{-1} fuel	31.7	8.41	8.01	4.63	9.88
o-Xylene	mg kg^{-1} fuel	13.31	2.87	3.33	2.06	3.30

[a] Not measured.

exhaust, which results in overall less efficient combustion than the highest non-afterburner conditions. This leads to higher emissions of CO and also of organic species. The nitrogen oxides are produced primarily by nitrogen fixation, so the emissions increase with combustion temperature, and this trend is observed in Table 3 for both engines. The contribution of NO to NO_x also increases at higher power settings for both engines. The magnitude of the emission factors for the carbon and nitrogen oxides is compared to emissions from other engine types later is this section. In previous studies Spicer et al. (1987, 1990, 1994) reported ethylene, acetylene, propylene and formaldehyde were the major contributors of organic gas emissions from aircraft turbine engines at a throttle setting of idle. These same four chemicals account for a major fraction of the organic emissions from the engines of C-130 and F-15 aircraft as well, contributing about 70% of the mass of identified organic gases at idle. These species are hydrocarbon cracking and partial oxidation products that are not present in the unburned fuel. Tables 4 and 5 show that the emissions of nearly all of the gaseous organic compounds drop sharply at throttle settings above idle. The exception is afterburner mode. At this power setting the emissions of many organic compounds are higher than at military power, due to the incomplete combustion of raw fuel injected into the exhaust stream. There is also a possibility that the afterburner emission factors have been influenced by some contamination from the second F-15 engine operating at idle during the afterburner tests, as noted earlier.

In the following section, the CO and NO_x emission factors determined by downstream extractive sampling are compared with emission factors determined simultaneously by sampling at the exhaust exit plane. Then in the remainder of this article we focus on nine exhaust constituents to illustrate the variability of emissions, the effect of engine power on emissions, comparisons of emissions from the C-130 and F-15 aircraft, and comparisons with emissions from other aircraft engines. These nine target chemicals were selected because of their importance either due

Table 5
Average organic emission factors for F-15 aircraft engines. (Results for additional chemicals are provided in Supplemental data).

Species	Units	Engine power				
		Idle	Low intermediate	High intermediate	Military power	Afterburner
Acetaldehyde	mg kg^{-1} fuel	69.0	2.00	0.48	0.71	14.5
Acetic acid + propanol	mg kg^{-1} fuel	10.2	2.36	1.13	0.59	3.80
Acetone	mg kg^{-1} fuel	11.6	1.77	2.99	1.97	3.27
Acetonitrile	mg kg^{-1} fuel	3.18	0.29	0.40	0.16	1.10
Acetylene	mg kg^{-1} fuel	132	<2.5	<2.27	<1.45	[a]
Acrolein	mg kg^{-1} fuel	50.0	0.42	0.46	0.29	5.51
Acrylonitrile	mg kg^{-1} fuel	0.46	0.10	0.06	0.11	0.10
Benzene	mg kg^{-1} fuel	32.4	1.30	0.47	0.39	3.71
1,3-Butadiene	mg kg^{-1} fuel	17.2	<0.31	<0.23	<0.16	<0.04
2-Butanone	mg kg^{-1} fuel	6.34	1.35	0.90	0.98	1.26
C3 hydrocarbons	mg kg^{-1} fuel	85.7	<0.25	<0.19	<0.13	10.5
Carbon disulfide	mg kg^{-1} fuel	0.95	0.34	0.63	0.62	0.14
Dichlorodifluoromethane	mg kg^{-1} fuel	0.63	0.13	0.22	0.14	0.08
Ethane	mg kg^{-1} fuel	8.00	5.10	1.87	0.71	[a]
Ethylbenzene	mg kg^{-1} fuel	1.58	<0.6	<0.45	<0.32	0.17
Ethylene	mg kg^{-1} fuel	403	214	201	223	[a]
4-Ethyl toluene	mg kg^{-1} fuel	1.57	<0.68	<0.51	<0.36	0.15
Formaldehyde	mg kg^{-1} fuel	261	7.99	4.96	2.32	46.2
Heptane	mg kg^{-1} fuel	1.56	<0.57	<0.42	<0.3	<0.08
Hexane	mg kg^{-1} fuel	1.29	<0.49	<0.36	<0.26	<0.07
Methacrolein	mg kg^{-1} fuel	18.8	<1.98	<1.48	<1.06	<0.29
Methane	mg kg^{-1} fuel	41.9	45.4	55.0	<90	[a]
Methanol + hydrazine	mg kg^{-1} fuel	32.2	2.77	2.02	4.57	6.90
Naphthalene	mg kg^{-1} fuel	6.18	1.22	0.60	0.31	3.50
Propylene/propyne	mg kg^{-1} fuel	79.2	<4.03	<3.67	<2.34	[a]
Quinoline	mg kg^{-1} fuel	0.80	0.71	1.58	0.89	0.30
Styrene	mg kg^{-1} fuel	2.45	<0.59	<0.44	<0.32	<0.09
Toluene	mg kg^{-1} fuel	9.60	0.42	0.25	0.20	1.21
Trichlorofluoromethane	mg kg^{-1} fuel	0.73	0.24	0.16	<0.42	0.09
1,2,4-Trimethylbenzene	mg kg^{-1} fuel	2.96	0.35	<0.51	<0.36	0.24
1,3,5-Trimethylbenzene	mg kg^{-1} fuel	1.65	<0.68	<0.51	<0.36	0.16
Vinyl acetate	mg kg^{-1} fuel	4.07	<0.49	0.44	<0.26	1.10
Vinyl chloride	mg kg^{-1} fuel	<1.2	<0.35	<0.26	<0.19	<0.05
m&*p*-Xylene	mg kg^{-1} fuel	2.97	<0.6	<0.45	<0.32	0.18
o-Xylene	mg kg^{-1} fuel	2.03	<0.6	<0.45	<0.32	<0.09

[a] Not measured.

to potential toxicity or to prevalence in the exhaust. The nine target chemicals are carbon monoxide, nitrogen oxides, ethylene, 1,3-butadiene, benzene, toluene, styrene, formaldehyde and acrolein.

4.1. Comparison of results from downstream and exit plane sampling

One of the goals of this research has been to develop a methodology that allows for rapid and accurate measurements of emissions from military aircraft engines at all power settings including afterburning. The approach we have instituted involves sampling of diluted exhaust sufficiently far downstream of the exhaust exit that chemical and physical processes in the exhaust stream are largely complete, and the temperature is low enough to permit extractive sampling using simple probes. This approach can be used to sample exhaust behind operational aircraft, as reported here, rather than sampling from engines mounted in a test cell, and this facilitates rapid measurements on a large number of engines.

Results from the downstream sampling approach can be compared to results from the more traditional exhaust exit plane sampling for the C-130H aircraft emissions. As noted earlier, the C-130H testing program was a collaborative effort where both sampling approaches were employed. Emissions of CO and NO_x were measured by extractive sampling at the exhaust exit plane simultaneously with the downstream exhaust measurements reported here, so a direct comparison is possible. Emission factors from the exit plane sampling have been reported by Corporan et al. (2008), and are compared with the downstream extractive sampling results in Fig. 1. The agreement between the two approaches is quite good. The error bars represent the standard deviations around the averages of all the measurements at each power setting, and the error bars overlap for all the comparisons except carbon monoxide at low speed ground idle. The CO emission factors all agree within 25%, and the high speed ground idle, flight idle and cruise results agree within 5%. The agreement is similar for nitrogen oxides: all the comparisons are within 30%, and four of the five power settings agree to better than 10%. This comparison provides confidence in the accuracy of the new downstream extractive sampling approach.

4.2. Variability of emissions from military aircraft engines

The variability of exhaust emissions is an important consideration when utilizing emission factors for regulatory purposes, health risk assessments, or other applications. The studies reported here were designed to provide estimates of two different measures of variability. The first is the reproducibility of emissions from multiple tests on a given engine, or "intra-engine" variability. We report intra-engine variability as the relative standard deviation of emission factors measured in replicate tests of a given engine. For example, we carried out duplicate tests at idle power on four F100 engines mounted on F-15 aircraft. The relative standard deviations of the duplicate test emission factors from each engine provide an estimate of intra-engine variability. Note that duplicate tests on four different engines (two engines at afterburner power) were undertaken during the F-15 campaign, and quadruplicate tests on

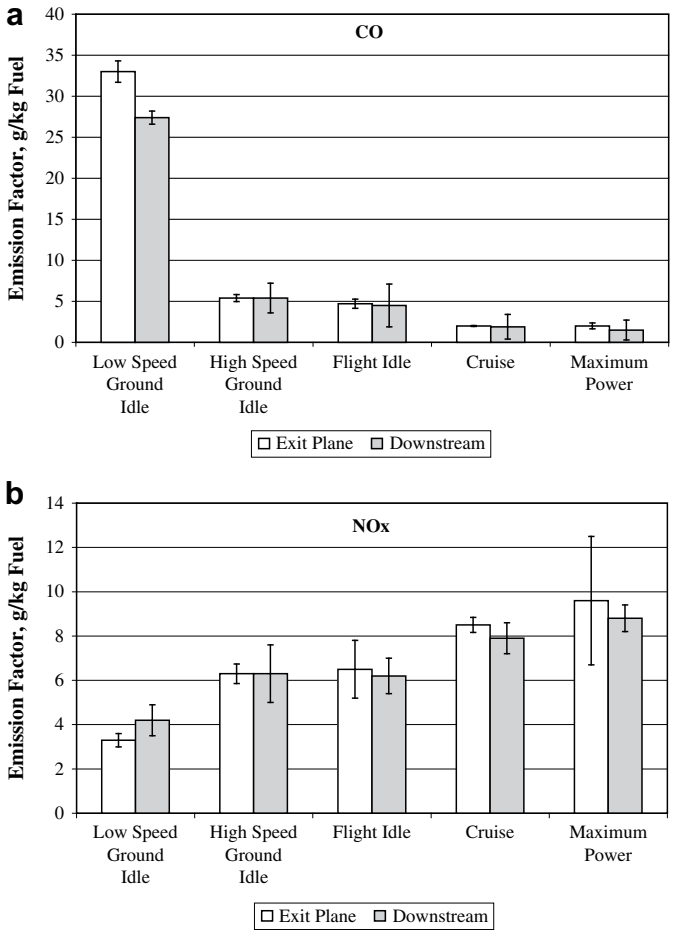

Fig. 1. (a) Comparison of CO emission factors for T56 engine measured at exhaust exit and 14.3 m downstream. (Error bars represent the standard deviation of replicate measurements.) (b) Comparison of NO_x emission factors for T56 engine measured at exhaust exit and 14.3 m downstream. (Error bars represent the standard deviation of replicate measurements.)

two different engines during the C-130 studies. The second measure of variability is "engine-to-engine" variability. This was determined by first calculating the mean emission factor of each chemical from all replicate tests on a given engine at a given power setting. The mean values for each engine tested were then used to calculate the mean, standard deviation, and finally the relative standard deviation, or engine-to-engine variability, across all engines tested.

The intra-engine variability results for the target chemicals are reported in Tables 6 and 7 for the C-130 and F-15 aircraft

Table 6
Intra-engine variability of emissions from T56 engines on a C-130 aircraft (relative standard deviation in %).

Target chemical	Low speed idle		Maximum power	
	Engine 1	Engine 2	Engine 1	Engine 2
CO	0.8	3.5	23	121
NO_x	24	11	6.9	7.8
Ethylene	8.5	16	–	–
1,3-Butadiene	9.6	32	–	–
Benzene	8.3	29	–	164
Toluene	28	27	–	178
Styrene	16	28	–	22
Formaldehyde	5.6	15	118	88
Acrolein	70	22	78	97

Table 7
Intra-engine variability of emissions from F100 engines on F-15 aircraft (relative standard deviation in %).

Target Chemical	Idle				Afterburner	
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5	Engine 6
CO	4.4	2.2	0.9	8.0	3.7	0.9
NO_x	1.3	2.5	14	13	7.4	0.7
Ethylene	4.7	–	–	–	–	–
1,3-Butadiene	17	3.7	–	3.7	–	–
Benzene	0.4	4.8	0.7	5.3	13	4.3
Toluene	11	9.3	5.6	2.3	34	8.1
Styrene	14	0.5	–	–	–	–
Formaldehyde	6.2	9.7	0.5	3.9	54	2.3
Acrolein	0.8	3.3	21	17	16	9.2

respectively. Results are shown for the lowest and highest throttle settings for each of the engine types. The intra-engine variability of two T56 engines on the C-130 ranged from 1 to 70% at idle, but was less than 30% for almost all of the target compounds in Table 6. Due to the much lower concentrations of the target chemicals (except NO_x) at maximum power, there was insufficient data to report variability for several of the compounds at this setting. For most of the target chemicals, the intra-engine variability is higher at the higher power setting. This is probably due at least partly to measurement uncertainty at concentrations close to the instrumental detection limits. The intra-engine variability of the four F100 engines at idle, shown in Table 7, is below 15% for nearly all of the target chemicals, and even at afterburner power only two of the chemicals show relative standard deviations greater than 30%.

The engine-to-engine variability is shown in Tables 8 and 9 for the C-130 and F-15 aircraft, respectively. At idle, the reproducibility of all the target chemicals was better than 22% for the C-130 tests. The engine-to-engine variability for the C-130 engines at maximum power was generally much higher than at idle for chemicals with sufficient data to permit an estimate. The engine-to-engine variability for the F-15 engines was generally less than 30% at idle and ranged from 4 to 42% for a limited set of chemicals at afterburner power.

To summarize these results on the basis of the nine target chemicals, both intra-engine and engine-to-engine variabilities were generally less than 30% for both types of engines at idle. Both types of variability are generally higher at maximum power compared to idle for the C-130 engines. The results are not as consistent for the F-15 engines, but both types of variability were often somewhat higher at afterburner power compared to idle. Across all target chemicals, the best reproducibility was observed for intra-engine tests of the F-15 engines. It is interesting that intra-engine variability was generally lower than engine-to-engine variability for the C-130 tests, while engine-to-engine variability was lower than intra-engine variability for tests of the F-15 engines. Many factors can influence test reproducibility, including mechanical differences in engines of the same type, small

Table 8
Engine-to-engine emissions variability for T56 engines on C-130 aircraft (relative standard deviation in %).

Target chemical	Low speed idle	Maximum power
CO	2.4	62
NO_x	6.6	1.1
Ethylene	4.4	–
1,3-Butadiene	13.5	–
Benzene	7.1	61
Toluene	10.4	92
Styrene	11.6	–
Formaldehyde	17.3	46
Acrolein	21.3	29

Table 9
Engine-to-engine emissions variability for F100 engines on F-15 aircraft (relative standard deviation in %).

Target chemical	Idle	Afterburner
CO	23.4	4.2
NO_x	26.8	8.1
Ethylene	–	–
1,3-Butadiene	19.6	–
Benzene	11.2	20.6
Toluene	31.7	42.4
Styrene	32.6	–
Formaldehyde	14.2	34.9
Acrolein	20.8	24.4

differences in engine power at the same nominal throttle setting, variations in fuel composition from test to test, differences in ambient conditions (e.g. humidity, temperature, etc.) and measurement variability. Many of the tests used to estimate intra-engine variability were conducted on the same day and with the same pilot for a given engine, while the tests used to determine engine-to-engine variability were often conducted with different pilots and on different days with different ambient conditions. These aspects of our testing protocols may have influenced the relative significance of the two types of variability.

4.3. Effect of engine power on emissions

It has already been noted that throttle setting has a major effect on exhaust emissions. This effect is demonstrated for the C-130 aircraft in Fig. 2, which shows the emission factors for the nine target chemicals at each of five throttle settings. The emission factors are plotted on a logarithmic scale. Note that different units are used for different chemicals, and that one of the data points is an upper limit based on instrument detection limits. For all the target chemicals except NO_x, there is a sharp drop in emissions for throttle settings above idle. Generally for chemicals other than NO_x, emissions continue to decrease with increasing power. However the toluene emissions remain fairly constant at settings above idle. The emission factor for NO_x increases with increasing engine power for reasons noted earlier.

The corresponding plot of target chemical emission factors for the F-15 is shown in Fig. 3. Due to the substantially lower emissions from the F-15 engines, many more of the plotted points represent upper limits based on detection limits. As with the C-130, the emissions drop sharply for throttle settings above idle, excepting NO_x. However, this trend is reversed for many of the species at afterburner power, and this occurs for both unburned fuel components such as benzene and toluene, as well as partial oxidation products like CO and formaldehyde.

4.4. Comparison of emissions from C-130 and F-15 aircraft

A comparison of emissions from the two types of engines is shown in Fig. 4 for a throttle setting of idle. The data are plotted on a logarithmic scale. Except for NO_x, the C-130 emissions exceed those from the F-15 for all the target chemicals. For some chemicals like CO, ethylene, benzene, formaldehyde and acrolein the C-130 engine emissions exceeded the F-15 by factors of 2–5, but other species including 1,3-butadiene and styrene were emitted at more than ten times the mass per mass of fuel burned by the C-130 engines. The T56-A-15 engine employed by the C-130H is a turbo-prop design. The original T56 engine was introduced in 1954, and the current T56-A-15 version has been in production since 1974. The F100-PW-100 is a high pressure ratio, afterburning turbofan engine first fielded in 1974. The engines were designed for different purposes, but the newer more advanced design of the F100 has definite benefits in terms of engine emissions for species other than NO_x.

The trend of higher C-130 emissions is also observed at higher power, as seen in Fig. 5. Because of differences in the design and operation of these two engines, the throttle settings shown in this figure are only roughly comparable, but both are the maximum continuous power available for the respective engines, and represent throttle settings used for takeoff. As noted earlier, all of the target chemicals except NO_x are significantly reduced at the higher engine power, but the C-130 engine emissions still exceed the F-15 emissions for all target compounds but NO_x, and by a factor of 3 or more for most of the target species.

4.5. Comparison with other aircraft engines

Emission factors for CO and NO_x from aircraft turbine engines have been measured routinely for many years, but similar data for individual organic species are relatively scarce. The emission factors for our nine illustrative target chemicals are compared with

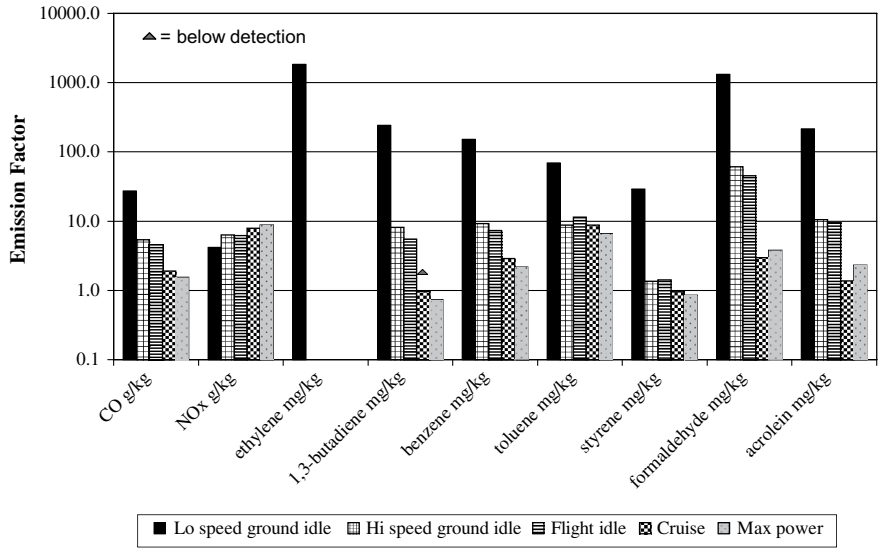

Fig. 2. Emissions of target chemicals from T56 engines on C-130 aircraft (log scale).

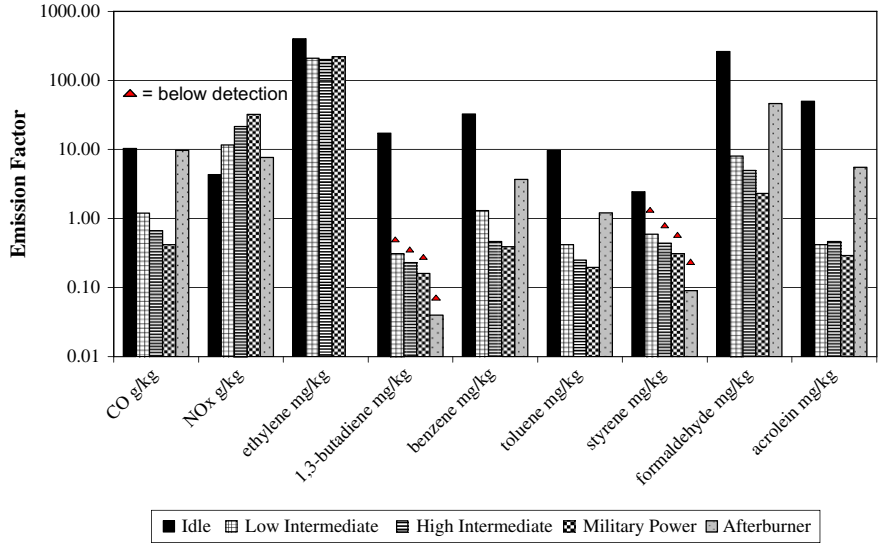

Fig. 3. Emissions of target chemicals from F100 engines on F-15 aircraft (log scale).

emissions' results from previous studies in Table 10. The table lists the engines that were tested, the engine category, rated thrust (turbofan and turbojet) or horsepower (turboprop), examples of aircraft which have used this engine, and the fuel that was used for emissions testing. Table 10 provides comparative emissions data for a throttle setting of idle. This setting was chosen for the comparison because it is a throttle setting shared by all the aircraft, because the highest emissions for all the target chemicals except NO_x are observed at this setting, and because the most likely exposure of humans to turbine engine exhaust is from idling aircraft. The emissions data in Table 10 were compiled from a variety of sources. Some of the engines were tested using indoor engine test facilities (F110, F101, J85-GE-5M, PT6A-68, TF41-A2, TF30-P103 and TF30-P109), while others were studied while mounted on outdoor engine test stands (TF-39-1C and CFM-56-3). The two engines which are the subject of this study were tested outdoors while mounted in normal fashion on their associated aircraft (T56-A-15 and F100-PW-100). The final column in the table reports emissions' estimates made on advected plumes from an ensemble of commercial passenger aircraft at an urban airport.

Emissions are reported for 2 turboprop, 1 turbojet and 8 turbofan engines. The specific engines were not identified in the advected plume tests. Fuel composition can have an important influence on exhaust composition, and the emissions tests reported in Table 10 utilized several different fuels. Another important factor affecting turbine engine emissions is the design goal of the engine. Some of the engines listed in the table are older generation designs from a time when fuel efficiency and emissions were of little concern, whereas the more recent generation of engines have been developed with these factors given strong consideration.

This factor relating to the age of engine design appears to have a very strong influence on the relative emissions of many of the target VOCs in Table 10 and of carbon monoxide. The older generation turbofan engines (TF-39, TF41 and TF30) show generally higher emissions of these chemicals than the other engines. Conversely, the newer turbofan engines (F100, F101 and F110) report substantially lower emissions than the other engines for many of the target chemicals. The older and smaller turboprop (PT6A-68) also showed considerably higher emission factors for most of the target chemicals than the newer turboprop (T56-A-15).

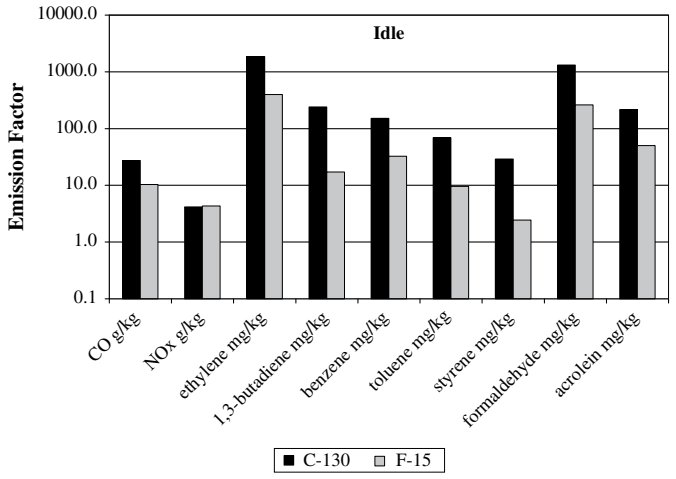

Fig. 4. Comparison of target chemical emissions for C-130 and F-15 aircraft at idle throttle setting.

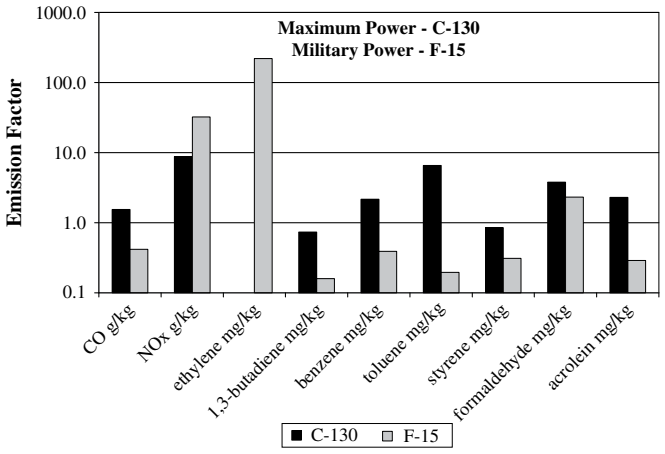

Fig. 5. Comparison of target chemical emissions for C-130 and F-15 aircraft at highest throttle setting.

Table 10
Comparison of emission factors from a variety of aircraft turbine engines operating at idle (A/B indicates afterburning).

Engine	T56-A-15	F100-PW-100	F110	F101	J85-GE-5M	PT6A-68	TF-39-1C	CFM-56-3	TF41-A2	TF30-P103	TF30-P109	Misc.
Type	Turboprop	Turbofan	Turbofan	Turbofan	Turbojet	Turboprop	Turbofan	Turbofan	Turbofan	Turbofan	Turbofan	
Example aircraft	C-130H	F-15	F-14, F-15, F-16	B-1B	T-38 Talon	T-6A Texan	C-5	737-300	A-7	F-111A/E	F-111	Commercial
Maximum power	4500	29,160 (A/B)	32,000 (A/B)	30,000 (A/B)	2950	1100 HP	41,100	20,000	15,000	18,500 (A/B)	20,800 (A/B)	
Fuel	JP-8	JP-8 + 100	JP-4	JP-4	JP-8 + 100	JP-8 + 100	JP-5	JP-5	JP-4	JP-4	JP-4	
Data source	This study	This study	[a]	[a]	[b]	[c]	[d]	[d]	[e]	[e]	[e]	[f]
Chemical, units												
CO, g kg^{-1}	27.4	10.4	24.0	21.7	191	123	50.8	66	176	100	103	–
NO_x, g kg^{-1}	4.18	4.31	6.6	5	0.79	2.78	2.96	2.62	4.0	4.0	4.3	2
Ethylene, mg kg^{-1}	1843	400	72	149	–	–	3279	1695	9093	6089	5167	–
1,3-Butadiene, mg kg^{-1}	241	17.2	4.91	2.66	12	149	436	192	1324	931	866	–
Benzene, mg kg^{-1}	152	32.5	11.4	23.0	30.5	284	392	199	1557	968	810	300
Toluene, mg kg^{-1}	69.5	9.6	142.1	15.5	27.6	165	143	75.0	1815	1469	1111	200
Styrene, mg kg^{-1}	29.1	2.44	0.72	1.11	7.90	47	72.7	36.5	663	581	461	–
Formaldehyde, mg kg^{-1}	1317	261	43.9	72.7	2260	4800	769	630	2092	1732	1669	1100
Acrolein, mg kg^{-1}	216	50.0	2.16	1.33	313	716	325	202	267	186	190	–

[a] Derived from data in Spicer et al. (1990); results from exhaust plane sampling, indoor test cell.
[b] Gerstle and Wade (2002a); results from slipstream sampling, indoor test cell.
[c] Gerstle and Wade (2002b); results from exhaust exit plane sampling, indoor test cell (Engine A).
[d] Derived from data in Spicer et al. (1994); results from exhaust exit plane sampling, outdoor test stand.
[e] Derived from data in Spicer et al. (1987); results from exhaust exit plane sampling, indoor test cell.
[f] Herndon et al. (2006); results averaged over 13 advected exhaust plumes from miscellaneous commercial aircraft.

5. Conclusions

A new approach for the determination of aircraft engine emissions has been demonstrated. Measurements are made using a simple extractive probe in the dilute exhaust 20–25 nozzle diameters behind the engine. Measurements can be made at all throttle settings including afterburner, and can be performed quickly on operational aircraft on the ground. Emission factors determined using this approach agree very well with emission factors from the traditional method of extractive sampling at the exhaust exit. The new approach has been used to develop emission factors for CO_2, CO, NO and NO_x, and more than 60 organic gases, for C-130H transport aircraft engines and F-15 fighter aircraft engines. Emissions were measured at five throttle settings including afterburner for the F-15. Particle mass, size and composition also were determined and are reported separately. Particle results for the C-130 are reported by Cheng et al. (2008) and Corporan et al. (2008), and Cowen et al. (in preparation) present particle results for the F-15. The four chemicals: ethylene, formaldehyde, acetylene and propylene accounted for about 70% of the mass of identified organic emissions at idle for both aircraft. The variability of emissions for multiple tests on a given engine (intra-engine variability) and for tests on multiple engines of the same type (engine-to-engine variability) was assessed. Based on a set of nine target chemicals, intra-engine variability was typically better than 30% for the C-130 and 10% for the F-15 engines at a throttle setting of idle. Engine-to-engine variability at idle was typically better than 20% and 30% for the C-130 and F-15 engines respectively. For both engines, the effect of engine power on emissions was as expected, with higher power leading to reduced emission factors for CO and organic gases and higher emission factors for nitrogen oxides. At afterburner power, the F-15 engine yielded higher emission factors for CO and many organics and lower NO_x emission factors compared with the military power throttle setting. The C-130 turboprop engine generally produced higher CO and organic emissions and lower NO_x emissions per unit of fuel consumed than the F-15 engines. Comparison of the emissions of the nine target chemicals from these two engines with emissions from nine other military aircraft engines also was discussed.

Acknowledgments

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.atmosenv.2009.02.012.

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