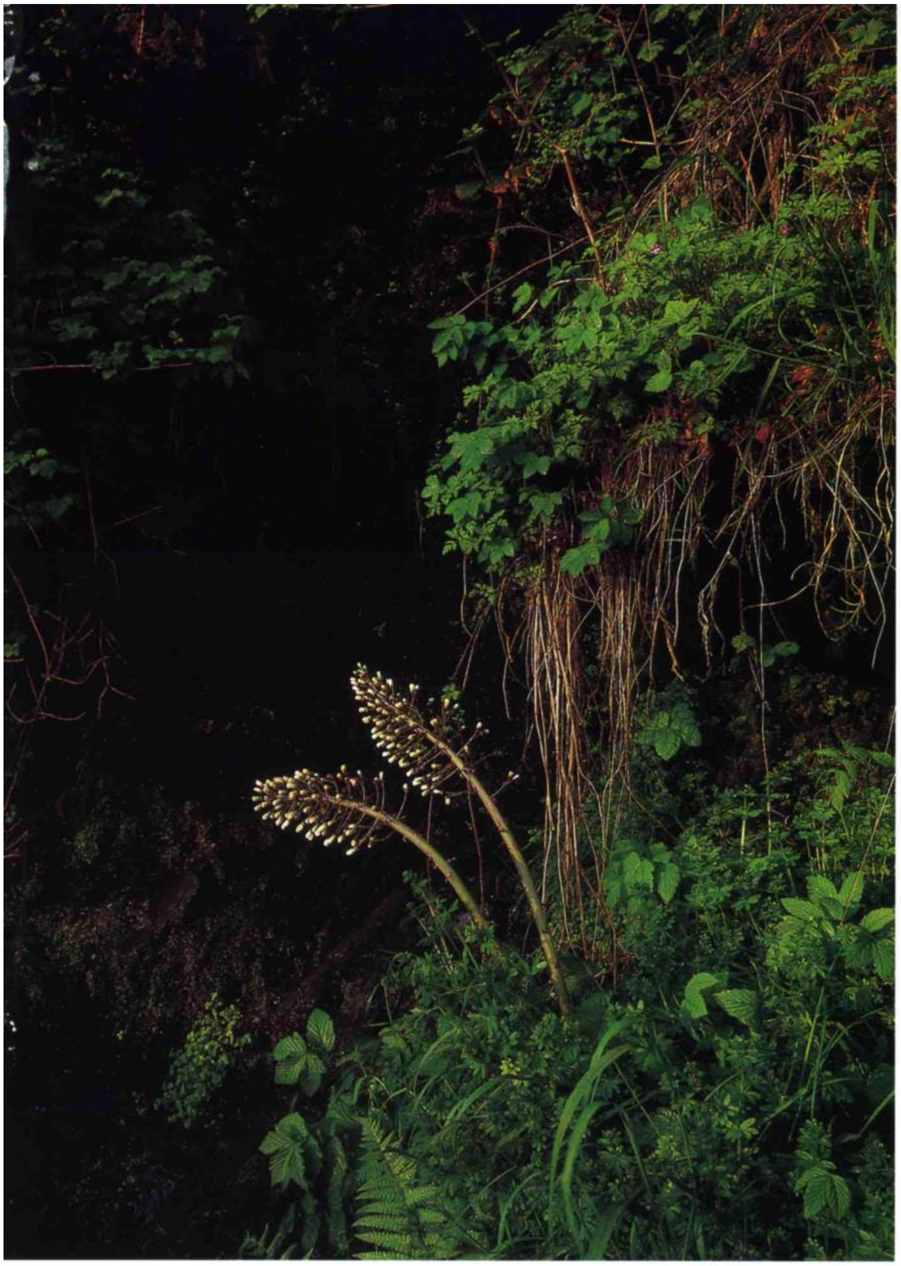
TECHNICAL SUPPLEMENTS

Additional Information on How Aviation Affects the Environment



A Noisy Discussion

Planes are getting quieter but they will never be silent.

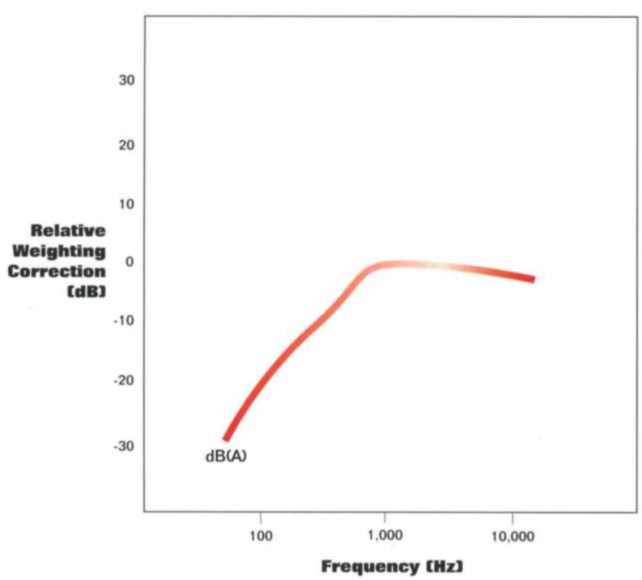
Today, the effects of aircraft noise are limited to the areas immediately surrounding airports and to the flight paths used for approach and departure. Because Luxembourg airport is located close to the city and in the midst of residential and industrial areas, reducing aircraft noise has been an important goal for both Luxair and Cargolux.

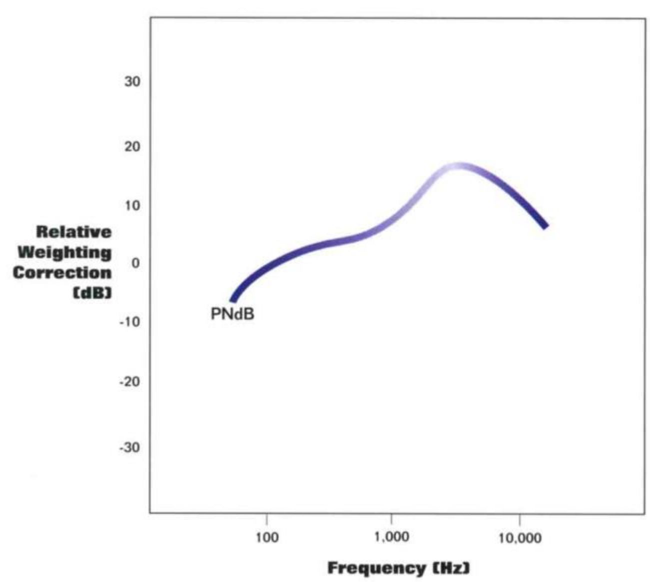
Noise values played an important role in selecting new B737 passenger jets and B747 freighters for the fleets of both carriers. It was important not only to meet, but to exceed, the legal noise standards.

Aircraft noise has been regulated for over 25 years. Even though each new aircraft type put into service was quieter than its predecessors, some communities near airports experience greater noise due to (1) increased operational frequencies as a result of the overall rise in air traffic, (2) growth of residential housing near airports, and (3) greater sensitivity and public awareness of environmental problems.

The air transport industry has an enviable record of applying technology in search of the quietest practical aircraft. Few industries other than aviation support comparable environmental protection policies, levels of investment, and research.

TWO PROFILES COMPARING THE SOUND INTENSITY CORRECTIONS FOR THE HUMAN EAR (LEFT) SHOWN IN dB(A) AND FOR AIRCRAFT NOISE (RIGHT) SHOWN IN PNdB





Measuring Loudness

Noise is measured in bels. A bel (B) is the logarithm of the ratio of measured loudness compared to a standard reference, which is defined mathematically as a minimal perceivable loudness. Since the difference between barely audible and unbearably loud is 1,000 billion times, physicists need to use a logarithmic scale to express loudness.

A decibel (dB) is one-tenth of a bel. On the log scale, sound pressure doubles with each 3 dB. Although 3 dB may not sound like much, a noise measuring 80 dB will sound twice as loud as one measuring 77 dB.

It is important to remember also that through the basic nature of a logarithm, each 10 decibels represent a multiplication factor of 10. So, 95 dB is 10 times louder than 85 dB, 100 times louder than 75 dB, and 1,000 times louder than 65 dB.

In the early 1960's the International Standards Organization recommended the use of the A-weighted sound pressure level known as dB(A). This unit emphasizes medium and high frequencies in a way that coincides with the response of the human ear. It is used most often for audio measurements and to describe consumer electronics.

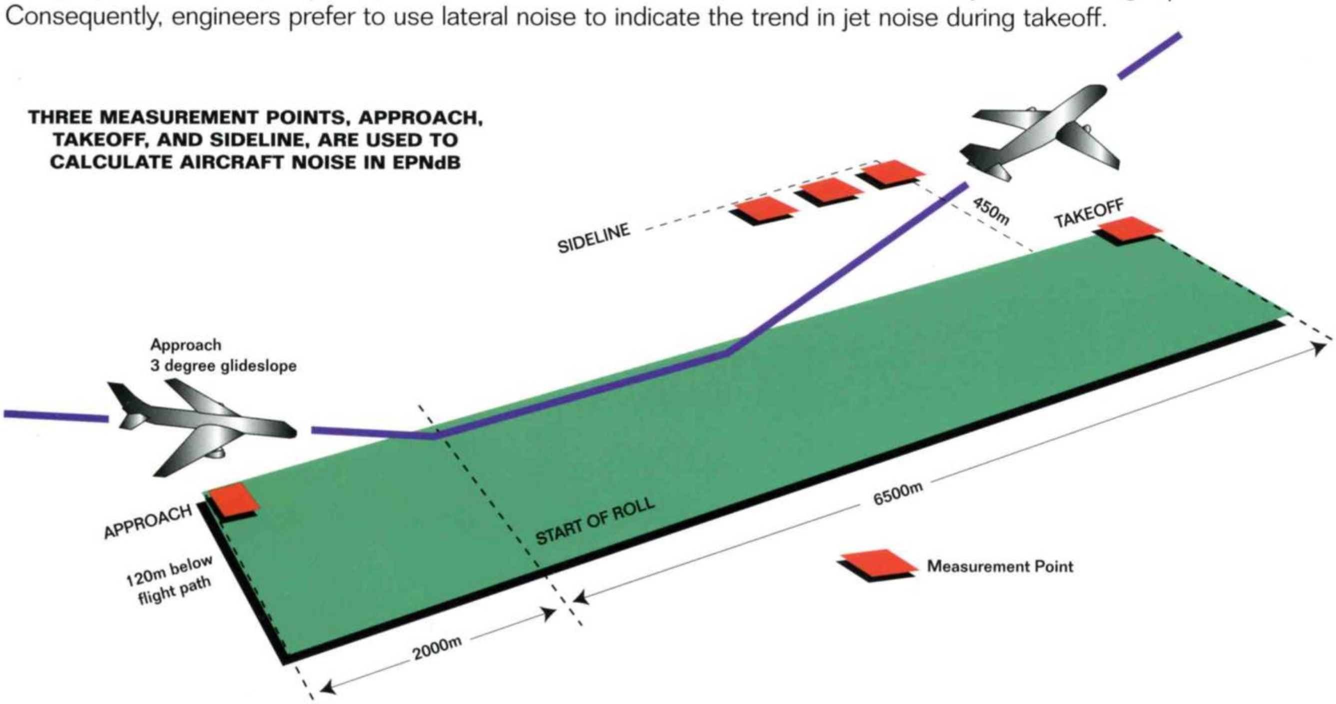
However, aircraft noise contains many high frequencies that are especially annoying. So engineers introduced a measurement called the perceived noise level PNdB that emphasizes this part of the sound spectrum.

For the purpose of aircraft certification, engineers took an additional step and defined a unit of effective perceived noise level called EPNdB. This measurement takes into account the typical frequencies and durations of the sounds generated by aircraft.

Sound technicians measure aircraft noise in dB(A) at three points around an airport (see figure below) and then convert the values to EPNdB: (1) under the approach at a point on a line extended 2,000 meters from the runway, (2) under the takeoff on a line extended from the runway to a point 6,500 meters from the start of the takeoff roll, and (3) laterally at a point 450 meters from the runway centerline where noise is loudest during takeoff.

Most of the noise during the approach is generated by the engines and the landing flaps and is heard in front of the aircraft. Noise heard laterally comes mainly from jet exhaust. Jet noise also dominates during takeoff. But the variety of flight profiles used by departing aircraft makes it difficult to measure noise accurately under the flight path. Consequently, engineers prefer to use lateral noise to indicate the trend in jet noise during takeoff.

THREE MEASUREMENT POINTS, APPROACH, TAKEOFF, AND SIDELINE, ARE USED TO CALCULATE AIRCRAFT NOISE IN EPNdB



LIMITS AND CERTIFICATION

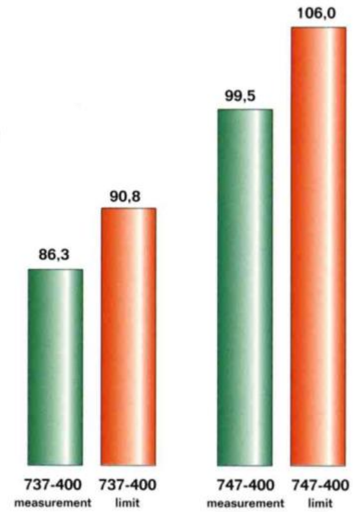
The United States Federal Aviation Administration (FAA) implemented the first national noise limits for certifying commercial aircraft in 1969. The International Civil Aeronautics Organization (ICAO) adopted similar rules in 1971. The ICAO directives, Volume 1, Part 2 of Annex 16 identify two loudness categories for aircraft: Chapter 2, and Chapter 3. The FAA makes roughly the same distinctions but calls them Stage 2, and Stage 3.

The first generation of jets manufactured between 1949 and 1965 were classified by ICAO as non-noise certificated.

Second generation aircraft, certified by ICAO before October 6, 1977, are referred to as Chapter 2 aircraft throughout most of the world. They produce a fraction of the noise of first generation aircraft.10 The old and still noisy Chapter 2 aircraft are scheduled to be phased out of airline fleets in Europe by April 1, 2002 and in the United States by January 1, 2000.

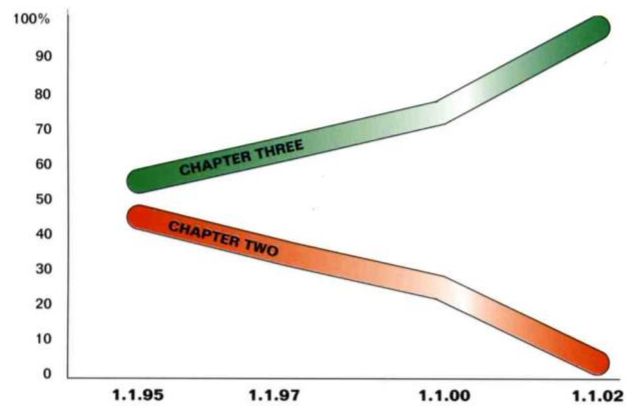
The current generation of aircraft are known as Chapter 3. Aircraft built after October 6, 1977 had to be certificated to meet the stricter Chapter 3 noise limits. Current noise limits vary with the weight of an aircraft and with the number of engines. The transition from Chapter 2 to Chapter 3 reduced the noise by a minimum of 2.5 EPNdB, or to almost half of the previous level.

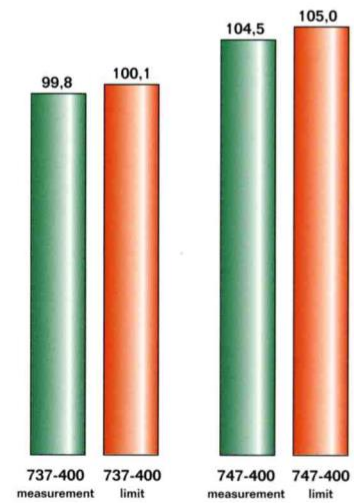
Noise certification standards have successfully contained noise at many airports where they are used to control the level of exposure to aircraft noise in the immediate airport vicinity.



TAKEOFF
(EPNdB)

WORLDWIDE RATIO OF CHAPTER TWO VERSUS CHAPTER THREE AIRCRAFT.

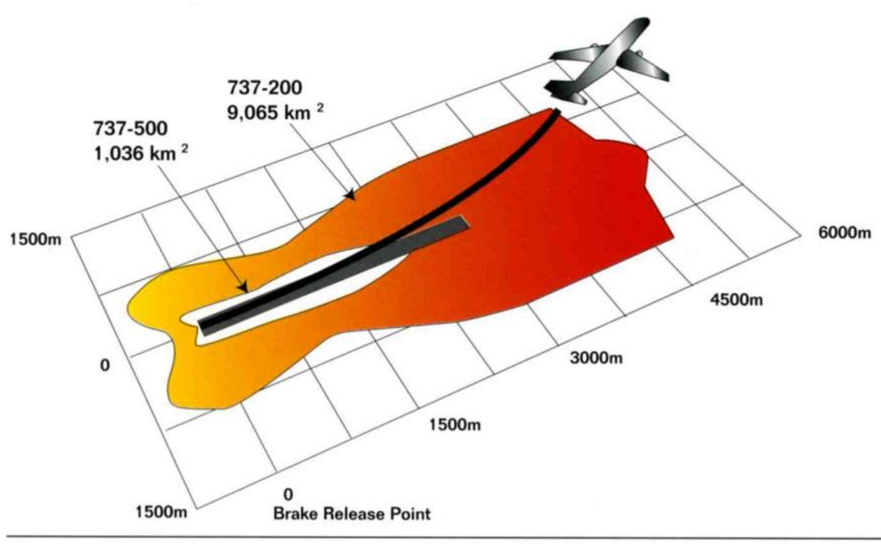


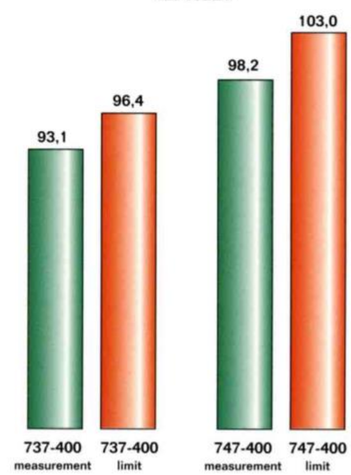


APPROACH
(EPNdB)

HOW TO INTERPRET A NOISE FOOTPRINT

A noise contour connects points of equal loudness. The pattern described by the contour, known as the noise footprint, is usually shown for an aircraft during takeoff. The drawing on this page shows a contour of 85 dB(A) loudness. Inside the contour the sound pressure is greater, outside it is lower.



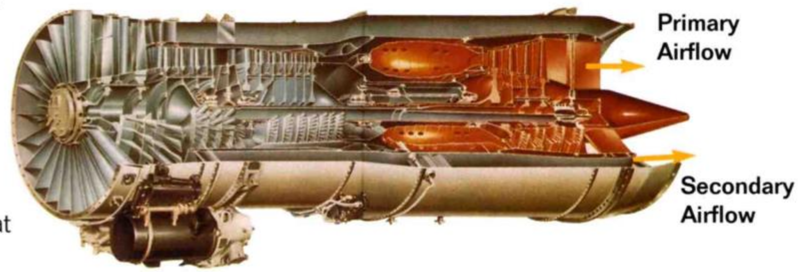


SIDELINE
(EPNdB)

Engine Developments that Reduce Noise

Aircraft have become quieter as a result of changes to jet engine designs that were intended primarily to make them more efficient.

The early JT3D turbofan engine that powered the B707 has the shape of a narrow tube. A fan at the front of the tube draws in air. Approximately half of that air is compressed in the engine, mixed with fuel and burned. Combustion forces the air out the back at high velocity. This hot exhaust stream creates most of the engine thrust and noise. It is called the primary flow.

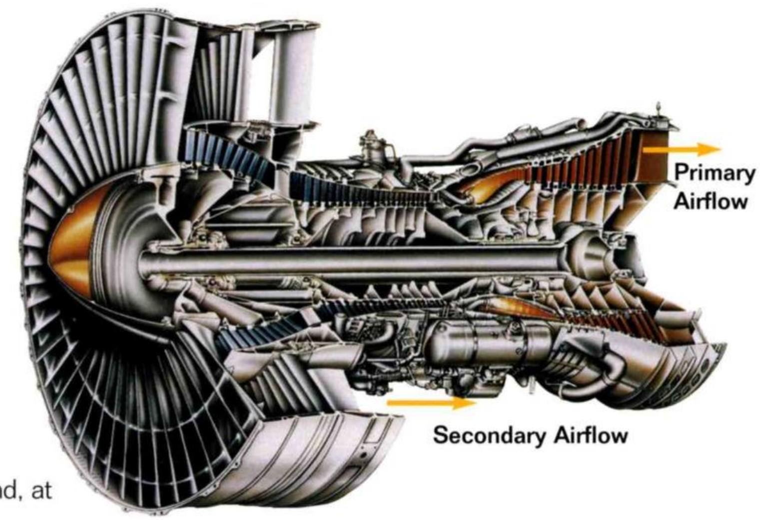


LOW BYPASS ENGINE

The other half of the air does not enter the engine combustors. It bypasses them. The fan pushes it backwards around the outside of the engine components where it acts as a coolant. This secondary flow exits the engine at a lower velocity and produces a smaller part of the engine thrust.

The ratio of the total airflow to the primary airflow is called the bypass ratio. The JT8D engine that still propels the B727, B737-200, and DC-9 has a bypass ratio of just under 2:1.

During the 1960's, engineers developed a more fuel efficient engine that also turned out to be quieter. By increasing the amount of air flowing past the engine, rather than through it, they lowered the average velocity of the exhaust gas stream. This achievement increased the engine's fuel efficiency and, at the same time, the slower moving exhaust gasses produced less noise.

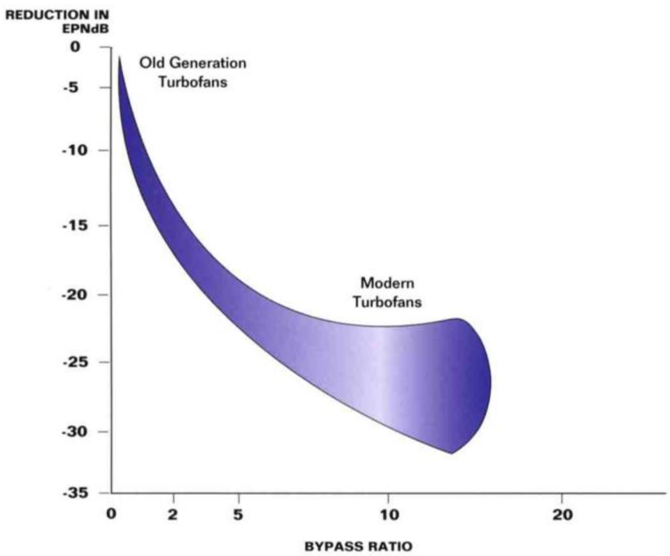


HIGH BYPASS ENGINE

These changes led to a new engine shape that incorporated a larger fan at the front in order to increase the volume and thrust of the secondary airflow. The new design appeared first in the late 1960's in the JT9D engine that was introduced on the B747. It has a bypass ratio of almost 5:1.

At about the same time, engineers improved the aerodynamics of the engine covering, called the nacelle, and this also reduced the noise. They applied multilayered linings about 50 millimeters thick to the inside of the nacelles in order to dampen as much of the noise frequency range as possible. They also increased the separation between the engine's static vanes and its rotating fan. This virtually eliminated the buzz-saw noise that characterized the sound of the early low-bypass ratio engines.

HIGHER BYPASS RATIOS LEAD TO LOWER JET EXHAUST NOISE. SOON THE NOISE FROM TURNING ENGINE PARTS WILL BE LOUDER THAN EXHAUST NOISE. THEN, ADDITIONAL REFINEMENTS TO THE EXHAUST WILL NOT DIMINISH ENGINE NOISE

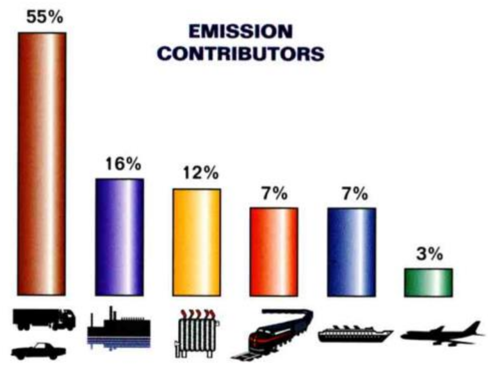


Engines on the latest generation of aircraft, the B747-400, B737-400, B737-500, B777, A340, and MD-11 have bypass ratios of from 5:1 to over 8:1. But these increases were primarily to improve engine performance and do not represent major advances in noise reduction.

Noise reduction has progressed to the point that for engines with bypass ratios greater than 5:1, the noise of the jet gasses are less than the noise of the rotating engine parts.

Furthermore, the noise created by the airframe of a jet moving through the sky today is only a few decibels below the engine noise. This airframe noise represents a floor that may establish the lower limit for additional noise reduction. For this reason, engineers believe that noise produced by the next generation of jets will not be substantially less than current models.

An Exhausting Subject



People worry about the effect of aircraft engine emissions on the quality of air near airports and at high altitudes.

Although aircraft contribute only a small fraction of the emissions around airports, they are the only man-made source of exhaust gas emissions at high altitude in the upper troposphere and lower stratosphere. Even though scientists have not yet determined aviation's actual impact on the atmosphere, great interest surrounds its possible role in global warming and depletion of the protective ozone layer.

The emissions of concern include:

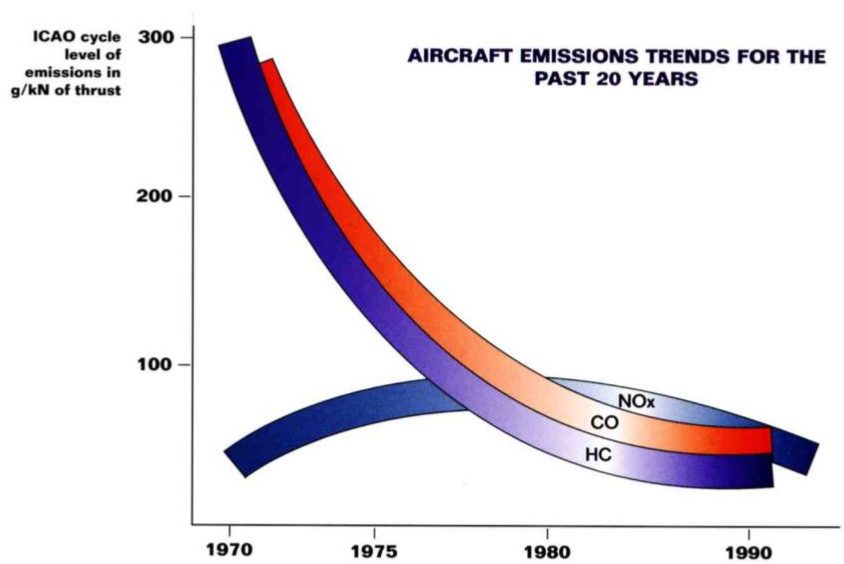
- ❑ Carbon dioxide and water vapor that compose more than 99 percent of the jet engine exhaust gasses. Most of these emissions are given off during cruise. They are not considered true pollutants, but they are relevant to global warming because of their greenhouse effect.
- ❑ Nitrogen oxides. These occur during all flight phases but mainly during takeoff when combustion temperatures are highest. Nitrogen oxides may contribute to depletion of the ozone layer and to the formation of acid rain.
- ❑ Carbon monoxide.
- ❑ Hydrocarbons. These volatile organic compounds are contained in unburned fuel and, along with carbon monoxide, occur at low engine power settings on the ground and are the main jet engine emissions around airports and urban areas.
- ❑ Sulphur dioxide, soot, and smoke. These are emitted in minute quantities during takeoff and climb. They smell noxious. Sulphur dioxide also contributes to acid rain.

Exhaust emissions from aircraft represent a tiny portion of the total emissions from all man-made sources, about 1 percent of the carbon monoxide, unburned hydrocarbons, nitrogen oxides, and sulphur dioxide emissions and less than 4 percent of the carbon dioxide emissions.

Aircraft emissions are less than 3 percent of the total mass of all emissions from transportation sources.

Emission levels are measured by an index for each pollutant according to the definition: EI = pollutant mass/fuel mass. The unit is expressed in grams of pollutant per kilogram of fuel burned

Regulatory Information

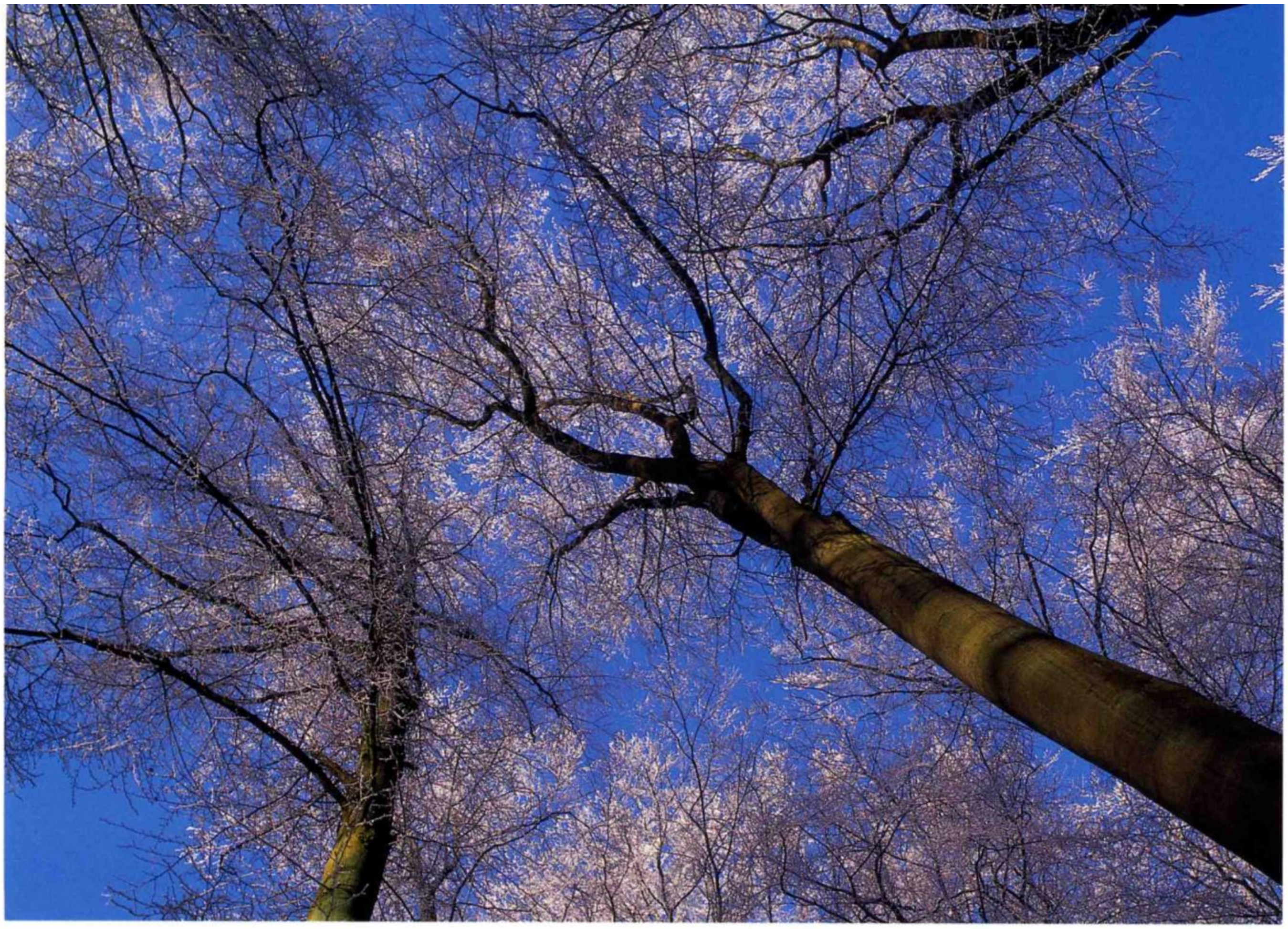


The International Civil Aviation Organization (ICAO) has a technical Committee on Aviation Environmental Protection (CAEP) that studies airports, noise, emissions, and environmental economics.

In 1981, ICAO began publishing standards for the control of fuel venting, smoke, and gaseous discharges from newly manufactured jet engines. The current version of these standards is found in Volume II - Aircraft Engine Emissions (second edition - 1993) of Annex 16 to the Convention on International Civil Aviation.

ICAO's fuel venting standards apply to all turbine-powered aircraft made after February 18, 1982 that are intended for international operations. Smoke standards apply to subsonic turbine engines made after December 1982. Gaseous emission standards apply to engines with a rated output of over 26.7 kN (6,000 lb) that were made after December 1985.

The gaseous emission standards cover discharges of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen. More recently, ICAO tightened the emission standards for nitrogen oxides for certain jet engines. These standards apply when the first production model was manufactured after December 1995 or the individual engine is to be manufactured after December 1999.



Aircraft Emissions Near Airports

Ninety-five percent of all pollution near airports comes from power stations, manufacturing industries, surface transportation, and heating systems. These activities produce most of the unburned hydrocarbons, sulphur dioxide, nitrogen oxides, carbon monoxide, and smoke.

Aircraft have only a slight impact on air quality near airports. This comes from engine emissions during approach, landing, taxiing, takeoff, and initial climb. There is also a small contribution from the work performed during aircraft maintenance and ground handling.

But poor air traffic control in the skies adds to the problem. When congestion in the air forces jets to wait on the ground for a departure slot, emissions around airports increase. A 747 burns 225 kilograms of fuel every 5 minutes that is idling on the runway.

Air traffic congestion in the skies over Europe also forces planes to deviate frequently from their most direct course and fly 30 percent farther than necessary to reach their destination

The Association of European Airlines is working hard to alleviate air traffic congestion in Europe because it significantly effects the environment and the economy.

Aircraft Emissions At Altitude

Most emissions are discharged by subsonic jet aircraft into the upper troposphere and lower stratosphere. Scientists are currently studying the environmental effects of these emissions on global warming and stratospheric ozone depletion. They are trying to identify whether aircraft discharges contribute to greenhouse gasses and thus alter the energy balance between the earth and the atmosphere. So far, they have not yet evaluated the possible effects of aircraft operations on climate change.

New Technology Reduces Emissions

Jet engines burn kerosene to produce power. This combustion also creates emissions in amounts that are proportional to the quantity of fuel consumed. Burning less fuel reduces emissions.

New jet engines that were designed during the past 20 years have reduced fuel consumption up to 50 percent and engine emissions by 10 percent to 75 percent depending on the specific byproduct.

Engineers were able to create engines that produce greater thrust and consume less fuel by improving both the propulsive and thermodynamic efficiencies of their designs.

FRONT AND REAR VIEW OF AN ANNULAR, OR RING, COMBUSTER FROM A NEW GENERATION ENGINE.
Photos Courtesy CFMI

To create more efficient propulsion, today's engines use a compressor fan with a very large diameter. The bigger fan produces a large volume of air that combines with the hot exhaust gasses exiting from the engine core to generate thrust.

Older jet engines developed thrust by forcing a small mass of air-gas flow from the rear of the engine at high velocity. But this design wasted energy because of the large difference between the high speed of the exhaust gas and the slower speed of the airplane.

Newer engines achieve greater propulsive efficiency by pushing a larger mass of air-gas flow from the engine at a lower velocity that is closer to the speed of the moving airplane.

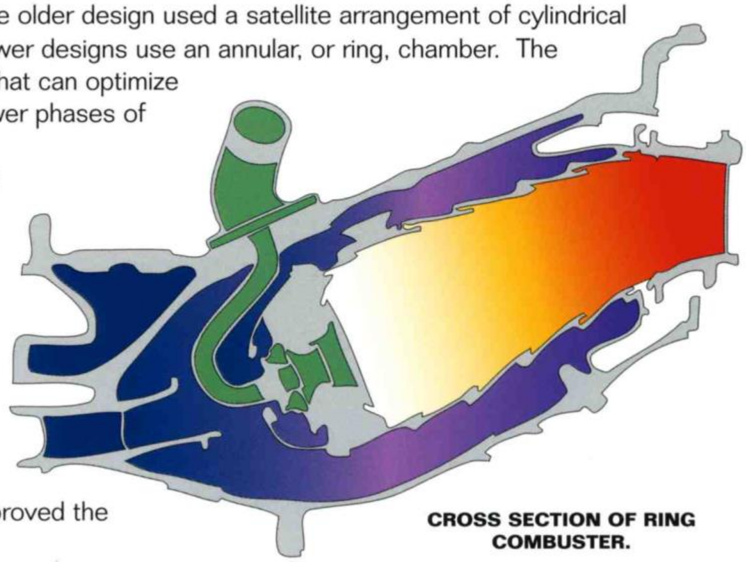
For a description of the development of modern high-bypass engines please refer to the section, Engine Developments That Reduce Noise.

To increase thermodynamic efficiency and thus extract more energy from each liter of fuel burned, new engines operate with higher internal combustion temperatures. They have automatic controls that constantly optimize fuel flow and engine settings for all altitudes, temperatures, and speeds. Newer designs also minimize energy losses by reducing turbulence in the air-gas flow through the rotating engine components.

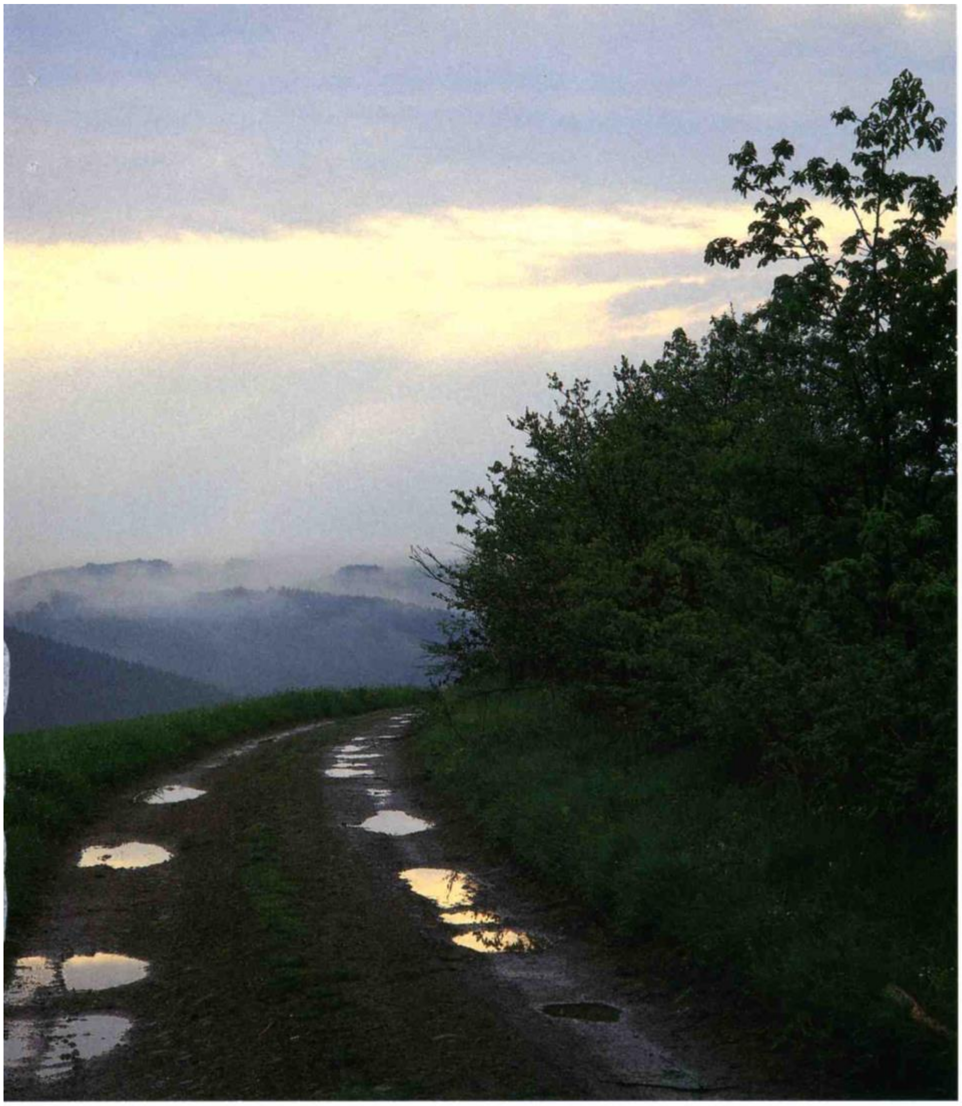
SATELLITE COMBUSTERS USED IN OLDER JET ENGINES.

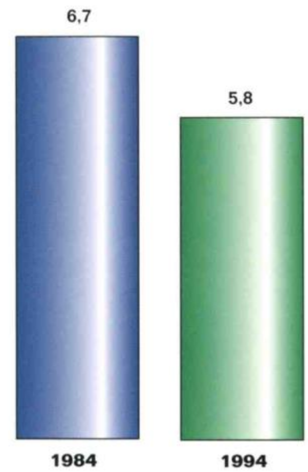
In pursuit of higher thermodynamic efficiency, engineers have achieved greater control over combustion chemistry and thereby reduced jet engine emissions. The thermal efficiency of the combustor in a modern jet engine is more than 99 percent. And the engine's overall thermodynamic efficiency has increased mainly by—

- Internal engine components are fabricated from new materials that can withstand higher temperatures and enable the engine to burn fuel more completely.
- Cooling air flows are directed so that they form an insulating barrier between the hot exhaust gasses and the high- temperature engine components, mainly the turbine inlet guide vanes and the first stage turbine blades.
- Fuel and air are homogenized as they flow into the combustor in order to minimize the temperature gradient in the flame and to control the residence time of the burning gas. Both temperature gradient and residence time influence the formation of nitrogen oxides.
- Combustion chamber geometry has changed. The older design used a satellite arrangement of cylindrical combustors around the turbine shaft while the newer designs use an annular, or ring, chamber. The latest designs incorporate double ring chambers that can optimize combustion during the most important engine power phases of takeoff and cruise.
- Adjustable guide vanes can now vary the angle of attack of the compressor blades in synchronization with changes in the engine's power settings.
- The distance between the tips of the rotating turbine blades and the turbine housing is now controlled precisely. This distance is called the tip clearance. New designs are able to compensate for the different thermal expansion rates of the turbine blades and the turbine housing in order to minimize tip clearance and improved the efficiency of the gas flow through the engine.



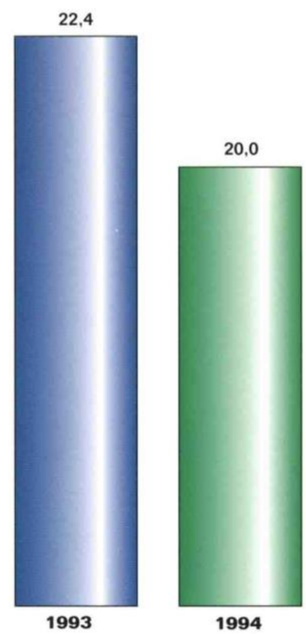
CROSS SECTION OF RING COMBUSTER.





LITERS PER PASSENGER X 100 KILOMETERS

LUXAIR'S NEW TECHNOLOGY FLEET LOWERED SPECIFIC FUEL CONSUMPTION 14%



LITERS PER TON X 100 KILOMETERS

CARGOLUX'S NEW 747-400 FREIGHTERS LOWERED SPECIFIC FUEL CONSUMPTION 11%

Fuel Consumption

Advanced engine designs have played a big part in improving the fuel consumption and therefore the environmental performance of the Luxair and Cargolux fleets.

In 1994, Luxair's new generation of 737-500, 747-400, F-50, and EMB-120 aircraft used 5.8 liters of fuel to fly one passenger 100 km, compared to 1984 when the earlier fleet of 737-200's and F-27's required 6.7 liters to fly one passenger 100 km. These newer aircraft resulted in a savings of 6.5 million liters of fuel in 1994. The new fleet also lowered specific fuel consumption by 14 percent since 1984 and an even greater reduction in atmospheric emissions.

Cargolux's new technology 747-400 freighter uses 2,9 liters of kerosene less than the older 747-200 to move one ton of cargo one hundred kilometers. This adds up to a savings of 18,500 liters of kerosene flying from Luxembourg to Dubai. The new 747-400 freighters are 17.7 percent more efficient than older 747-200 models and lowered specific fuel consumption for the entire fleet by 11 percent..

Both airlines also added larger planes and increased the efficiency of their flying operations. That means that for each ton of passengers and freight they carried, they consumed less fuel and lowered the amount of emissions released. Luxair flights carried an average of 21 percent more passengers in 1994 that they did in 1984. Cargolux flights flew with 32 percent more freight than they did in 1984.

Carbon Dioxide and Water

Carbon dioxide formation is not a combustion problem but is related solely to the amount of fuel burned. Each kilogram of kerosene jet fuel consumed creates 3.15 kilograms of carbon dioxide.

Combustion also creates water vapor in direct proportion to the amount of fuel burned, 1.25 kilograms of water for each kilogram of fuel. Water and carbon dioxide are the major components of greenhouse gasses and their concentration in the atmosphere can influence the life of an ozone molecule.

The only way to reduce carbon dioxide and water emissions is to burn less fuel. But since fuel consumption is rising with the overall increase in air traffic, some people predict that these emissions will grow in Europe initially by 2.7 percent each year, finally doubling over the next decade.

On a worldwide basis, the ongoing buildup of carbon dioxide in the atmosphere contributes to increasing global warming. Jets do not add significantly to the amount of carbon dioxide, less than 4 percent, compared to other consumers of fossil fuels. However the demand for kerosene jet fuel is increasing faster than can be offset by improvements in jet engine efficiency. This means that in the future, aircraft will consume a larger share fuel and produce a larger share of carbon dioxide and water vapor.

ICAO forecasts that the world's airlines will have increased their annual consumption of jet fuel almost 65 percent between 1990 and 2010, from 133 million tons to 220 million tons, due to the increase in air traffic.

Nitrogen Oxides

The emission of nitrogen oxides has been one of the airline industry's chief concerns. The worry is over potential consequences at two altitudes.

In the upper troposphere, about 9,000 meters above the earth's surface, they may produce ozone by photochemical reaction. This ozone acts as a potent greenhouse gas at that altitude and it has a life of from 1 to 2 months, insufficient for diffusion into the stratosphere.

Nitrogen oxides also react with water in the troposphere to produce clouds of crystallized nitric acid, a small component of acid rain.

In the lower stratosphere, about 16,000 meters above the earth's surface, nitrogen oxides can effect the concentration of ozone by adding to it at some altitudes and latitudes and by destroying it at others through catalytic reaction. This shift of ozone concentration is influenced most by supersonic flight and to a lesser extent by subsonic flights through the polar regions.

However, recent information from the Mosaic Study suggests that ozone is not being destroyed at altitudes where airliners cruise. In this ongoing study, five Airbus A340 transports are equipped with measuring equipment to analyze ozone, water vapor, and temperature. These aircraft have so far collected data from more than 200,000 measurements taken from 2,200 flights, most of them during long-haul operations.

Why Ozone?

Most ozone is concentrated in the stratosphere. It is located near the equator between 25,000 and 30,000 meters above the earth's surface and over the north and south poles at about 16,000 meters.

Ozone in the lower stratosphere filters ultraviolet radiation from the sun in the wavelengths between 0.240 and 0.300 microns and is also believed to act as a greenhouse gas.

The total amount of ozone in the atmosphere is small and would represent a layer only 3 millimeters thick at ground temperature and pressure. Both increases and decreases in ozone concentration are of environmental concern although these stratospheric phenomena will probably not be understood completely for at least another decade.

Engine Parameters that Effect Nitrogen Oxides

Nitrogen oxides are produced during combustion at a slower rate than carbon monoxide and unburned hydrocarbons. Nitrogen oxides form inside a jet engine combustion chamber. More specifically, they form on the outside surface of kerosene particles as they burn in the air. These oxides are created in the region of the chamber where the flame temperature is hottest, known as the primary combustion zone.

A hotter flame will produce more nitrogen oxides than a cooler one. Similarly, the longer that the nitrogen in air is allowed to remain in contact with fuel in the combustion chamber, the more nitrogen oxides will be produced.

The quantity of nitrogen oxides that a jet engine creates will depend on (1) the temperature and pressure of the air leaving the compressor and entering the combustion chamber, (2) the ratio of fuel to air, and (3) the length of time the mixture spends traveling through the combustion chamber, called the residence time.

The chamber design that is best for the environment is one that produces a maximum flow of homogenized air and fuel through the combustors while maintaining a smooth internal temperature gradient.

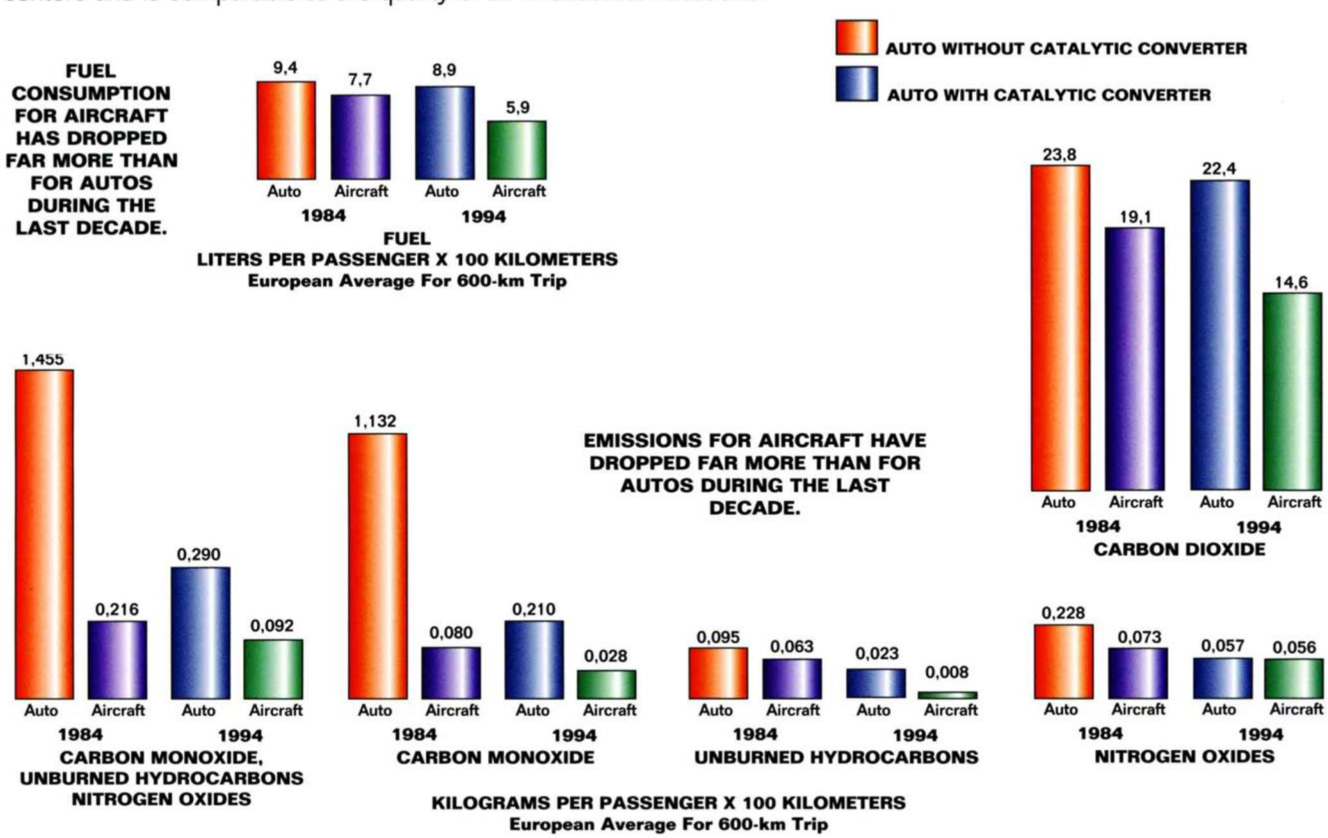
In order to achieve more favorable temperatures, engineers have created a new geometry for engine combustors. They replaced the traditional design in which small combustion chambers were positioned like satellites around the longitudinal axis of the engine, with a single large combustor in the shape of a ring. This new design is called an annular combustion chamber.

The Good News

The newest jet engine designs use two annular combustion chambers in order to produce the power needed for takeoff and cruise while minimizing the residence time and maintaining smooth temperature gradients. This double annular design has considerably reduced the specific emissions of subsonic commercial aircraft.

Most of the reduction in nitrogen oxide emissions in Luxembourg have come from new Luxair and Cargolux aircraft equipped with advanced engines designs. Nitrogen oxides emitted from the 747-400 are 37 percent less than from the 747-200. From the 737-500 they are 8 percent less than for the 737-200, an aircraft with engines that already produced a low level of nitrogen oxide emissions.

Continuous air quality measurements at airports show that the concentration of pollutants is far lower than in city centers and is comparable to the quality of air in suburban locations.



Unburned Hydrocarbons

Modern jet engine technology has had the most pronounced effect on reducing the emission of unburned hydrocarbons. As the name indicates, unburned hydrocarbons are the result of incomplete combustion and therefore can be effectively reduced by optimizing engine performance.

Aircraft in the current fleets of both Luxair and Cargolux emit significantly fewer unburned hydrocarbons than models that preceded them. Specific emissions for Luxair dropped 87 percent between 1994 and 1991 from 0.63 grams per passenger-kilometer to 0.08 grams per passenger-kilometer. For Cargolux they decreased 74 percent during the same period from 0.92 grams per ton-kilometer to 0.24 grams per ton-kilometer.

Carbon Monoxide

Carbon monoxide is also a result of an incomplete combustion process.

The aircraft in service today with Luxair and Cargolux emit significantly less carbon monoxide than the models that preceded them. Prognos AG calculated for a study titled, "Significance And Environmental Impact of Rail And Air Transport in Germany," that carbon monoxide emissions per passenger kilometer from air traffic are 9 to 10 times lower than for automobiles.

Comparing 1994 with 1990, the specific carbon monoxide emissions from Luxair decreased 65 percent to 0.28 grams per passenger-kilometer and for Cargolux they decreased 30 percent to 1.01 grams per ton-kilometer.

Sulphur Dioxide

The emission of sulphur dioxide can not be calculated as readily as other pollutants. According to international binding specifications, kerosene jet fuel may contain up to 0.3 percent of sulphur.

Reducing the sulphur in jet fuels would have little effect on urban air quality and acid deposition because most jet fuel is burned at high altitudes. Less than 1 percent is burned within the airport boundary.

Fuel Dumping

During an inflight emergency, an airplane may release fuel into the atmosphere in order to reduce its weight and diminish the danger from fire prior to an emergency landing.

When this happens, the ejected kerosene is emulsified in the air. It disperses into the atmosphere and the minute quantity that reaches the ground cannot be measured.

There have been only two fuel dumping incidents near Luxembourg in the last 10 years.