Appendix D: Aircraft Emission Methodology

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LIST OF EQUATIONS

Appendix D: Aircraft Emission Methodology

D1. OVERVIEW

This appendix discusses the emissions inventory calculation methodology, data inputs, and data sources for three types of aircraft emission sources: commercial, general aviation and air taxi, and military aircraft.

D2. COMMERCIAL AIRCRAFT

Commercial aircraft are operated by domestic and foreign air carriers. Foreign carrier aircraft operations can range from a few charter operations to a significant portion of an airport's total scheduled operations. The methodology in Section D2.1 can be applied for the aircraft operations of both domestic and foreign air carriers. Section D2.2 addresses the sources of data inputs for both domestic and foreign operations.

D2.1 Methodology

The EPA has set forth procedures for calculating exhaust emission inventories of commercial aircraft standard LTO cycle operations. Exhaust emissions are calculated for one complete LTO cycle of each aircraft type by knowing the emission factors for the aircraft's specific engines at each power setting or mode of operation, as well as the time spent in each mode. Then the activity of aircraft for the inventory period can be applied to calculate their total emissions. This emissions calculation procedure is presented in EPA's *Procedure for Emission Inventory Preparation*, Volume IV, Chapter 5 (Reference 82). Currently, no information is available on calculating evaporative-related emissions (e.g., refueling emissions) from commercial aircraft. Evaporative related emissions are small due to the low vapor pressure of the fuel and quick-connect refueling nozzles.

This EPA procedure addresses emissions for five operating modes of a standard LTO cycle: approach, taxi/idle-in, taxi/idle-out, takeoff, and climbout. A sixth operating mode, reverse thrust, often is included in a standard LTO cycle but is not included in EPA's procedure. After aircraft land, engine thrust reversal typically is used to slow the aircraft to taxi speed (otherwise the aircraft is slowed using only the wheel brakes). Reverse thrust is now considered by EPA as an official mode and should be included in calculation procedures as a sixth operating mode when applicable. Since reverse thrust engine operating conditions are similar to takeoff, time spent in reverse thrust should be combined with takeoff mode emission indices and fuel flow as a means of accounting for reverse thrust mode emissions. Aircraft reverse thrust typically is applied for 15-20 seconds on landing.

The emissions calculation methodology presented in EPA's *Procedure for Emission Inventory Preparation* estimates emissions for HC, CO, NO_x, SO_2, and PM-10. The NO_x emission factors provided in EPA's procedures should be used to calculate a NO_x emissions inventory that is used to compare against NO_2 emission standards. (When both nitric acid (NO) and NO_2 are emitted, they are referred to collectively as total oxides of nitrogen, or NO_x.)

D2.2 Data Sources

D2.2.1 Aircraft type and number of LTOs

Sources of site-specific aircraft fleet and activity data include published references, records of aircraft and airport operators, and the Department of Transportation (DOT). Domestic carrier aircraft fleet and activity data by airport and airline are reported to the FAA by certificated route air carriers on FAA Form 41, Schedule T-3s: Airport Activity Statistics. FAA T-3 data are available on data tape (Reference 64) or in FAA's *Airport Activity Statistics of Certificated Route Air Carriers* (Reference 53). The data also includes activity information for certificated route air carrier operations at military air bases. Foreign carrier aircraft operations are available from the DOT Bureau of Transportation Statistics. Conducting on-site activity monitoring and contacting individual airports for data are alternative options for collecting domestic and foreign data on aircraft type and operating frequency.

D2.2.2 Engine Type and Number

Site-specific engine data are not readily available, although it should be used if obtainable. If the specific engine type is not known for an aircraft but the aircraft operator is known, an appropriate surrogate engine can be chosen based on the operator's national fleet. Domestic and foreign airline fleet data that includes aircraft engine models are published in Bucher & Co.'s *JP Airline-Fleets International* (Reference 2) and Jet Information Service's *World Jet Inventory* (Reference 24). If the aircraft operator is not known, typical aircraft-engine combinations are provided in EPA's *Procedure for Emission Inventory Preparation*, Volume IV, Chapter 5. Finally, on-site collection of engine type data is feasible but not recommended due to the difficulty in identifying specific engine models.

D2.2.3 Engine Emission Indices and Engine Fuel Flow

Emission indices (i.e., emission factors) and average fuel consumption rates for aircraft engines are listed by operating mode in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5 and in the ICAO *Engine Exhaust Emissions Databank* (Reference 27). Generally, emission factors are listed in pounds of pollutant per 1000 pounds of fuel consumed and fuel flow is listed in pounds per minute. Only EPA's *Procedures* document provides particulate emission factors, and data are available for only a few engines. A recent investigation of particulate emissions by EPA indicates that the particulate emission factors can be used to calculate reasonable estimates of PM-10 emissions from these engines. Until further data is available, PM-10 emission factors of engines for which no data is available should be assumed to be zero. The EPA Office of Mobile Sources should be contacted for additional guidance. Neither source provides SO_x emission factors. A SO_x emission factor of 0.54 lb/1000 lb can be used for most air carrier aircraft, which is based on a national average sulfur content of aviation fuels.

As mentioned above, reverse thrust mode is not included in EPA's methodology. There also are no specific reverse thrust emission factors available. Takeoff emission indices and fuel flow should be used as inputs for calculating emissions from reverse thrust (as well as takeoff) mode.

D2.2.4 Time in Mode

There are six possible operating modes of aircraft standard LTO cycles: approach, taxi/idle-in, taxi/idle-out, takeoff, climbout, and reverse thrust (if applicable). the time an aircraft operates in each mode depends on a variety of factors and should be adjusted to represent local conditions when possible. Approach and climbout times in mode vary based on the local mixing height.

The methodology for determining approach and climbout is described in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5 Taxi time is highly site- and situation-specific. Potential sources of site-specific taxi/idle times include aircraft operators and the FAA. The FAA compiles monthly taxi data received from aircraft operators for many airports. These aircraft taxi time data are available from FAA's Office of Aviation Policy, Plans and Management Analysis (Reference 66). On-site monitoring of taxi times over an extended period also is a feasible means of estimating this data. The time spend in takeoff mode is fairly standard and will not vary much from location to location. Therefore, a standard default time usually is used in emission calculations. Default takeoff times are provided for several aircraft categories in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. If reverse thrust is used on aircraft landing, it typically is applied for approximately 15 seconds. Unless site-specific data is available, 15 seconds should be used as a default reverse thrust time in mode for LTOs that include reverse thrust on landing.

D3. GENERAL AVIATION AND AIR TAXI AIRCRAFT

D3.1 Methodology

The following discusses the procedures for calculating standard and non-standard LTO exhaust emission from general aviation and air taxi aircraft, as well as general aviation aircraft evaporative emissions.

There are two approaches for calculating exhaust emissions from standard operations of general aviation and air taxi aircraft. The approach used above in Section D2.1 to calculate emissions from standard operations of commercial air carrier aircraft (i.e., presented in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5) also can be used for standard operations of general aviation and air taxi aircraft. Due to the nature and tracking of general aviation and air taxi operations and operators, often it is difficult to find the detailed information on aircraft mix and activity needed to estimate emission using this detailed approach. Where detailed information on specific aircraft mix and activity is unavailable, the EPA alternative methodology can be used. The alternative methodology uses "generalized" emission indices, in pounds per LTO, to estimate emissions. Separate generalized emission indices are provided in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5 for general aviation aircraft and air taxi aircraft. The generalized emission indices are based on default values for key data inputs and a representative general aviation or air taxi fleet mix.

Not all aircraft operations follow the standard LTO cycle. The more detailed EPA procedure can be adjusted for the non-standard conditions and used to calculate emissions from non-standard operations of general aviation and air taxi aircraft. An example of non-standard operations are practice touch-and-goes. In a touch-and-go, the taxi/idle mode is eliminated, the approach and climbout modes shortened, and a "return flight" mode is added (to allow the pilot to turn around and repeat the procedure). To calculate the emissions from a touch-and-go, the taxi/idle mode should be eliminated from the calculations. Rather than reducing the approach and climbout times and then adding additional time for circling the airfield, the full approach and climbout times should be used (assuming this will account for the additional flight time within the mixing zone).

Most general aviation aircraft are powered by piston engines, which are fueled by aviation gasoline (AvGas). Aviation gasoline has a much higher volatility than jet fuel and the fuel tanks are vented to the atmosphere resulting in significant HC evaporation. Evaporative emissions are associated with refueling, pre-flight safety procedures, and fuel venting due to diurnal temperature changes. The EPA methodology for calculating refueling losses is provided in an EPA Office of Air and Radiation memorandum from Mary Manners to Susan Willis dated October 20, 1996; Subject: *Revised Methodology for Calculating the Refueling Losses for General Aviation Aircraft*. The following equations, **Error! Reference source not found.** and **Error! Reference source not found.** ***(Mariano this should be Equation D-2)*** , developed for the EPA, should be used for quantifying HC evaporative emissions from general aviation aircraft pre-flight safety procedures and fuel venting. [Note: These calculations are *not* to be used for turbine engines.]

$$E_T = 0.20\ \text{lb/LTO}_L \times \text{LTO}$$

Where: E_T - total HC emissions, in pounds, resulting from pre-flight safety checks
LTO_L - number of landing and takeoff cycles by piston-engine aircraft during the period of interest, excluding landing and takeoff cycles by itinerant aircraft

Equation D- 1: Emissions from Pre-Flight Safety Checks

$$E_T = 0.15\ \text{lb/day/based aircraft} \times A_b \times D$$

Where: E_T - total HC emissions, in pounds, resulting from diurnal losses
A_b - number of aircraft based in the region of interest
D - number of days in the period of interest

Equation D- 2: Emissions from Diurnal Temperature Changes

D3.2 Data Sources

The calculation data inputs vary based on the calculation methodology used. If the detailed calculation methodology is being utilized to calculate exhaust emissions, data inputs needed are aircraft type and number of LTOs, engine type and number, engine emission indices and fuel flow, and time in mode. If the alternative, generalized calculation methodology is being used to calculate exhaust emissions, data inputs needed are number of LTOs and the generalized emission factors. For evaporative emissions from pre-flight safety checks and diurnal temperature changes, total piston-engine aircraft LTOs and number of based aircraft are needed. Inputs for calculating refueling losses are discussed in the EPA Office of Air and Radiation memorandum from Mary Manners to Susan Willis dated October 20, 1996; Subject: *Revised Methodology for Calculating the Refueling Losses for General Aviation Aircraft*.

D3.2.1 Aircraft Type and Number of LTOs

Site-specific aircraft fleet and activity data (i.e., LTOs by aircraft type for an airport or air base) is not readily available. Potential sources of site-specific aircraft fleet and activity data include sampling and aircraft and airport operators. Potential sources of site-specific local and total activity (i.e., local or total LTOs for an airport or air base) include records of aircraft or airport operators. Local and total activity by airport are available from FAA *Airport Master Records* (Form 5010-1) (Reference 54) or FAA *Air Traffic Activity* (Reference 59). FAA *Airport Master Records* also provide activity data for operations at military air bases.

D3.2.2 Engine Type and Number

Site-specific engine type and number data is not readily available. Potential sources of site-specific engine type and number data include sampling and aircraft operators. Default, typical aircraft-engine combination data is provided in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. On-site collection of engine type data is feasible but not recommended due to the difficulty in identifying specific engine models.

D3.2.3 Engine Emission Indices and Fuel Flow

Emission index and fuel flow data for a limited number of general aviation and air taxi aircraft engines is included in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5 and in the *ICAO Engine Exhaust Emissions Databank*. Generally, emission factors are listed in pounds of pollutant per 1000 pounds of fuel consumed and fuel flow is listed in pounds per minute. If engine-specific data is not available or sufficient, generalized emission indices, in pounds per LTO, also are provided in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5.

D3.2.4 Time in Mode

The five operating modes of aircraft standard LTO cycles are approach, taxi/idle-in, taxi/idle-out, takeoff, and climbout. The methodology for adjusting approach and climbout is described in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. Potential sources of site-specific taxi/idle times include aircraft operators, airport operators and on-site measurement. The time spend in the takeoff mode is fairly standard and will not vary much from location to location. A standard default time is usually used in emission calculations. Takeoff default times are provided for several aircraft categories in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5.

D3.2.5 Based Aircraft

Potential sources of site-specific based aircraft data include sampling and airport operators. Total number of based aircraft by airport also is available from FAA *Airport Master Records*.

D4. MILITARY AIRCRAFT

D4.1 Methodology

The following discusses the procedures for calculating standard and non-standard LTO exhaust emissions from military aircraft, whether occurring at a civil or military facility. The USAF document *Calculation Methods for Criteria Air Pollutant Emission Inventories* (Reference 23) also should be consulted for further guidance. Currently, no information is available on calculating evaporative-related emissions (e.g., refueling emissions) from military aircraft. Evaporative related emissions are small due to the low vapor pressure of the fuel and quick-connect refueling nozzles.

Procedures are set forth in EPA's *Procedures for Emission Inventory* Preparation, Volume IV, Chapter 5 for calculating military aircraft exhaust emission inventories of standard LTO operations, which is the same detailed procedure used for commercial, general aviation, and air taxi aircraft. Emissions are calculated for one complete LTO cycle of each aircraft type by knowing the emission indices for the aircraft's specific engines at each power setting or mode of operation, as well as the time spent in each mode. The activity of aircraft for the inventory period can then be applied to calculate their total emissions.

This EPA procedure addresses emissions from five operating modes of a standard LTO cycle: approach, taxi/idle-in, taxi/idle-out, takeoff, and climbout. A sixth operating mode, reverse thrust, often is included in a standard LTO cycle but is not included in EPA's procedure. After aircraft land, engine thrust reversal typically is used to slow the aircraft to taxi speed (otherwise the aircraft is slowed using only the wheel brakes). Reverse thrust is now considered by EPA as an official mode and should be included in calculation procedures as a sixth operating mode when applicable. Since reverse thrust engine operating conditions are similar to takeoff, time spent in reverse thrust should be combined with takeoff mode emission indices and fuel flow as a means of accounting for reverse thrust mode emissions.

The emissions calculation methodology presented in EPA's *Procedure for Emission Inventory Preparation* estimates emissions for HC, CO, NO_x, SO_2, and PM-10. The NO_x emission factors provided in EPA's procedures should be used to calculate a NO_x emissions inventory that is used to compare against NO_2 emission standards. (When both nitric acid (NO) and NO_2 are emitted, they are referred to collectively as total oxides of nitrogen, or NO_x.)

Not all aircraft operations follow the standard LTO cycle. The more detailed EPA procedures, adjusted for the non-standard conditions, also can be used to calculate emissions from non-standard operations of military aircraft. Examples of non-standard operations include pilot training, engine operation/testing, and the addition of an afterburn mode. In a training touch-and-go operation, the taxi/idle mode is eliminated, the approach and climbout modes shortened, and a "return flight" mode added (to allow the pilot to turn around and repeat the procedure). To calculate the emissions from a touch-and-go, the taxi/idle mode should be eliminated from the calculations. Rather than reducing the approach and climbout times and then adding additional time for circling the airfield, the full approach and climbout times should be used (assuming this will account for the additional flight time within the mixing zone).

D4.2 Data Sources

D4.2.1 Aircraft Type and Number of LTOs

For those operations that occur at military facilities, this data should be obtained from the base operations sections. If the operation occurs at a civilian facility, this data should be obtained from the individual airport.

D4.2.2 Engine Type and Number

A potential source of site-specific engine type and number data is the base operations section of the air base where the operation occurred or the air base where the aircraft is stationed. If site-specific data is not available, default, typical aircraft-engine data is provided in the EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5 and the USAF's *The Engine Handbook* (Reference 44).

D4.2.3 Engine Emission Indices and Fuel Flow

Emission indices (i.e., emission factors) and average fuel consumption rates for aircraft engines are listed by operating mode in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. Generally, emissions indices are listed by operating mode in pounds of pollutant per 1000 pounds of fuel consumed and fuel flow is listed in pounds per minute. EPA's

Procedures document provides particulate emission factors, but data are available for only a couple engines. A recent investigation of particulate emissions by EPA indicates that the particulate emission factors can be used to calculate reasonable estimates of PM-10 emissions from these engines. Until further data is available, PM-10 emission factors of engines for which no data is available should be assumed to be zero. The EPA Office of Mobile Sources should be contacted for additional guidance.

The Air Force is in the process of converting from JP-4 to JP-8 fuel. This conversion is expected to continue Air Force-wide through 1998. The effort was undertaken to increase survivability of air crews and aircraft and to standardize fuel type with allies (e.g., NATO). JP-8 is essentially commercial grade Jet A-1 aviation kerosene. Because it vapor pressure is much lower than that of JP-4, the potential for fire and explosion is significantly reduced. As of this writing, specific criteria pollutant emission indices for the various flight operation modes are not available for JP-8. Average emission index data for engines by operating mode for JP-4 is included in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. Information on the environmental impact of the JP-4 to JP-8 conversion expected by the Air Force is provided in *Calculation Methods for Criteria Air Pollutant Emission Inventories* (Reference 23).

D4.2.4 Times in Mode

The operating modes of a military aircraft standard LTO cycle are the same as for civil aircraft, although the power settings may be different. There are six possible operating modes: approach, taxi/idle-in, taxi/idle-out, takeoff, climbout, and reverse thrust. The power settings for a civil aircraft standard LTO cycle are takeoff at 100%, climbout at 85%, approach at 30%, taxi/idle at 7%, and reverse thrust at 80-100%. For military aircraft, examples of possible alternative power settings are takeoff at afterburner power and takeoff or climbout at military, intermediate, or IRP. Taxi time is highly site- and situation-specific. Potential sources of site-specific taxi/idle times include sampling and the air base operations department. Approach and climbout times in mode vary based on the local mixing height. The methodology for adjusting approach and climbout times is provided in EPA's *Procedures for Emission Inventory Preparation*, Volume IV, Chapter 5. Takeoff time in mode is fairly standard. Default takeoff times are provided for several aircraft categories in EPA's *Procedures for Emissions Inventory Preparation*, Volume IV, Chapter 5. If reverse thrust is used on aircraft landing, sampling should be conducted or the air base operations department should be consulted to estimate the reverse thrust time in mode. For non-standard LTO cycles, the times in mode should be adjusted for site-specific conditions (e.g., taxi/idle mode times and power settings should be adjusted for touch-and-go cycles).