Regulatory Support Document

Control of Air Pollution from Aircraft and Aircraft Engines

For the Direct Final Rule
for aircraft emission standards

Published May 8, 1997

Harmonizes US aircraft standards
with international standards

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources

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Definitions of Acronyms

CAA	Clean Air Act (Amendments of 1970)
CAEP	Committee on Aviation and Environmental Protection
CO	Carbon monoxide
DOT	Department of Transportation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
Foo	Rated output of an engine, or 100% thrust
HC	Hydrocarbon
ICAO	International Civil Aviation Organization
IGIA	Interagency Group on International Aviation
LTO	Landing-Takeoff Cycle
NOx	Oxides of Nitrogen
NME	Newly Manufactured Engine
rO	Rated output of an engine, or 100% thrust
rPR	Rated pressure ratio
TF	Turbofan engine
TP	Turboprop engine
TSS	Engines employed for propulsion of aircraft designed to operate at supersonic speeds
T8	JT8D class of turbofan engines manfactured by Pratt & Whitney
T3	JT3D class of turbofan engines manfactured by Pratt & Whitney
SN	Smoke Number--a dimensionless quantity used to measure the opacity of an engine's exhaust

Part 1
Introduction

This Regulatory Support Document (RSD) provides information pertaining to aircraft engines and their emissions and presents a background of aircraft engine emissions regulation. This document supports a Direct Final Rulemaking (DFRM) to amend the existing regulations of exhaust emissions from newly manufactured commercial aircraft turbofan, turbojet, and propfan engines.

Section 231(a)2 of the Clean Air Act (CAA) directs the Administrator of the United States Environmental Protection Agency (EPA) to "issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft or aircraft engines which in his judgement causes, or contributes to, air pollution which may reasonably be anticipated to endanger the public health or welfare."

Furthermore, section 232(a) of the CAA directs the Secretary of Transportation to prescribe regulations to ensure compliance with all aircraft engine emission standards prescribed by the EPA.

1.1 Background

The International Civil Aviation Organization (ICAO) was created by the United Nations in 1947 to "achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the human environment." The United States is one of more than 150 participating members or "Contracting States" of the ICAO. To achieve its objective, ICAO established exhaust emissions standards and test procedures for three pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x), that are expected to be met by each of the Contracting States. If there are any variations in the intensity of the standards, each state is required under Article 38 to notify ICAO in writing. In 1990, there were about 10 states that notified ICAO of variations (the United States was one of them), 20 that had no differences, and about 130 that sent no information. However, ICAO has no punitive powers, and cannot require individual states to accept their rules.

The EPA has a responsibility under section 231 of the CAA to issue emission standards for any class of aircraft or aircraft engines which causes or contributes to potentially dangerous levels of air pollution. The EPA has taken steps to accept a portion of the ICAO standard. The first HC, CO, and NO_x standards were established in the early 70's. The CO and NOx standards were withdrawn in 1982 because of costs and technical concerns in view of the relatively small environmental impact of aircraft emissions at that time. NO_x control strategies at the time were expensive and unproven, so NO_x standards were left out of 1982 regulations. Also, a CO standard was thought not to be necessary because CO emissions are usually reduced as HC emissions are reduced. A revised HC standard applicable only to turbofan and turbojet engines was reintroduced in 1982 and became effective in 1984. The hydrocarbon standard was reintroduced since, unlike the CO and NO_x standards, it was considered practicable in terms of cost and technical concerns. ICAO published standards for all three pollutants (HC, CO, and NO_x) for turbofan and turbojet engines in 1981 that were applicable to engines manufactured after 1986. In 1993 ICAO issued an amendment reducing the NO_x standard by 20 percent for engines newly certified after 1996 and newly manufactured after 2000.

1.2 Description of Regulatory Action

This RSD is for the EPA DFRM to adopt existing ICAO NOx and CO aircraft engine emission standards and the new ICAO NOx standard to take effect in 1996 for newly certified engines and 2000 for newly manufactured engines. (In this RSD, the existing ICAO NOx standard and the new ICAO NOx standard are also referred to as the first-stage and second-stage NOx standards, respectively.) Aircraft emissions are measured in terms of a composite gas sample representing an engine's maximum total production of pollutant over the takeoff, climbout, approach, and idle operating cycles. The total time spent in all four cycles is the total average time that an aircraft would spend in the vicinity of the airport, from ground level to the mixing height (approximately 2000 feet). These four cycles make up the Landing-Take-Off (LTO) cycle.

The EPA is also responsible for setting the test procedure for determining engine emissions, which it has adopted from ICAO. Emissions standards represent the maximum amount of pollutant in grams (g) that an engine is allowed to generate per kilonewton of thrust (g/kN) over a typical LTO cycle. The Time In Mode (TIM) and thrust settings for each engine class differ slightly. Time In Mode values are the average times that a particular engine class spends in each phase of an average LTO cycle at a major airport during peak times. Thrust settings are the percentage of maximum power the engine class normally generates for each specific cycle. This value depends on the particular mode of the LTO cycle (e.g., takeoff, idle, climbout, approach). The current aircraft engine test procedure can be found in Appendix A.

All newly built gas turbine engines must meet the current EPA standards for their category (see Appendix A). Since a large portion of the engines operating today were manufactured before 1984 (the effective date of the existing HC standard), they are exempt from the HC standard. With typical life spans of up to 35 years, these higher-emitting engines could be in service until almost 2020.

The difference between the existing EPA and ICAO emissions standards is that ICAO includes CO and NO_x standards and has different effective dates of the HC, CO, and NO_x standards. ICAO's standards can be found in Appendix A.

1.3 Certification Process

The Federal Aviation Administration (FAA) is a part of the Department of Transportation and is charged with the responsibility of enforcing EPA's rules concerning aircraft emissions.

As a part of its overall enforcement responsibilities, the FAA delegates the responsibility of carrying out engine emissions tests to engine manufacturers and evaluates the data from these engine tests. The rest of its responsibilities involve evaluating the application, issuing a certificate, and other related administrative matters. Since the FAA does not have the resources nor the funding to test engines themselves, they select engineers from each manufacturer to serve as representatives (called designees) for the FAA while the manufacturer performs the test. The designees' responsibilities are determined by the FAA and this direct final rulemaking will not affect their duties. Typically they oversee the setup and operation of an engine emission test and send the emission test report to the FAA for final approval. A more detailed list of their responsibilities can be found in Appendix B.

The FAA can also grant exemptions for engines that meet certain specified criteria for maximum production rate, maximum total production, or special use.

Part 2
Turbine Engine Technology

2.1 Overview

Current EPA emissions standards apply only to commercial turbojet, turbofan, and, when they enter service, propfan engines. This section presents a general discussion of the technological characteristics of each of these engine types as well as emission formation and control.

All turbine engines ingest air, compress it, mix it with liquid fuel, ignite the high pressure mixture, force the exhaust through a set of turbine blades and expel it through a nozzle faster than the intake air entered. Earlier aircraft engines used pistons in a setup similar to an automobile engine to turn a shaft which was connected to a propeller. This propeller helped to pull in the air needed for combustion as well as supply bypass air (sometimes used to cool the engine and increase its thrust). A propeller is similar to a screw, which when turned in a vertical circle, causes air to move horizontally because of the twist designed into the propeller blade. Piston engines, due to their design, had a low maximum propeller speed and therefore a low aircraft maximum speed. As the need for faster flight at higher altitudes increased, advances in technology brought forth the turbine engine. Instead of depending on large propeller blades solely to supply most of the intake, turbine engines (turbofans and turbojets) relied mainly on the compressor, which has smaller blades that can spin a lot faster, to ingest most of the air and turbine blades to extract the energy from the combusted mixture. The four types of turbine engines that will be discussed are the turboprop (TP), turbojet (TJ), the turbofan (TF), and to a lesser extent, the propfan (PF).

In a typical turbine engine, air is drawn in and compressed by a set of vanes (blades) called a compressor. The rotor (rotating) and stator (stationary) blades in the compressor are twisted so that as the air passes through the compressor it is forced in opposite directions while the area of the compressor is gradually diminished. This compresses the air. The air is then mixed with a determined amount of fuel and ignited in an area of the engine called a combustor. After passing through a turbine, it then passes through a nozzle that converges for all subsonic aircraft so that the exhaust gas will speed up as it passes through the nozzle to generate thrust.

Turboprops have large propellers which give a large mass of air a small change in velocity, whereas turbojets and turbofans have smaller, more numerous blades which give a small mass of air a large change in velocity.

2.2 Turboprops

Turboprops (TP)(Figure 3) are an effective and efficient way to power airplanes flying at lower altitudes and flight speeds up to Mach 0.5. The Mach number is a ratio of the speed of the aircraft relative to the sound speed (i.e., M=1 is equivalent to an airspeed equal to the speed of sound). All TPs have a propeller that is a curved and twisted blade that displaces air axially (perpendicular to the blades) to create bypass flow as well as supply air for the compressor. The action of the propeller accounts for about 85% of the total thrust generated by the engine. The propeller hub is connected to a pitch control mechanism that varies the angle at which the spinning blades meet the incoming air to maintain maximum efficiency at all flight speeds. A speed reducer (usually 1:15 - reduces the compressor shaft velocity by fifteen times) is incorporated in the design to reduce stress on the engine by rotating the much larger blades at a slower speed than the engine.

A compressor is present to increase the available energy of the air. Turboprops will usually employ a centrifugal compressor that resembles a broad-based vase lying on its side. The incoming air flows between the ridges along the outside of the "vase." As the compressor rotates, the air flows past it and is turned at least 90 degrees in a relatively small distance. The air molecules contact each other at high velocity and are compressed.

From the compressor, the high pressure gas is sent to the burner to be mixed with fuel and combusted. Air leaving the burner still has a high pressure and temperature and this energy is extracted by the turbine to turn the shaft connected to the compressor and propeller. These components continue feeding air into the engine. The turbine is the opposite of the compressor; it expands and accelerates the gas via several stages of rotating blades. Finally, the subsonic exhaust is forced out the back end of the engine through a converging nozzle that helps to accelerate the flow similarly to how water squirts out of a garden hose when the exit is pinched shut. There is a large increase in flow velocity through the nozzle, contributing 15% towards the total engine thrust. The turboprop can be as much as 1.5 times as heavy as a comparable turbojet because of the speed reduction and pitch control mechanisms, but is more efficient because it requires smaller fuel flow values to operate.

One limitation of this type of engine is its limited speed of around Mach 0.5. As airspeed increases so does the stress on the propellers. Propeller speed must be limited to avoid failure. In addition, the faster the propellers rotate, the greater the likelihood that the flow passing over them will separate (break away from the blade surface creating very turbulent flow and high levels of friction) and cause major shock losses from pockets of supersonic air that form. Research is currently being performed on the effect of sweeping propeller blades back as a means to increase maximum speed.

2.3 Turbojets

Turbojets (TJ) have the simplest design of all the types discussed in this report. The engine is physically smaller which helps to reduce shock losses at high speeds. A turbojet engine can be seen in Figure 4. In place of a fan, turbojets have a component called a diffuser to slow incoming air down to around M=0.2. For subsonic flight, the diffuser has a diverging duct and for supersonic flight, it has a converging-diverging duct. Besides intake design, turbojets are different from turboprops in a couple of other ways. First, axial compressors are found in turbojets (and turbofans which are discussed below). They consist of many stages of rotating and stationary blades of decreasing size. The flow passing through the compressor will be constantly pushed in opposing directions by the blades causing an increase in the pressure of the air. Secondly, turbojets also use concentric shafts as a way to rotate different engine parts (including high and low pressure compressors and the fan) at different speeds. Turbojets may also be equipped with afterburners which add a large amount of thrust but also burn an enormous amount of fuel. Engines of this type will have converging-diverging nozzles or nozzles where the trailing end can open up (diverge) when necessary (Figure 14). When a flow is supersonic it behaves oppositely than would normally be expected. To speed up water traveling supersonically through a garden hose, one would have to open the end up not pinch it shut. An example of this is a military aircraft using an afterburner. As the throttle is advanced beyond 100% and the afterburner is activated, the exhaust nozzle's back end opens to allow the supersonic exhaust to accelerate.

Turbojets typically have higher thrusts than the other types because all of the air flows through the engine and is accelerated out of the nozzle. This gives turbojets the highest thrusts of the group, but also the lowest efficiency due to the losses associated with having a high exhaust velocity. Turbojets are best suited for high speed subsonic and supersonic flight.

2.4 Turbofans

If one took a turbojet engine and added a fan before the compressor, one would have a basic turbofan (TF) engine (Figure 5). The fan circulates bypass air (not used directly for combustion) and supplies air for combustion (Figure 6). Turbofans also employ axial compressors and concentric shafts (discussed above in the turbojet section).

Turbofans can achieve higher speeds (up to M=0.8) than a turboprop because the nacelle helps to control the flow going around the blades to reduce the losses from flow separation and shocka that will occur. Turbofans in general have less power than turbojets, but are more efficient due to their incorporation of a fan in their design to supply bypass air. The bypass air is air that would otherwise be used for combustion but instead is circulated around the outside of the engine. By doing this, the turbofan can have a lower exhaust velocity than a turbojet and a higher propulsive efficiency. Turbofan engines are characterized by the amount of air bypassed, with low-bypass ratio engines having bypass air roughly 4 or 5 times the air fed into the engine for combustion and high-bypass ratio engines being 9 times or higher. Up to a point, the higher the bypass, the greater the efficiency. Turbofans will most commonly be found on subsonic commercial and transport planes where efficiency is of greater value than speed.

2.5 Propfan/Unducted Fan

The last type of aircraft turbofan engine is the propfan or unducted fan (PF) (Figure 9) which can be thought of as either an advanced version of the turboprop having a propeller capable of very high Mach numbers or a turbofan with an extremely high effective bypass ratio (>25:1). This high bypass ratio decreases fuel consumption and thus has a higher propulsion efficiency. PF's have blades that are thin and swept back to increase their capability to withstand high relative velocities.

Pratt & Whitney's Advanced Ducted Prop (ADP) is an example of a propfan engine. The ADP offers significantly reduced fuel consumption, low noise, and low emissions compared to high-bypass ratio turbofans. The engine does this through the use of a special fan drive system allowing for a lower fan tip speed and slower exhaust gas velocities. Both the fan tip speed and the exhaust gas velocity are major sources of inefficiency in a turbine engine. The engine's nacelle is made of a slimline composite making its weight comparable with today's turbofans.

2.6 Combustion

To make an engine as efficient as possible, one would prefer to stage the combustion process. Staging is accomplished when the fuel is first mixed and burned in a manner known as "rich" (i.e., having a small amount of air) and then mixed and burned with secondary air that is "lean" (i.e., having a lot of air). By doing this, the engine can operate with a much lower overall fuel to air ratio than would have been permitted if all the fuel was mixed with all the air at once and burned. In addition, the mass flow rate of air needs to be as high as possible so that the leanest combustible mixture will be used. However, this makes it difficult for the combustor to maintain a stationary flame and would cause the engine to operate roughly or even extinguish the flame. The average velocity of the reactants in the combustor is around 30 meters per second (m/s), but for combustion to occur, a decrease to at least 8 m/s is necessary to maintain a stationary flame. This is accomplished by creating swirling regions inside the combustor using cooling (bypass) air. An igniter initially ignites the fuel-air mixture in the combustion chamber and once the igniter is lit, it stays lit similarly to a pilot light on a gas stove. The fuel-air mixture speeds past the flame and is combusted. To make an engine run more efficiently (which will also tend to reduce HC and CO emissions), fuel must be combusted lean and at a high temperature. But these high temperatures contribute directly to the formation of NO_x.

Three types of combustion chambers used today are the annular combustor, the can or tubular combustor, and the can-annular combustor. Figure 10 shows schematics of all three types. Each type employs some sort of diffuser to slow air leaving the compressor from speeds of 100-150 m/s to 20-30 m/s and swirl vanes to further slow the air and improve mixing by creating a turbulent region. Both of these tactics improves combustion efficiency.

The can or tubular type of combustor offers the easiest control over the fuel-air ratio and is the simplest and least expensive to repair. Unfortunately, its many components tend to be relatively large and heavy, it doesn't burn as efficiently, and doesn't ignite as easily as the annular designs. In addition, can combustors have high pressure losses. This design is hardly used in current large gas turbines due to these drawbacks.

Can-annular chambers (Figure 11) have the easiest ignition, least total cross-sectional area, least pressure drop, and least length and weight. It can be difficult to have a uniform fuel-air ratio and outlet temperature and it is very expensive to repair. When the outer surface of the chamber liner expands, it can induce a heavy buckling load.

Annular combustors (Figures 12 and 13) present less ignition problems than can-annulars and will have a lower pressure drop.

Pressure drops for all three types of combustors are typically 5-7%. This design will also offer the best control of the fuel-air and outlet temperature distribution. This means it will give you the best combustion.

As the pressure diminishes, dissociation increases producing some well known products: CO, NO, H, OH, O, and N. Oxides of nitrogen formed during high-temperature combustion can stay near equilibrium in the high temperature zone of the combustor, but the rapid cool down afterwards freezes them in a higher than equilibrium concentration. The temperature of the reactants during combustion (T03) is around 400 K (600 F), and after combustion (T04), temperatures can be over 1600 K (2421 F). The higher T04 is, the more efficient the combustion process is, but this temperature is limited by the turbine blades which will melt if the temperature exceeds their capabilities.

2.7 Emissions Control Strategies

Unburned HC and CO emissions are highest at low power settings because turbine engines need high operating speeds and temperatures to have a high combustion efficiency. Unfortunately, as with all combustion processes at high power settings and therefore high temperatures, NO_x emissions are higher.

HC and CO emission control strategies are fairly straightforward. By increasing the pressure and temperature in the combustor more energy is available for combustion. This makes for a more complete burning of the fuel-air mixture. A more complete burning means lower production of hydrocarbons as well as carbon monoxide. The maximum temperature and pressure in the combustor are limited by the materials comprising the combustion liner and turbine blades. By using ceramics and routing bypass air around and into the combustor, the upper limit on temperature and pressure can be extended. A high swirl region is also desirable to promote better mixing of fuel molecules among the air molecules to encourage thorough burning. An increased combustor temperature unfortunately encourages NO_x formation.

The chain of events (Zeldovich mechanism) that leads to NO_x formation is initiated by the dissociation of oxygen. At a high enough temperature, oxygen molecules break into free oxygen atoms which in turn react with nitrogen molecules present in the air forming nitrogen oxide (NO) and nitrogen (N). NO and other nitrogen components that result from combustion are collectively called "NO_x". The reactions which formed NO freeze out (don't act to return to equilibrium concentrations by decomposing NO) after the post-flame region because of the rapid drop in temperature leaving NO_x free to be released into the atmosphere. If the dissociation of oxygen can be prevented, then the series of reactions that form NO_x are less likely to occur. One approach to lowering the combustion temperature is to stage the combustion. Staged combustion involves igniting the mixture at different points as it travels through the combustor. A rich (a lot of fuel) zone is created to facilitate ignition, which then spreads to lean (a lot of air) zones where combustion continues. This gradual burning allows the maximum temperature at any given instant to be lower and allows combustion to occur with a lower overall fuel-air ratio. However, staged combustion produces an unsteady flame, posing a stability problem that is still being addressed by engine designers. In general, pre-mixed, high swirl, staged combustion engines appear to have a good potential to reduce NO_x emissions while also reducing HC and CO emissions.

A June 1995 report of the combined ICAO/Third Meeting of Committee on Aviation and Environmental Protection (CAEP III) technology and certification subgroups, stated that most high thrust turbofan engines, equipped with the best current combustor technology available, could achieve a NO_x level 40 percent below the 1986 ICAO standard. Pratt & Whitney has targeted one of its engine types for installation of a new low-NO_x can-annular combustion chamber. This new chamber is equipped with improved fuel nozzles to optimize mixing, flame temperature, and residence time in the combustion chamber. The airflow in the primary zone would be reduced and shifted downstream from the dilution zone to the secondary combustion zone. This approach results in an enriched primary combustor zone and a rapid secondary combustion zone transition that Pratt & Whitney believes would reduce the formation of NO_x by about 20 percent below the 1986 ICAO standard.

CAEP III also analyzed a number of scenarios ranging from an additional 10 to 40 percent reduction in NO_x standards below the ICAO standard adopted in 1993. CAEP III recommended a 16 percent reduction in NOx standards to the ICAO Council for review, and the Council is expected to make a decision on the recommendation in the Spring of 1997. CAEP III could have recommended any option under consideration including no change from the current 20 percent level. The effective date for any increased stringency is 2000 or 2005 with an assumption of full compliance by 2008 or 2013. The industry may need to apply low-NO_x control technologies, including those outlined below if such a standard is adopted.

The above discussed CAEP III technology and certification subgroup report stated that new technologies under development include Double Annular Combustors (DAC), Axially Staged Combustors (ASC), Rich Burn/Quick Mix/Lean Burn (RQL) and Lean Premix/Prevaporised (LPP) combustors. These low NO_x technologies are being offered by a number of aircraft engine manufacturers.

However, technologies that are used in medium/high thrust engines may not be applicable to small/low thrust engines because of combustor design limitations. According to this report, these new technologies could decrease NO_x by 30 to 40 percent from the 1993 ICAO standard.

Part 3
Description of the Industry

3.1 Commercial Aircraft of U.S.

In 1992, there were almost 7,000 commercial aircraft in the U.S.; worldwide, the total is just over 11,000. These numbers have been growing about 5 to 7 percent every year. Presently, the U.S. commercial fleet consists of more than 25 different aircraft models and 20 different engine families.

Table 1 shows how engines were distributed among the 1993 fleet by engine manufacturer. U.S. companies manufacture a large portion of engines and aircraft. Pratt and Whitney is the largest engine manufacturer worldwide producing 45 percent of aircraft engines, General Electric (11 percent), Rolls Royce (11 percent), CFM International (9 percent), and International Aero Engines (1 percent). Several other companies manufacture the remaining 23 percent. Almost twice as many engines were exported than imported.

3.2 Engine Emissions

Emissions data were collected from the FAA Aircraft Engine Emissions Database (FAEED), AP-42 (EPA), and engine manufacturers for the commercial aircraft fleet and is presented in Table 2. For each engine type, the table shows hydrocarbon (HC) emissions in units of mass of pollutant per unit thrust (Dp/Foo with the units g/kN) and the corresponding EPA HC standard, carbon monoxide (CO) emissions and the corresponding promulgated EPA CO standard and nitrogen oxide (NO_x) emissions and the corresponding promulgated EPA NO_x standards (first- and second-stage NOx standards). The rated output (maximum thrust) or Foo of the engine in kilonewtons (kN), the pressure ratio of the compressor (rPR) (the multiplication factor that the ambient air pressure is increased by as it passes from the entrance of the compressor to its exit) and any miscellaneous notes can also be found on the table. Dp (mass of pollutant) for HC, CO, and NO_x is determined by calculating the total mass of each pollutant after the engine is run through the applicable LTO cycle specified by the EPA. Existing HC standards are applicable only to turbofan and turbojet engines manufactured after January 1, 1984 and the newly promulgated standards for CO and NOx will take effect 60 days after the direct final rule is published (the second-stage NOx standard is effective in 1996 for newly certified engines and 2000 for newly manufactured engines, but the standard is not federally enforceable until 60 days after the rule is published).

Dp/Foo for a particular pollutant (e.g., HC) is found by multiplying the HC index by the product of the fuel flow and the time in mode (TIM) divided by one thousand. This value summed over the 4 or 5 operating cycles is the Dp value. This number divided by the maximum thrust the engine can provide, Foo, generates a value for the Dp/Foo.

Most of the in-use engines exceeding HC standards were manufactured before 1984 making them exempt from standards. These engines make up almost 50 percent of the current in-use population. Available data suggests that all engines except two meet EPA's promulgated NO_x standard. According to the manufacturers, plans are already underway to bring these two engines into compliance. Also, available data suggests that all engine types subject to the promulgated CO standard meet that standard. Table 2 lists commercial aircraft engines, their emissions performance and emissions standards. There are three engine types for which no data was available.

Part 4
Inventory and Impacts

4.1 Aircraft Emissions Inventory

Airports and aircraft are now or are projected to be, significant sources of emissions of NOx and CO in some of the air quality control regions in which the National Ambient Air Quality Standards (NAAQS) are being violated. Table 3 shows that at 16 different airports commercial aircraft emit over 1,000 tons per year of NOx and 2,000 tons per year of CO at the ground level. Currently, aircraft are about 2 percent of the total U.S. mobile source NOx and CO ground level emissions inventory (see Table 4 for commercial aircraft contribution to total emissions inventory). Commercial aircraft emissions are about 70 and 30 percent respectively of these NOx and CO aircraft emissions inventories. Commercial aircraft emissions are a fast growing segment of the transportation sector's emission inventory. This growth in commercial aircraft emissions is occurring at a time when other significant mobile and stationary sources are drastically reducing emissions, thereby accentuating the growth in aircraft emissions. For instance, commercial aircraft in the Los Angeles area will consume about 4 percent of the basin's allowable emissions inventory by 2010, which would be double its current contribution.

4.2 Regulatory Impacts

The DFRM establishes current ICAO standards as U.S. Federal standards. Aircraft engines are international commodities, and thus, they are designed to meet international standards. The rule will have the benefit of establishing consistency between U.S. and international emission standards and test procedures. Thus, an emission certification test which meets U.S. requirements will also be applicable to all ICAO requirements. All engines covered by the DFRM's promulgated federal standards already meet the standards or will meet them by the standards' effective dates. EPA knows of only 2 engine types that do not currently meet all of the standards. Pratt & Whitney and Rolls-Royce, the manufacturers of these two engine types, are already developing improved technology in response to the ICAO standards that match the standards adopted in the DFRM, and EPA does not believe that the costs incurred by the aircraft industry as a result of the existing ICAO standards should be attributed to the DFRM regulations. Also, the test data necessary to determine compliance are already collected by manufacturers during current engine certification tests. Therefore, EPA believes that the promulgated regulations will impose no additional burden on manufacturers.

The existence of ICAO's requirements results in minimal cost as well as air quality benefits from the DFRM promulgated requirements. Since aircraft and aircraft engines are international commodities, there is some commercial benefit to consistency between U.S. and international emission standards and control program requirements (i.e., easier to qualify products for international markets since FAA can certify engines for ICAO compliance).

Part 5
Military Engines

5.1 Introduction

Historically, military aircraft engines have been exempt from EPA's emissions standards. As part of a renewed effort that EPA has taken to examine aircraft emissions, we have begun to examine previously unregulated sources of emissions including military aircraft emissions. This part presents the results of EPA's evaluation of the emissions status of military aircraft engines.

5.2 Limitations of the study

Our evaluation of military aircraft engine emissions examined 26 military aircraft engines that are in service today and for which emissions data is available. Table (5) shows many engine characteristics, most notably emissions levels, for each engine. Emissions data were received from three different sources: the EPA's *Procedures for Emission Inventory Preparation Volume IV* (AP-42); the U.S. Air Force Armstrong Labs (AL); and the U.S. Navy Aircraft Environmental Support Office (AESO). There were some differences in the data from source to source. The fundamental difference between the sources is that AP-42 reports emissions data in index form (pounds of pollutant per thousand pounds of fuel), whereas AL and AESO report them in rate form (pounds of pollutant per hour); all were converted to grams. Also, AP-42 only reports data on the four engine modes required by the EPA to determine emissions levels, while AL and AESO data generally had more than these four. To resolve this problem, EPA chose data from the four modes which were closest to the four required by ICAO and EPA.

The table consists of two parts. The first part shows calculations based on AP-42 data and the second on AL/AESO data. Data from AP-42 took priority, so AL/AESO data were used for engines that were not reported in AP-42.

5.3 Calculations and Results

Table 5 presents the engine type along with its assigned aircraft and mission, maximum thrust in kilonewtons (kN), compressor pressure ratio (PR), engine modes and respective time in modes (TIM). TIMs come from Table 5-1 in AP-42 and are dependent on which branch of the military in which the aircraft is in service as well as its primary mission (combat, transport, or trainer). Fuel flows and emissions indices at each power setting or mode are also presented.

For the AP-42 data, EPA calculated Dp (lb) or mass of pollutant in pounds by multiplying an emissions index times the fuel flow times the TIM (in minutes) and dividing by one thousand. The conversion from Dp (lb) to Dp/Foo (g/kN) involves multiplying Dp (lb) by 454 to convert pounds to grams and dividing Dp by the maximum thrust of the engine (Foo) from the second column of the table.

For the AESO data, calculations for Dp (lb) were more straightforward. Multiplying the emissions rate times the TIM (min) and dividing by 60 produces Dp (lb). Once again, to go from Dp (lb) to Dp/Foo (g/kN), one should multiply Dp (lb) by 454 and divide by the maximum thrust of the engine.

Current EPA standards limit HC Dp/Foo (mass of pollutant per kilonewton thrust) values to 19.6 grams per kilonewton (g/kN) and promulgated EPA standards limit CO Dp/Foo values to 118 g/kN and NO_x Dp/Foo values to 40 + 2 x Pressure Ratio in the first stage and 32 + 1.6 x Pressure Ratio in the second stage. Figures (1) and (2) illustrate graphically how military engines stand with respect to current and possible future standards. According to Figure 1, 18 out of 26 engines in the study (69.2 percent) exceeded the HC standard and 8 out of 26 engines or 30.8 percent exceeded the CO standard. The 8 engines that exceeded the CO standard were above the HC standard as well. Figure 2 shows how the engines stood with respect to two NO_x standards, the first-stage NOx standard and a 20 percent reduction of this standard for the second-stage NOx standard. Only 24 out of 26 engines are represented in this figure since pressure ratios for two of them were not available. Of the remaining 24, none exceed the current ICAO NO_x standard and only 1 out of 24 or 4.2 percent would exceed a 20 percent reduction in the standard. Of the two engines for which no pressure ratios were available, only one is expected to exceed the new ICAO standard. The other should be below both NO_x standards.

Part 6
Conclusion

Available data on commercial aircraft engine emission levels suggest that all but two affected engines currently meet the promulgated CO and NO_x standards. The manufacturers of these two engines are developing improved technology in response to the ICAO standards approved in 1993 and are expected to comply with the ICAO standards, as well as EPA promulgated standards, by their effective dates. Therefore, minimal costs as well as air quality benefits are realized from the implementation of the emission standards adopted in association with this document. Furthermore, since manufacturers already collect all the data necessary to determine compliance, the DFRM will impose no additional burden on manufacturers.

Military aircraft have historically been unregulated. From a brief study in which all military engines were weighted equally, it was determined that military engines contribute greatly to aircraft HC emissions and slightly to CO and NO_x emissions. They exceeded the HC standard by over 250 percent, the CO standard by 98.3 percent, and the NO_x standard by 0.7 percent on average.

Appendix

(Appendix not available in this electronic version of document)

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