POLLUTANTS PRODUCTION SCENARIOS IN AIRCRAFT TURBOFAN ENGINES

Abstract Aircraft engines produce emissions that are similar to other emissions resulting from fossil fuel combustion. However, aircraft emissions are unusual in that a significant proportion is emitted both in different altitudes and in large quantities. These emissions give rise to important environmental concerns regarding their global impact and their effect on local air quality at ground level. International Civil Aviation Organization (ICAO) is the specialized agency with authority to develop standards and recommended practices regarding all aspects of international aviation. This present work intends to shows one general scenario about aircraft emissions. The whole data were obtained through ICAO data sheets. While the emissions measurements were obtained for a reference landing and take-off (LTO) cycle below 915 meters of altitude (3 000 ft), but they also help how reference to limit emissions at higher altitudes.

1. INTRODUCTION

International Civil Aviation Organization (ICAO), established by the Chicago Convention in 1944, is the specialized agency with authority to develop standards and recommended practices regarding all aspects of international aviation. Among its functions are the certification of standards for emissions and noise. Additionally, it is the organization responsible to ensure that such objectives are met on an internationally harmonized level, as far as possible. Today, there are 185 membership countries, among these, Brazil. (ICAO, 2006).

In fact, aircraft are required to meet the engine certification standards adopted by the Council of ICAO. These are contained in *Annex 16 — Environmental Protection, Volume II — Aircraft Engine Emissions* in the Convention on International Civil Aviation. They were originally thought to respond to concerns regarding air quality in the vicinity of airports. As a consequence, they establish limits for emissions of oxides of nitrogen (NO_x), carbon monoxide, unburned hydrocarbons for a reference landing and take-off (LTO) cycle, which is below 915 meters of altitude (3 000 ft). There are also provisions regarding smoke and vented fuel. The standards are based on an aircraft's LTO cycle but they also help to limit emissions at altitude. Of particular relevance is the standard for NO_x, a precursor for ozone, which at altitude is a greenhouse gas. The standard for NO_x was first adopted in 1981, then were made more stringent in 1993, when ICAO reduced the permitted levels by 20 per cent for newly certificated engines, with a production cut-off on 31 December of 1999. In 1999, the Council further tightened the standard by about 16 per cent on average for engines newly certificated from 31 December of 2003 onwards.

Since that the whole data analyzed were about turbofan engines, in the following paragraph we present one brief summary that intends to show the place of this type of engine in the aviation world and its usual performance parameters.

2. TURBOFAN AND PERFORMANCE PARAMETERS

Jet engines today are of two dominant forms, the low-bypass and high-bypass types. See Fig. 1. The high-bypass type gains its thrust from a jet-driven propeller called the fan, and has a large frontal area and diameter. It is suitable for commercial planes when installed under the wings. The low-bypass type is more like a rocket that gains thrust by emitting hot gas out the back. It is long and thin, and is suitable for mounting inside the fuselage of a combat jet. The cockpit of such a plane is mounted ahead of the engine. A high-bypass engine could not be mounted in this way in a fighter jet. It is also more difficult to rapidly change the RPM and thus the thrust of a high-bypass engine as it is required by combat maneuvers. For a history of these engines, see Smith and Mindell (2000).

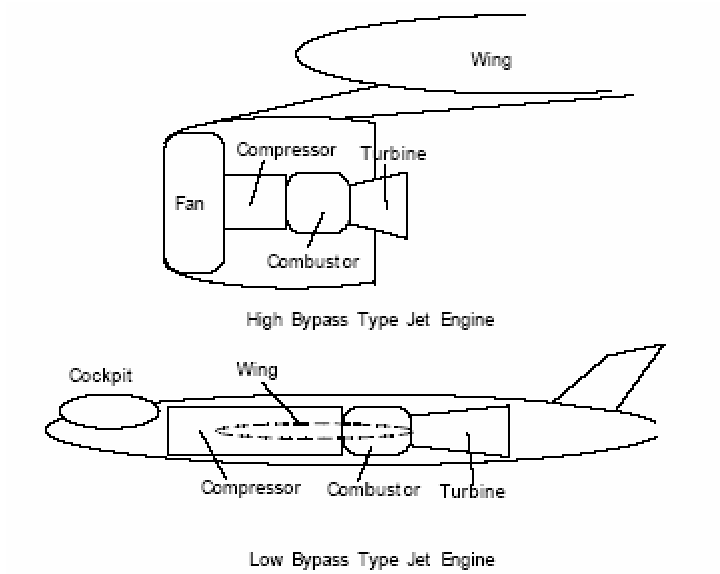

Figure 1: Schematic Comparison of Architectures of Two Types of Jet Engines (Crawley et al, 2004)

Figure 2 below presents one more illustration, a turbofan schematic drawing:

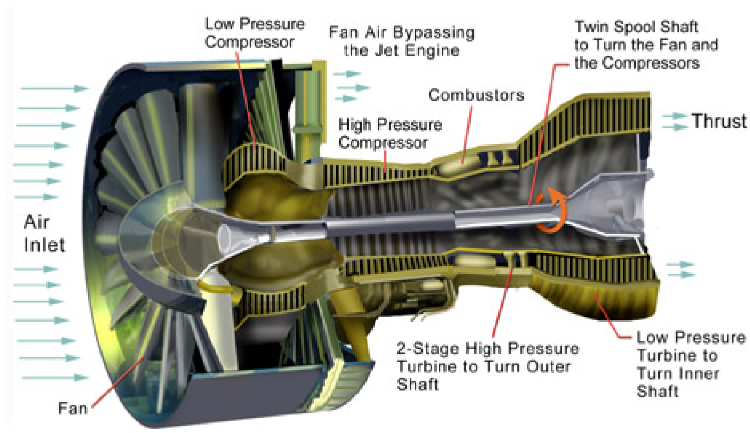

Figure 2: A typical high bypass-ratio turbofan (Adapted from Pratt & Whitney, MIT Notes Lectures (2005)).

For a propulsion system there are two interesting performance parameters, one is the force that it produces (*thrust*, *T*) and other is the overall efficiency which it uses energy to produce this force $(h_{overall})$. Thrust seems clearly self-explanatory, whereas the overall efficiency includes both thermal efficiency and propulsive efficiency.

Figure 3 shows the trend in aircraft engine efficiency.

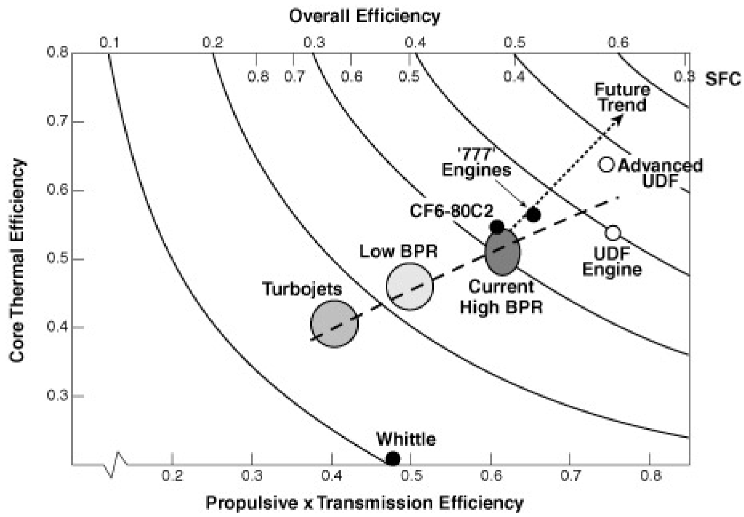

Figure 3: Trends in aircraft engine efficiency (after Pratt & Whitney).

Thermal efficiency is driven by the increase in compression ratios and its corresponding increase in turbine inlet temperatures. Figure 4 presents several commercial engines and their corresponding pressure ratios. Pressure Ratio is defined as the ratio between the mean of the total pressure at the last compressor discharge plane with respect to the mean of the total pressure at the compressor entry plane, when the engine is developing its take-off thrust rating (in ISA sea-level static conditions).

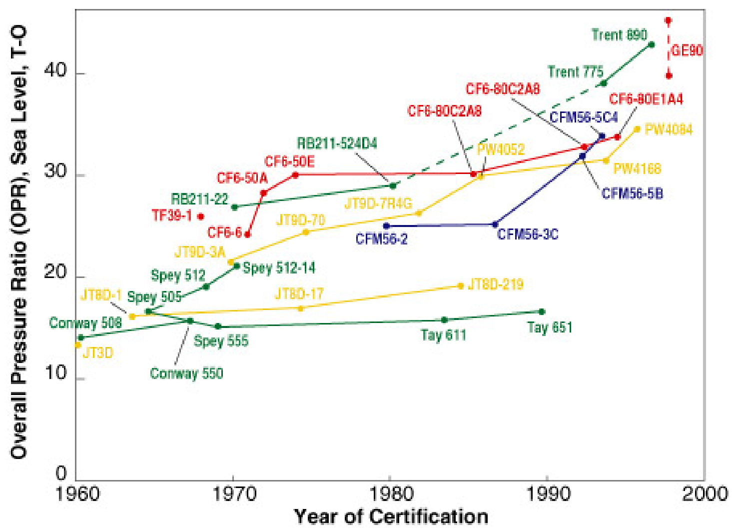

Figure 4 Pressure ratio trends for commercial transport engines (Jane's, 2001).

Trends in propulsive efficiency are due to generally higher bypass ratio engines. By-pass ratio is the ratio of the air mass flow through the by-pass ducts of a gas turbine engine to the air mass flow through the engine core, calculated at maximum thrust when the engine is stationary in an international standard atmosphere at sea level. Figure 5 shows Bypass ratio versus Cruise Fuel Consumption (TSFC), which is the ratio between mass of the burned fuel and the thrust delivered (in time), in fact it is the measure of jet engine effectiveness at converting fuel to useable thrust.

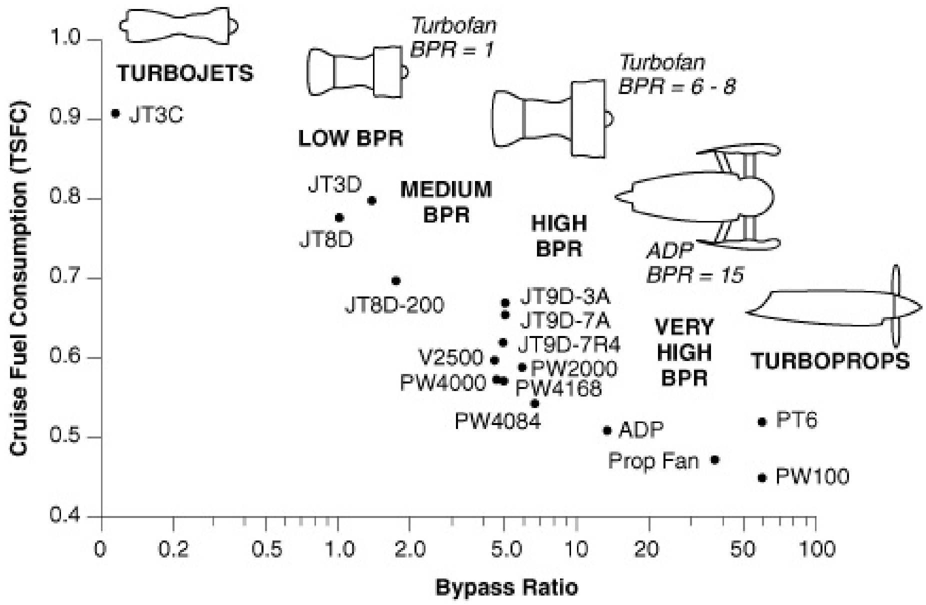

Figure 5: Trends in engine bypass ratio (Jane's, 2001)

The aircraft emissions are the subject of the next session.

3. AIRCRAFT EMISSIONS

Like most transportation vehicles, aircraft engines emit a variety of pollutants when burning fuel. Among important emission species are CO2 (carbon dioxide), NOx (nitrogen oxide), CO (carbon monoxide), SO2 (sulfur dioxide), VOCs (volatile organic compounds), CH4 (methane) and particulates.

In addition, aircrafts have one particularity, their altitude range. Most present-day jet aircraft cruise in an altitude range (9-13 km) that contains two well-defined atmospheric regions, the stratosphere and troposphere, and the one situated in the transition between them, the tropopause. Each of these regions is characterized by different dynamics and photochemistry.

As stated before, in present works the pollutant emissions are considered during the so-called LTO cycle. Landing/Take-Off (LTO) Cycle is a reference cycle for the calculation and reporting of emissions, composed of four power settings and related operating times, for subsonic aircraft engines simulating situations near and at an airport (ICAO, 2006). The specified cycles with duration and loads are in Table1.

Table 1 - LTO cycle specified by ICAO for measuring emissions during aircraft engine tests

Phases	Load (%)	Time (minutes)
Take off	100	0.7
Climb out	85	2.2
Approach	30	4.0
Idle (Taxi in and Taxi out)	7	26

LTO cycle is confined to the so-called atmospheric boundary layer (up to 1 km), through which pollutants are mixed back down to ground level in a few days. Figure 5 shows a schematic view of the cycle.

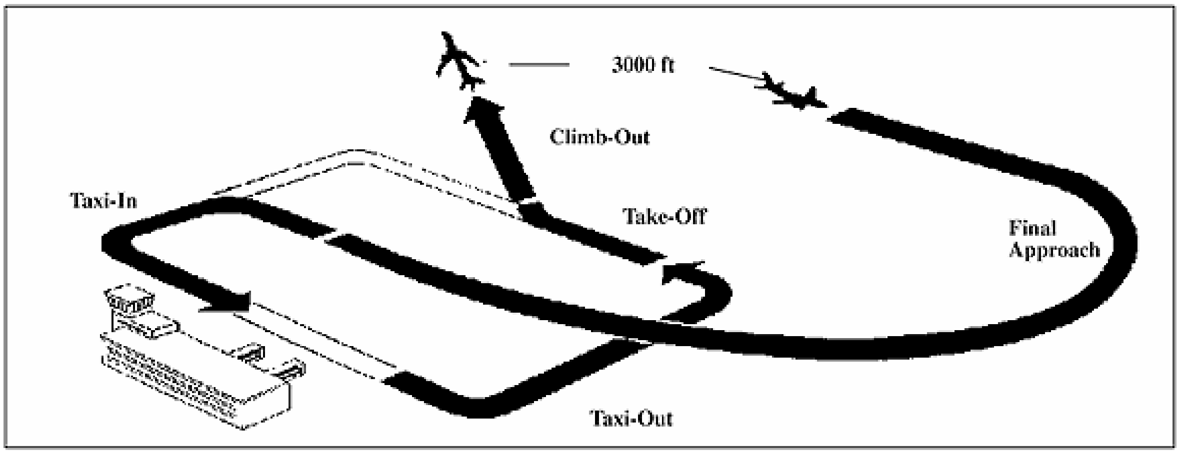

Figure 5: LTO cycle representation, ICAO.

According to Archer (1993) and NLR (1997), the major share of CO, particles and VOCs is emitted during the LTO, but this is not true for NOx. However, given the limited lifetime of NOx, FPC (1998) concludes that only a small part of NOx emissions emitted at higher altitudes will reach ground levels. Therefore, considering only LTO emissions in the assessment of the contribution of air transport to local air pollution is justifiable.

4. METHOD DESCRIPTION

The data was obtained in the Aircraft Engine Emissions Home Page (2006). According to the home page notice, this DataBank contains information on exhaust emissions only of those aircraft engines that have entered production. Additionally, the whole information was provided by engine manufacturers, who are solely responsible for its accuracy. There are available data of the Allied Signal, Allison Engine Company, AO Aviadgatel, BMW Rolls-Royce GmbH, CFM International, GE Aircraft Engine, Rolls Royce Corporation, International Aero Engines, KKBM, Pratt & Whitney Aircraft Group, Textron Lycoming, and ZMKB manufactures.

Each engine data test was executed by one of three different motivators: Pre-regulation, Certification and Revised. Pre-regulation is the data obtained on engines generally prior to the promulgation of the Standards of Annex 16, Volume II, and for which the manufacturer was not required to apply for emissions certification, whereas Certification means data which have been submitted for certification approval after the applicability dates or which have been obtained at an earlier date, generally after the promulgation of the Standards of Annex 16, Volume II, with the intention of finally gaining approval, and finally, Revised is the denomination regarding existing data which have been modified, and which do not require the engine to be re-certificated.

Figure 6 presents part of one data sheet. Note the values of LTO Total Fuel (kg) and emissions (g). In this example, average of HC, CO e NOx emissions are 3.4, 16.2 and 15.6 respectively.

ICAO ENGINE EXHAUST EMISSIONS DATA BANK

SUBSONIC ENGINES

ENGINE IDENTIFICATION:	CF6-80C2A3	BYPASS RATIO:	5.1
UNIQUE ID NUMBER:	1GE018	PRESSURE RATIO (π_{oo}):	31.64
ENGINE TYPE:	TF	RATED OUTPUT (F_{oo}) (kN):	262.22

MEASURED DATA

MODE	POWER SETTING (%F_{oo})	TIME minutes	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg) HC	CO	NOx	SMOKE NUMBER
TAKE-OFF	100	0.7	2.457	0.06	0.58	34.5	7.8
CLIMB OUT	85	2.2	2.003	0.08	0.56	25.46	-
APPROACH	30	4.0	0.649	0.19	2.07	9.93	-
IDLE	7	26.0	0.202	8.94	41.51	3.92	-
LTO TOTAL FUEL (kg) or EMISSIONS (g)			838	2874	13611	13074	-
NUMBER OF ENGINES				2	2	2	2
NUMBER OF TESTS				3	3	3	3

Figure 6 - Data sheet segment: frame with Identification Engine and Measured Data

This work concentrated the analysis in the seven manufactures first mentioned. Table 2 shows their characteristics and the number of data sheets analyzed. This number corresponds to at least one engine. Note, for example, at Figure 6, that 2 engines were tested.

Table 2: Quantity of turbofan engines analyzed by manufactures

Manufactures	Out of Production	Out of Service	In Production / In Service
AO Aviadgatel	5		
Allison Engine Company			3
Allied Signal		2	
BMW Rolls-Royce GmbH	4		6
CFMI	7		25
GE Aircraft Engine	53		60
Rolls Royce Corporation			21

5. RESULTS AND DISCUSSIONS

The data is presented separated in two series, the engines that are 'IN PRODUCTION / IN SERVICE' and the others that are 'OUT OF PRODUCTION'. The 'OUT OF SERVICE' engines with only 2 data sheets available (see Table 2) were discarded because it is impossible to yield some comparative or even qualitative results with numbers this small.

Pressure and By-pass Ratio is already defined. Emission Index is defined as the mass of material or number of particles emitted per burnt mass of fuel, for NO_x in g of equivalent NO_2 per kg of fuel; for hydrocarbons in g of CH_4 per kg of fuel whilst Rated Output is the maximum thrust available for take-off under normal operating conditions at ISA sea level static conditions without the use of water injection, as approved by the certificating authority. Thrust is expressed in kiloNewtons.

The whole data was placed with the same ordinate scale (EI, g/kg). This allowed both visualization and comparison easy. Abscises are the Pressure Ratio, By-pass ratio and Rated Output with their suitable scale.

Comments made in Section 2 showed trends about the thermal, propulsive and overall efficiency. Overall efficiency is the product of thermal and propulsive efficiency, so its behavior is set by the behavior of the thermal and propulsive efficiency.

The trends in thermal efficiency are driven by the increase in compression ratios and its corresponding increase in turbine inlet temperatures. It is clear that for a given turbine inlet temperature, there is a compressor pressure ratio that maximizes the work per unit of airflow. Here, only the pressure ratio is considered as an indicative of thermal efficiency, whereas Bypass Ratio and Rated output will be used as propulsive efficiency indicators.

Figures 7 to 9 present the results. Considering the higher data concentration, it can be observed that the EI range of HC < 10 g/kg, NOx were 10-25 g/kg and CO stayed in range of 5-35 g/kg of fuel burned.

Higher cycle pressure ratios lead to improved engine fuel efficiency. However, in spite of this, when the compressor delivery/combustor inlet air temperature rises, by a certain amount, yields one collateral effect, which is the reduction of the cooling capacity of the air. A greater proportion of the total airflow is then needed to cool the hottest parts (blades, liner, etc.). Consequently, this demand reduces airflow available for primary combustion and dilution, making it more difficult to control turbine inlet temperature profiles and emission levels. This cycle of primary and secondary problems, which stem from the increase in the engine pressure ratios, can be observed in both the results graphs showed in Fig. 7. NOx emissions clearly raise starts at the 25 Pressure Ratio value. CO emission values present major dispersion, although a general observation could be made as to how some decrease with the Pressure Ratio increase.

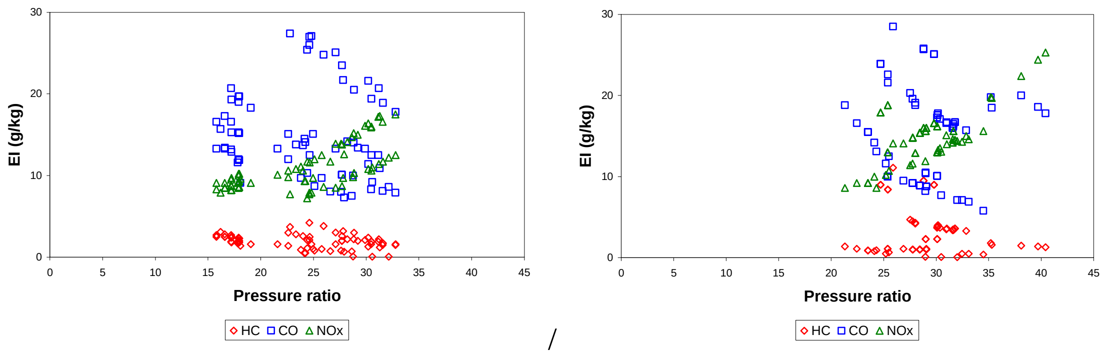

Figure 7: Emission Index versus Pressure Ratio for
(a) 'In Production / In Service Engines' and (b) 'Out of Production' Engines.

Increasing the bypass ratio clearly offers the prospect of further increases in propulsive efficiency. The sensibility of NOx emission seems lower than that for Pressure Ratio.

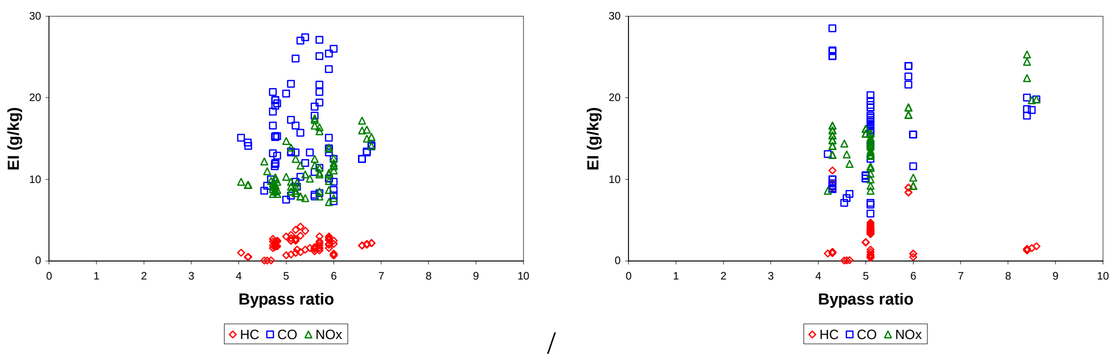

Figure 8: Emission Index versus By-pass Ratio for
(a) 'In Production / In Service Engines' and (b) 'Out of Production' Engines.

NOx emission has three main routes of production: via thermal or Zeldovich prompt and fuel-NO mechanisms. Each one has different characteristics that are more easily found under determined burning conditions. Here, deep considerations were not made about any of these routes. There is some consensus that the production of NOx is dependant on turbine entry temperature, fuel-air ratio and combustion pressure. As higher the values of these parameters, greater is the NOx produced in the combustion process. These parameters increase with engine power output; hence an increase in NOx with an increase on engine power output will be expected. This behavior is know to be true only between 50 - 200 kN, and above 300 kN, up to 50 kN it seems to maintain an almost constant value and the same behavior is observed between 200 - 300 kN.

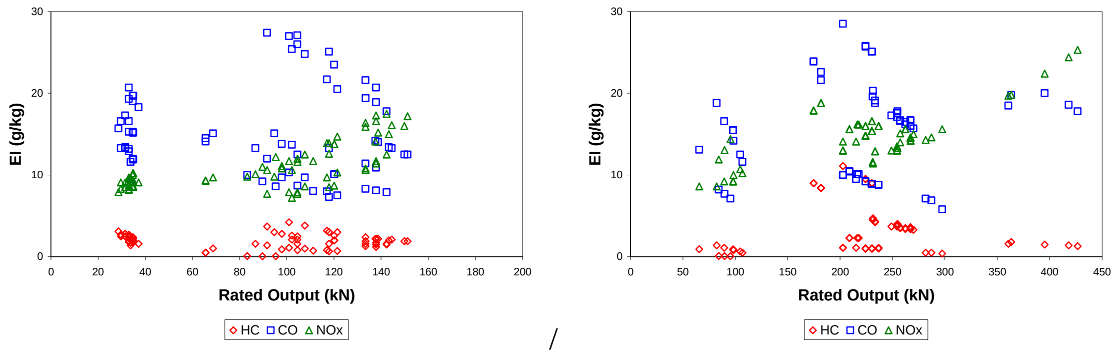

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Figure 9: Emission Index versus Rated Output for
(a) ‘In Production / In Service Engines’ and (b) 'Out of Production' Engines.

Table 3 shows a summary of the tendency of each EI pollutant versus engine performance parameters.

Table 3: Resume of Emission Index with engine performance parameters

Rated output (kN)	EI NOx	EI CO	EI HC
< 50	no effect (~ 8,5 g/kg)	no effect	no effect
50 - 200	increase	not well defined	slight decrease
200 - 300	no effect (~ 15,5 g/kg)		
> 300	increase		
Pressure Ratio			
15 - 25	no effect (~ 15 g/kg)	no effect	no effect
25 - 40	increase	decrease	decrease
Bypass Ratio			
4-7	slight increase	slight increase	slight decrease
7-9	increase	not well defined	not well defined

CONCLUSION

Due to the availability of LTO emissions information being greater than the information on emissions during cruise, all data obtained was for this cycle only. It showed the evaluation of NOx, CO and UHC emissions. All data was obtained though ICAO data sheets. Aircraft designers have one main requirement, which is safety. Following this primary concern is the necessity of one acceptable system concerning both efficiency and environmental requirements for transport, from ground level to the demanding conditions associated with high-speed flight at high altitudes.

The intent of this work is to show a summary, not complete considerations, about emission scenarios in aircraft turbofan engines.

5. REFERENCES

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