ON THE REDUCTION OF NOX-EMISSION LEVELS BY PERFORMING LOW NOX FLIGHTS

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Abstract

For aero-engines using hydrocarbon fuels, the major exhaust products that are discharged into the atmosphere are carbon dioxide (CO_2) *and water vapor* (H_2O)*. Minor products of combustion may include soot (smoke), carbon monoxide (CO), a variety of unburned hydrocarbons (UHC), nitrogen oxides* NO_x *(that is, nitric oxide (NO) and nitrogen dioxide* (NO_2)*) , and sulfur dioxide* (SO_2)*.*
A favorable feature of the kerosene fuel used for jet aircraft propulsion is that it contains almost no sulfur. Therefore, the emission of SO_2 *by aircraft is very low and usually negligible.*
The modern high bypass ratio turbofan engines employed for the propulsion of transport airplanes have high compressor pressure ratios and therefore high turbine entry temperatures. Due to the resulting high flame temperatures in the combustion chambers, the NO_x *- formation rates at takeoff and cruise conditions have been substantially increased during the past decades.*
When transmitted to or emitted directly into the stratosphere, nitrogen oxides act as catalysts in chemical reactions that contribute to the depletion of the ozone layer [1]. When emitted into the upper troposphere, NO_x *may participate in the formation of tropospheric or "bad" ozone. Emissions of* NO_x *thus affect global warming indirectly through tropospheric ozone formation.*
At lower altitudes, aircraft emission products may contribute to the occurrence of acid rain and ground level smog. These effects may cause serious environmental problems in the foreseeable future if the world air fleet increases further and new advanced turbofan engines come into operation. Such engines could have even larger compression ratios and, therefore, may emit increased NO_x *emission rates than the present engines.*
It seems generally accepted that the bulk of the reduction of the harmful impact of aircraft emissions on the atmosphere is the responsibility of the gas turbine combustor designer [2]. Accordingly, at present, considerable effort is being made to lower the NO_x *production in the combustion chamber well below the current levels.*
However, in addition, performing a so-called Low NO_x *Flight may deliver a noticeable contribution to the reduction of the* NO_x*-emissions. Regrettably, when executed with the current aircraft types, this certainly will result in a considerable increase in fuel consumption and direct operating cost.*
Surely, growth of aviation would have to be severely restricted unless one is able to avoid the risk of any perturbation in climate and/or in health.

1 General Introduction

1.1 Earth atmosphere

As one ascends in the atmosphere from ground level, the air temperature normally decreases up to a height of about 10 km (Fig. 1). The region of decreasing temperature is called the troposphere, where due to the negative temperature gradient the air usually is unstable. As a consequence, convective motions occur through which the air normally is well-mixed [3].

Above the troposphere, the temperature at first becomes roughly independent of altitude and then increases with height up to a level of about 50 km. This is the region that is known as the stratosphere.

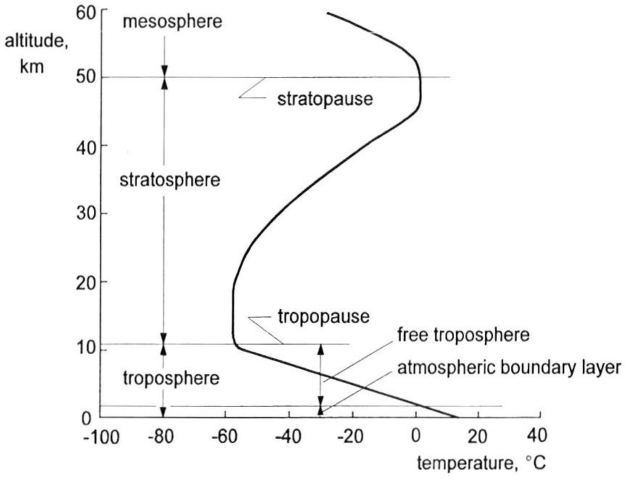

Fig 1: Temperature rates in the atmosphere

The dividing plane between the troposphere and the stratosphere is called the tropopause. For average latitudes, this plane is located at a height of about 11 km. Near the polar regions the troposphere extends to about 8 km, while at the Equator it reaches up to approximately 17 km.

1.2 Vertical stability of the atmosphere

The constant temperature as well as the temperature inversion occurring in the stratosphere cause stable atmospheric conditions, which allow existing pollutants in the stratosphere to escape only slowly from this layer. Clearly, aircraft flying in the stratosphere, where they are the only anthropogenic source of pollutants, can leave behind there their effluents, which may remain in the stratosphere for years until they are ultimately transported downwards into the troposphere. Below the tropopause the effluents are readily transferred and removed by processes, such as precipitation and dispersion. It is only the slow downward transport caused by atmospheric mixing that tends to rid the stratosphere of pollutants.

Like the vertical spreading of combustion products, also the horizontal spreading in the stratosphere in the north-south direction is rather slow, while the spreading in east-west direction is faster and notable extensive. This means that most stratospheric effluents produced in the northern hemisphere will remain there and will have a more zonally symmetric distribution.

1.3 Emission altitude and effect on atmosphere

For sound reasons, commercial airliners cruise at altitudes between about 9 and 13 km, that is, well into the stratosphere at middle and high latitudes. However, in that altitude region, their exhaust gases may contribute to both global warming and ozone layer depletion.

Clearly, the concentrations of pollutants occurring in the tropopause region will be greatest near the latitude of the North Atlantic flight corridor, the main flight route between the US and Europe.

In the stratosphere, molecular oxygen O_2 absorbs ultraviolet solar radiation and in this process ozone O_3 is formed. The absorption of solar radiation required for the formation of the ozone is the cause of the temperature inversion in the stratosphere. The presence of high ozone concentrations (the ozone layer) in the stratosphere is very important to the protection of the Earth's biosphere by absorbing harmful short-wave ultraviolet radiation.

A decrease of the amount of ozone in the stratosphere creates an increase of UV-radiation to the Earth and possibly a small change in temperature at its surface.

The substances that especially give rise for concern are nitrogen oxides NO_x, which are formed in the high temperature zones of the combustion chamber of aero engines, mainly through the oxidation of nitrogen N_2 by oxygen radicals O. The latter are formed by dissociation of molecular oxygen O_2 at high temperatures ("thermal NO_x").

On the other hand, near the tropopause aircraft emissions are the only source, since emissions of NO_x from lightning occur below an altitude of ca 8 km.

When NO_x is emitted in the stratosphere, it may participate in the depletion of the ozone layer. When emitted in the upper troposphere, NO_x may participate in the formation of tropospheric ozone, which acts as a strong greenhouse gas, and therefore may lead to an enhanced greenhouse effect.

1.4 Low NOx flight

To control possible effects caused by flight operations near to the tropopause, the options available for aero engines, besides improving the combustion process, are reducing fuel consumption and performing a Low NO_x Flight.

In aviation the emphasis has always been on fuel conservation. The result of this ambition can be seen from Fig. 2, where the effect of engine technology on the development of specific fuel consumption over the past forty-five years is portrayed.

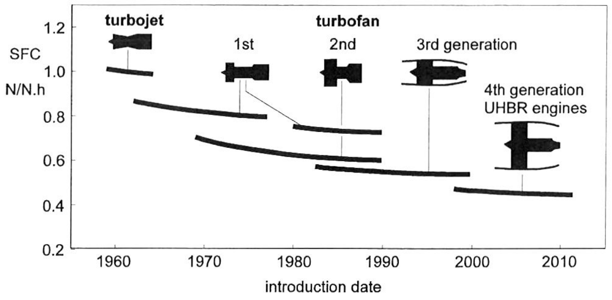

Fig 2: Development history of specific fuel consumption of engines for commercial aircraft in cruise.

The most fuel-efficient propulsion systems for today's transport airplanes are turbofan engines with bypass ratios up to about nine. These so-called Ultra High Bypass Ratio (UHBR) engines employ high compressor pressure ratios in combination with high turbine entry temperatures.

Minimizing fuel consumption also implies minimizing the emissions of the greenhouse gases carbon dioxide CO_2 and water vapor H_2O, because the amounts of these combustion products are directly related to the amount of fuel burned. The emissions of CO_2 and H_2O in gram per kg of fuel consumed have constant values, which amount to about 3150 and 1250 g/kg, respectively.

This rule does not apply to soot (smoke), carbon monoxide CO, and unburned hydrocarbon UHC, which species are produced by incomplete burning of the kerosene fuel, and are a function of thrust setting (Fig. 3). Fortunately, under cruise conditions, essentially, complete combustion occurs, so that these products have a minor significance.

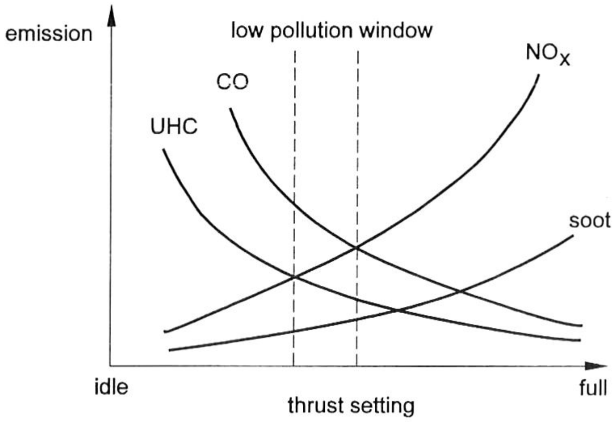

Fig 3: Emission level versus thrust setting

Consistently with their improved fuel efficiency, the modern turbofan engines show high combustion temperatures and gas pressures, through which especially the NO_x - formation rates at takeoff and cruise conditions have been substantially increased during the past decades [4]. Besides the peak temperature, the amount of NO_x - emission also depends on the amount of time the gas mixture of nitrogen and oxygen is at that temperature.

In the early days of aviation environmental considerations used to come a long way after other topics such as safety, reliability, performance, and economics. However, nowadays, environmental considerations have become important design criteria. A reflection of the concern for the environment are the standards set by the ICAO, restricting the emissions of the species: soot, CO, UHC, and NO_x [5].

There is reason to expect that also for flight operations near to the tropopause additional regulations are likely to follow.

Currently, no restrictions exist to the production of CO_2 by aircraft. Quoting a statement of the International Civil Aviation Organization given in [6]: “In the case of CO_2, it has been decided not to develop an ICAO standard, since CO_2 production is directly related to fuel consumption and there is already intense economic pressure to keep fuel consumption to a minimum and, in addition, there would be significant difficulties in designing a certification condition”. Therefore, it seems more realistic to expect that taxes will be imposed on the exhaust of CO_2.

Returning to the prevailing standards, it can be said that reductions have been obtained for the emissions of CO and UHC, which pollutants are dominating at low thrust settings. Also soot emission, which dominates at high thrust settings, have been greatly reduced.

However, the formation of NO_x has been increased during the past decades [4]. This is caused by the high overall pressure ratios and the high gas temperatures in the combustion chambers of the modern high-bypass ratio turbofan engines. Therefore, the formation of NO_x mainly occurs at the high power settings applied during takeoff, climb, and cruise.

It should be noted that the ICAO standards include a dependence of the admissible NO_x - levels on the compressor pressure ratio. This is consistent with the fact that the emission of NO_x increases with increasing compressor pressure ratio.

2 The importance of NOx - emissions

The high-altitude gas emissions from air traffic may play a significant role in (future) stratospheric ozone depletion and tropospheric ozone production.

To explain these statements, predictions of the percentage distribution of the pollutant substances, CO, UHC, NO_x, and soot, over the various flight phases are presented in Table 1 of a medium-haul airliner performing a stage length of 500 nautical miles [7].

The quantifications show that NO_x, by far, contributes most to the total emission of the pollutants. For the landing and takeoff cycle, 77.4% of these emissions consist of NO_x, while the contribution from the climb, cruise and descent is even 89.0%. For the whole flight, the NO_x emissions comprise 85.9% of the total production of pollutants.

Table 1: Percentage distribution of emissions per flight phase for a flight distance of 500 nautical mile

constituent	takeoff and landing	climb, cruise, and descent	total flight
CO	5.4	7.0	12.4
NO_X	20.6	65.3	85.9
UHC	0.6	1.0	1.6
soot	-	0.1	0.1
total	26.6% (77.4% NO_X)	73.4% (89.0% NO_X)	100.0% (85.9% NO_X)

Obviously, if a reduction of the emissions would be desirable, NO_x is the most appropriate constituent to suppress.

Another study on the emission of NO_x is reported in [8], where is considered a flight between London and Tokyo with a Boeing 747-400 airplane. Investigated is a cruise climb, i.e., a flight path whose altitude increases continuously as fuel is burned off. Assumed is a flight in International Standard Atmosphere (ISA), at a mean cruise altitude of ca 10.8 km and a constant flight Mach number of 0.85.

Results are specified in Table 2, indicating that on this long-haul flight the airplane produces 1321 kg of NO_x, of which around 85% is emitted during the cruise. The NO_x - emission at higher altitudes even constitutes about 97% of the total production.

Table 2 NO_x-emissions per flight phase for B747-400 airplane on the London – Tokyo route

flight phase	NO_X emissions	
	kg	% total
takeoff	15	1.1
climb out to 457 m (1500 ft)	15	1.1
continued climb (457 m to 9500 m)	158	12.0
cruise climb (9.5 km to 11.8 km)	1113	84.3
descent	5	0.4
approach	7	0.5
taxi	8	0.6
total	1321	100.0

As yet, data on the NO_x - emission levels by applying alternative flight techniques are scarce. Therefore, to obtain an impression of the potential of performing low-NO_x flights, some results from a “Cruise NO_x Simulation Model” developed in [9], will be given here. Using this computer simulation model, the effects of variations in cruise conditions on the emission level of NO_x and the accompanying effects on fuel consumption and direct operating costs of a Boeing 747-400 aircraft are predicted.
Anticipating this consideration some attention will be given to the point performance conditions for the flight for minimum fuel, minimum NO_x - emission, and minimum direct operating cost.

3 Point performance conditions

3.1 Minimum fuel for a fixed cruise distance

Since the mass of an airplane decreases continuously with time due to the consumption of fuel by the engines, we can write for the fuel mass flow rate F:

$$F = \frac{dM_f}{dt} = -\frac{dM}{dt} \qquad (1)$$

where M_f and M is fuel and airplane mass, respectively.

Assuming still air, the range of the airplane (R) is obtained from the following integral:

$$R = \int_{t_1}^{t_2} V dt = \int_{M_1}^{M_2} -\frac{V}{F} dM = \int_{M_1}^{M_2} \frac{V}{F} dM_f \qquad (2)$$

where V/F is the distance flown per unit mass of fuel or specific air range (SAR) in km/kg. The subscripts “1” and “2” refer to the initial and final conditions at the beginning and end of cruise, respectively.

Obviously, for a minimum amount of fuel to cover a given cruise distance, the specific air range should be maximum for each momentary flight condition.

3.2 Minimum NO_x emission for a fixed cruise distance

The emitted mass of pollutant substance dQ, after consuming an amount of fuel mass dM_f is given by:

$$dQ = EIdM_f \qquad (3)$$

where EI is the emission index of the pollutant in gram per kilogram of fuel consumed, and Q is in gram.

With $dR = (V/F)\, dM_f$, we obtain:

$$Q = \int_0^R \frac{EI}{V/F} dR \qquad (4)$$

The parameter [EI/(V/F)] is called pollution number, P. For the emission of NO_x we can write:

$$P_{NO_x} = \frac{EI_{NO_x}}{V/F} \qquad (5)$$

Apparently, for a given range R, the amount of pollutant Q is minimum if the pollution number is as low as possible for each momentary flight condition. Clearly, for a given emission index, a high specific air range (high fuel efficiency) results in a low amount of NO_x emitted.

3.3 Minimum direct operating costs for a given range

The direct operating costs (DOC) are those costs which are directly related to the operational characteristics of the airplane. They may comprise the costs of fuel and oil, crew, landing fees, depreciation of capital invested, insurance, interest and maintenance.

For analysis, the direct operating costs can be subdivided into costs of time and fuel:

$$DOC = CT \times E + CF \times M_f \qquad (6)$$

where CT designates the costs of time in \$/h, E the endurance of the flight in hour, CF the cost of fuel in \$/kg, and M_f the mass of the fuel consumed for a given range.

A criterion employed to express the relative costs of time and fuel is the cost index, CI, defined as the ratio of time cost to fuel cost [10]:

$$CI = \frac{CT}{CF} \tag{7}$$

where CI is expressed in (\$/h)/(\$/kg) = kg/h.

Application of the cost index combines time cost and fuel cost to an equivalent fuel mass, $M_{f,eq}$, which is used as a measure for the direct operating costs:

$$M_{f,eq} = CI \times E + M_f \tag{8}$$

Since DOC = $M_{f,eq}$ × CF, the mass $M_{f,eq}$, in fact, is the fuel mass that could be purchased for the direct operating cost.

In order to investigate the minimum DOC for a given range, the specific economic range, (SER), is introduced, which parameter is defined as the ratio of the rate of change of distance to the rate of change of equivalent fuel mass.

In still air, the rate of change of distance is the airspeed V, and the rate of change of equivalent fuel mass is given by:

$$\frac{dM_{f,eq}}{dt} = CI \times F \tag{9}$$

where $F = dM_f / dt$ is the fuel mass flow rate in kg/h. This results in the following expression for the specific economic range:

$$SER = \frac{V}{CI \times F} \tag{10}$$

where SER has the unit km/kg.

Similar to the condition for minimum fuel, i.e., maximum specific air range $(V/F)_{max}$, the condition for minimum DOC in cruise flight is that SER should be maximum for each momentary flight condition. Then the equivalent fuel mass is minimized, and therefore the total cost for the distance flown.

4 Low NOX Flight

The calculation procedure reported in [9] is aimed at the determination of the effect of cruise conditions on the emission of NO_x and the accompanying effects on fuel consumption and DOC. Varying cruise conditions include variations of flight altitude, cruise Mach number or airspeed and atmospheric conditions. The cruise is taken as a continuous succession of quasi-steady state motions.

Considered is a cruise range of 5800 km with a Boeing 747-400 aircraft, powered by a fictitious turbofan engine model. Some characteristic data of this typical wide-body airplane are given in Table 3.

Table 3: Characteristic data of Boeing 747-400 airplane.

year of introduction	1989
wing loading	7151 N/m^2
wingspan	64.92 m
wing area	541.16 m^2
maximum thrust	4×258 kN
cruise Mach number	0.85
maximum takeoff weight	3870 kN
operating empty weight	1792 kN
fuel capacity	1603 kN
range	13157 km
initial cruise altitude	10030 m
takeoff field length	3352 m
landing field length	2072 m
maximum lift-drag ratio	18

The emission indices EINOx are calculated according to the empirical relation suggested in [11]:

$$EI_{NO_x} = 10^{\left[1+0.0032\left(T_{tc}-581.25\right)\right]} \sqrt{\frac{p}{p_0}} \tag{11}$$

where T_{tc} is the combustor inlet total temperature, p is the atmospheric pressure and p0 is sea-level atmospheric pressure in ISA. It may be noted that the above expression for EINOx reflects the well-known Lipfert plot given in [12].

The following point performance capabilities for flight in ISA, taken from [8], are shown here: specific air range SAR = V/F, specific economic range SER = V/(CI+F), and NO_x - pollution number PNOx = [EI /(V/F)].

Fig. 4 presents the effects of flight Mach number and altitude on specific air range. At a given airplane weight (W = 2800 kN) an optimum Mach number as well as an optimum cruise altitude occurs for maximum specific range, $(V/F)_{max}$.

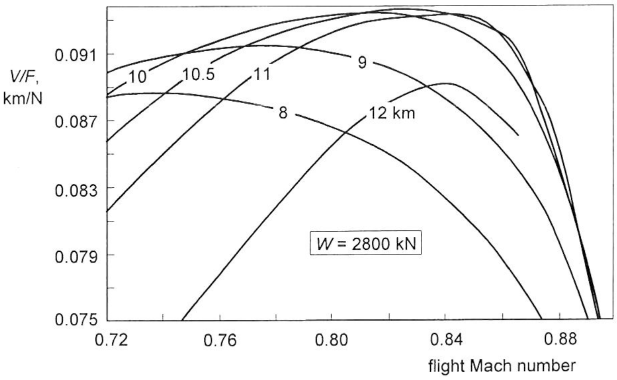

Fig 4: Specific range as functions of Mach number and altitude

Fig. 5 indicates that at a given cruise speed (V = 860 km/h), the altitude for $(V/F)_{max}$ increases with decreasing weight. Hence, when minimum fuel consumption is aimed for, the airplane should ascend in altitude during the cruise.

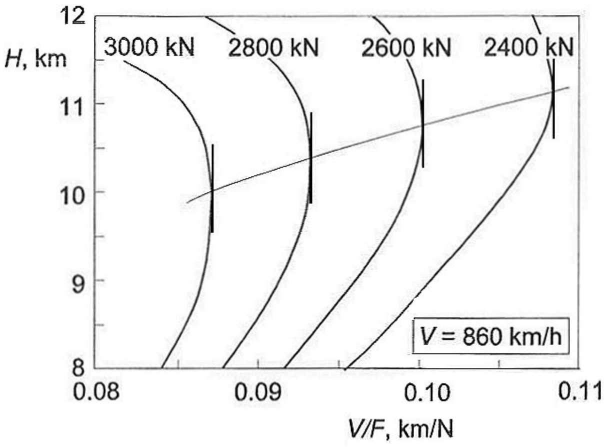

Fig 5: Specific air range as functions of altitude and weight

Fig. 6 displays the effects of flight Mach number and cruise altitude on specific economic range at a given airplane weight (W = 2800 kN).

Used is a cost index of CI = CT/CF = 3220 kg/h, where the time cost CT = 1288 \$/h and the fuel cost CF = 0.40 \$/kg fuel.

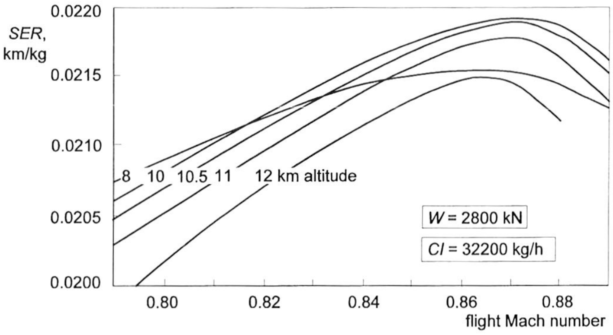

Fig 6: Specific economic range as functions of Mach number and altitude.

Consistent with Fig. 4, the curves in Fig. 6 emphasize the importance of a relatively high flight Mach number and cruise altitude (up to 11 km) for an economic operation of the aircraft. If a cruise for minimum cost is aimed for, then similar to minimum fuel consumption, the aircraft should ascend in altitude.

In Fig. 7 are shown the effects of cruise altitude and aircraft weight on the NO_x - emission index for given airspeed (V = 860 km/h). The plot reveals that at a given weight and airspeed, an optimum cruise level occurs for minimum emission index.

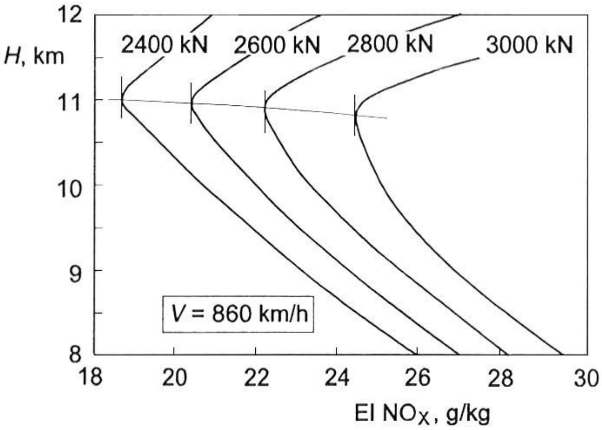

Fig 7: NOx – emission index as functions of altitude and weight.

The curves also manifest that when at a given airspeed and altitude, weight is reduced, a lower NO_x production is obtained due to the lower thrust setting required. Clearly, aircraft empty weight and trip fuel are challenging parameters for aircraft designers and airline operators, since restricting them will have a direct effect on fuel consumption as well as on the emission of NO_x .

Another observation from Fig. 7 is that the optimum altitude at which $(EINOx)_{min}$ occurs, is almost independent of aircraft weight.

Fig. 8 shows that when at a given airplane weight the higher the airspeed, the higher the NO_x production and the lower the optimum cruise altitude.

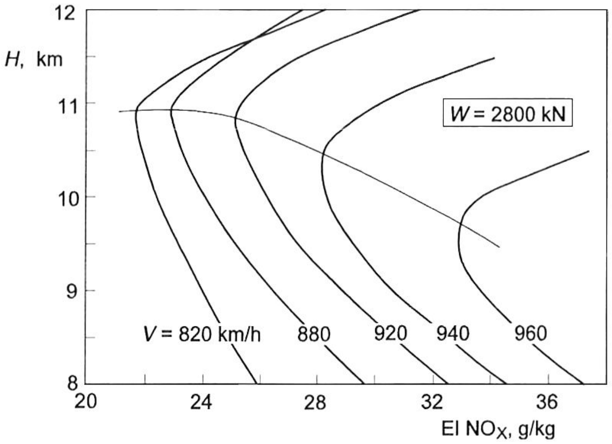

Fig 8. NOx – emission index as functions of altitude and airspeed.

According to the definition of the pollution number, the effect of varying cruise conditions on PNOx (= EINOx /(V/F)) is the combined effect of NO_x - emission index and specific air range. From these two influences the curves shown in Fig. 9 result.

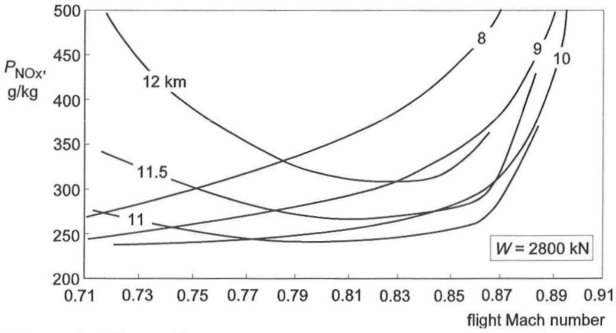

Fig 9: NOx – pollution numbers as functions of Mach number and altitude.

It can be seen that at an altitude of approximately 11 km, a minimum for PNOx will occur. Apparently, hardly any variation of $(PNOx)_{min}$ with flight Mach number is found. It appears that the altitude yielding the lowest pollution number is virtually independent of cruise Mach number. Beyond a Mach number of 0.86, the pollution number increases sharply.

The effects of flight Mach number on range performance for low-NO_x emission, are shown in Fig. 10. The NO_x - reductions and associated changes in cost and fuel are expressed in terms of percentages. The data are obtained by considering the cruise part of the flight only and assuming that the airplane is allowed by ATC to perform a cruise climb. Also, the additional fuel consumption, NO_x emission, and cost change due to an extended climb to a higher initial cruise altitude, are neglected.

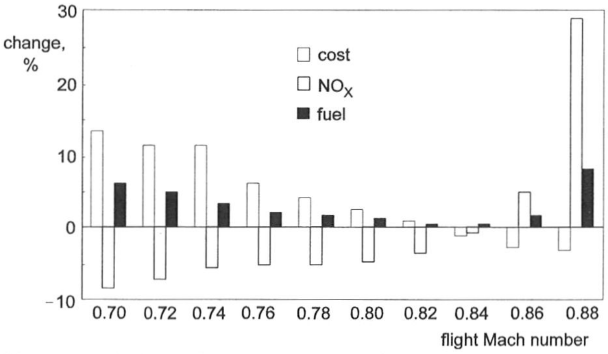

Fig 10: Effect of flight Mach number on changes in NOx, fuel and cost for low NOx floght of 5800km.

The diagram shows, as an almost general result, that NO_x - reductions up to 10% are achievable as the cruise Mach number is lowered. However, this measure is accompanied by a considerable cost increase and also penalizes the flight time. Obviously, a reduction in NO_x is also attended by an increase in fuel consumption, leading to an increase in CO_2 and H_2O emissions. The harmful effect of these pollutant species should be carefully weighted against the harmful effects of NO_x.

As mentioned before, emissions of NO_x affect global warming indirectly through tropospheric ozone formation. This process is highly dependent on altitude, latitude, and season, as different chemical regimes will produce different amounts of ozone for the same amount of NO_x. Therefore, the resulting environmental harm may be represented by the product of NO_x and its Global Warming Potential (GWP) value as a weighing factor [3].

To this end, use may be made of the curve shown in Fig. 11, which would be valid at mid-latitudes and summer atmospheric conditions.. The curve is established originally in [13], where is stated that they must be seen as a first approximation only.

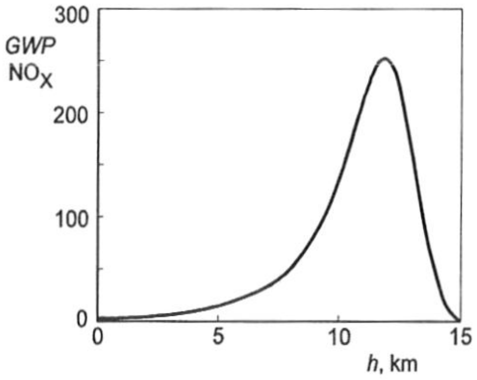

Fig 11: GWP-NOx versus altitude

4 Epilogue

The production of NO_x can be affected by changing the cruise conditions of the aircraft, however, at the expense of a considerable cost increase. This fact makes that the magnitude of the improvements predicted in [9] are of a limited significance for solution to the problem.

Doubtless, implementation of environmental design criteria focused on preventing NO_x - emissions, may demand for drastic changes of future aircraft configurations, introducing a lot of attendant problems. Moreover, it will require several aircraft related technological developments having large influence on the aviation system as a whole.

Therefore, it is hoped so that also combustor design changes will yield a substantial reduction of NO_x production.

The principle of the latter approach is to prevent the gases in the combustion chamber of the engine from exceeding a temperature critical to the formation of nitric oxide NO. Today, the most advanced concept is a lean combustion process, which is achieved by feeding the whole of the compressor air directly to the combustion chamber. One of the real problems in its application is that a weak mixture is more difficult to light, especially a relight after a flame blow-out under high-altitude conditions. The challenge right now is to develop injector designs that are able to cope with such conditions while meeting targets for low emission [6].

Obviously, of vital importance is the fact that the latter solution would have no major effects on the operation of existing airliners and on the design of future aircraft.

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