16.50 Lecture 35

Subjects discussed: Pollutant. Motivations for control. Formation. Strategies for reduction

Motivations for control

The motivations for control of emissions from aircraft, other than purely esthetic or ethical, stem from legislation regulating the amounts of emission in the neighborhood of airports, and the possibility of regulation of emissions into the upper atmosphere. We will discuss each of these in turn.

Emissions in airport neighborhoods;

In 1973 the EPA published standards, to go into effect in 1979. They are compared in the table to the actual emissions from three engines in wide use at the time the standards were issued.

1979 EPA Proposed Standards

	1979	Actual Emissions		
Pollutant	Std	JT8-D	JT9D-7	CF6-50
CO	4.3	1.9	10.4	10.8
UHC	0.8	2.7	4.8	4.3
NO_X	3	8.0	6.5	7.7
smoke*	19-20	visible 4	1.3	

All values are grams per kg thrust, per hr. in standard approach-taxi-takeoff cycle.

* Smoke, $SN = 100(1 - \dfrac{R_S}{R_W})$, the reduction in optical transmission through a glass witness plate exposed for a prescribed time.

Since the FAA has regulatory jurisdiction over civil aviation, the implementation of these standards fell to it. In July 1973 FAA issued SFAR27 to enforce only smoke regulations but 1979 regulations were never incorporated into regulating process.

Note: Manufacturers lobbied against them on the basis that the increasing pressure ratios required for better fuel consumption would make their realization difficult.

In 1981 ICAO issued international emissions standards in terms of g/kg fuel:

Pollutant	Standard
CO	118
UHC	19.6
NOx	$40 + 2(\pi_{00})$
Smoke	$83.6 \, (F_{00})^{-.274}$

π_{00} = rated pressure ratio F_{00} = rated thrust in Newtons

In 1990 FAR 34 was issued by the FAA, regulating only smoke and unburned hydrocarbons, and setting the limits for these essentially at the values attained by the oldest engines in operation.

The Committee for Aviation Environmental Protection (CAEP), an international organization under ICAO, has periodically updated the emission limits on NO_X. The various CAEP regulations, including CAEP-6 , in effect as of 2008, are displayed in the figure below. The units on the ordinate are in grams of pollutant per kN of thrust, averaged over a standard airport turnaround cycle. The abscissa is the overall pressure ratio of the engine. For reference, the CAEP-1 regulation is from 1986, and the CAEP-4 is from 1998. It is clear that the trend is to tighten the emission rules over time, and also that commercial engines do comply, as they must, with the rules in effect at the time they enter service (and usually ahead of time, in anticipation of further strengthening of the rules).
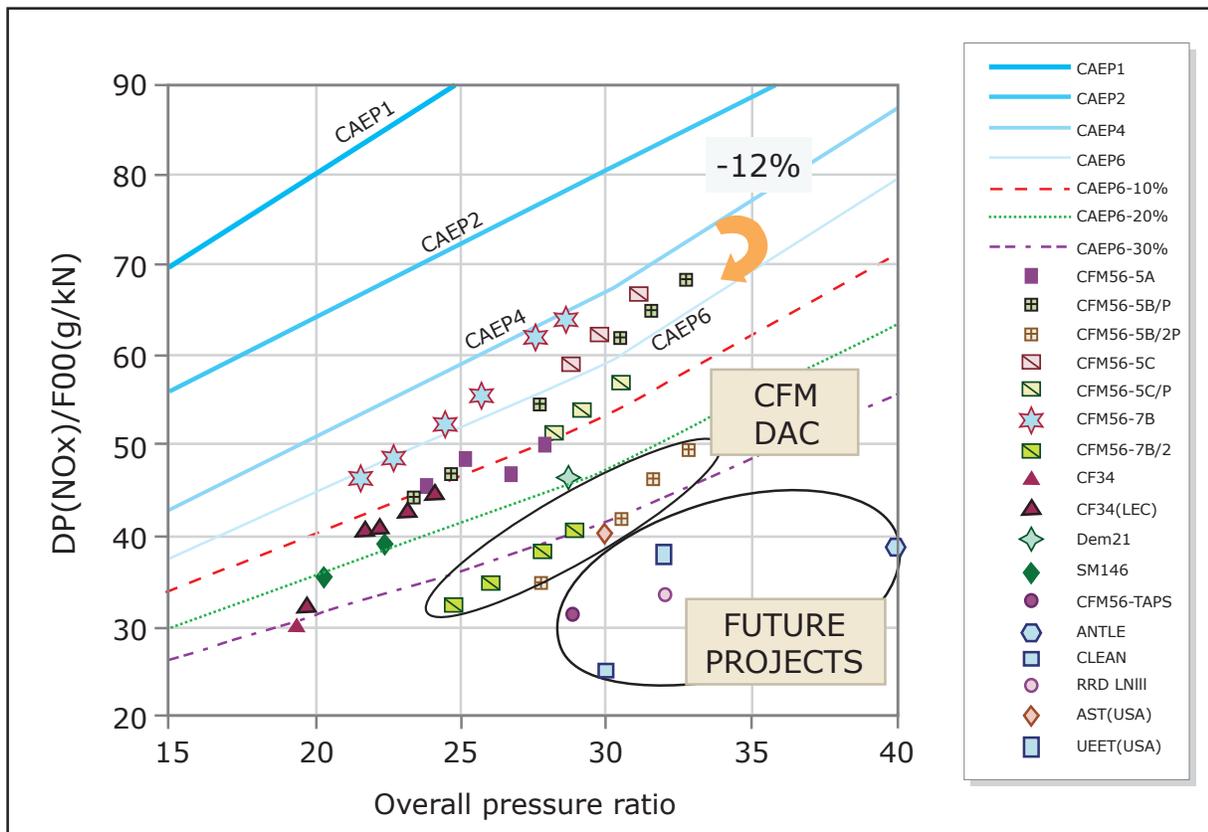
Image by MIT OpenCourseWare.

Mechanisms for formation of pollutants;

The principal pollutants are Unburned Hydrocarbons, Carbon Monoxide, and Nitrogen Oxides. They are formed as follows.

UHC - mostly at idle and low power, due to poor atomization etc. Also from venting of fuel systems.

<u>CO</u> - Due to fuel-rich combustion in primary zone.

<u>Smoke</u> - Due to fuel-rich <u>droplet</u> burning by diffusion flames

NO_x - Following an element of fuel and air through the combustor we would see the following history of temperature and concentrations.
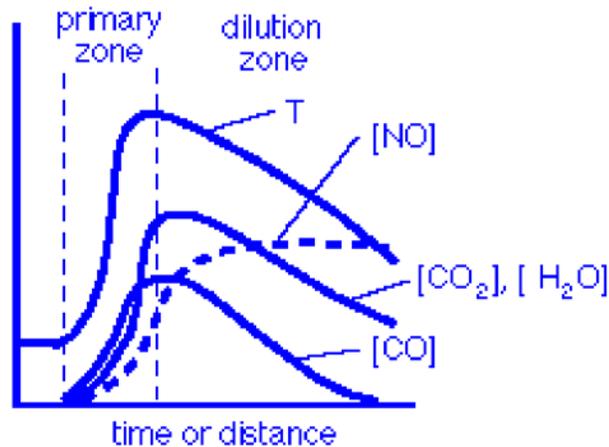
From Kerrebrock, Jack L. *Aircraft Engines and Gas Turbines*. 2nd edition. MIT Press, 1992. © Massachusetts Institute of Technology. Used with permission.

During this transport, NO_x is formed by the following sequence of reactions.

$$N_2 + O \Leftrightarrow NO + N; \quad \text{where the O is from (near-equilibrium) dissociation of}$$

$H_2O, O_2:$

$$K_p(T) = \frac{p_0^2}{p_{02}}$$

$$N + O_2 \Leftrightarrow NO + O$$

$$N + OH \Leftrightarrow NO + H \quad \text{where the H, OH are also from dissociation}$$

$$\frac{d[NO]}{dt} = 2k[N_2][O] \approx [N_2][O_2]^{1/2} \times 1.45 \times 10^{17} T^{-1/2} e^{-\frac{69,460}{T}}$$

(units are mol, cc, K)

The result of this set of reactions can be summarized as in the figure (for 1 atm. pressure, starting at 700K).
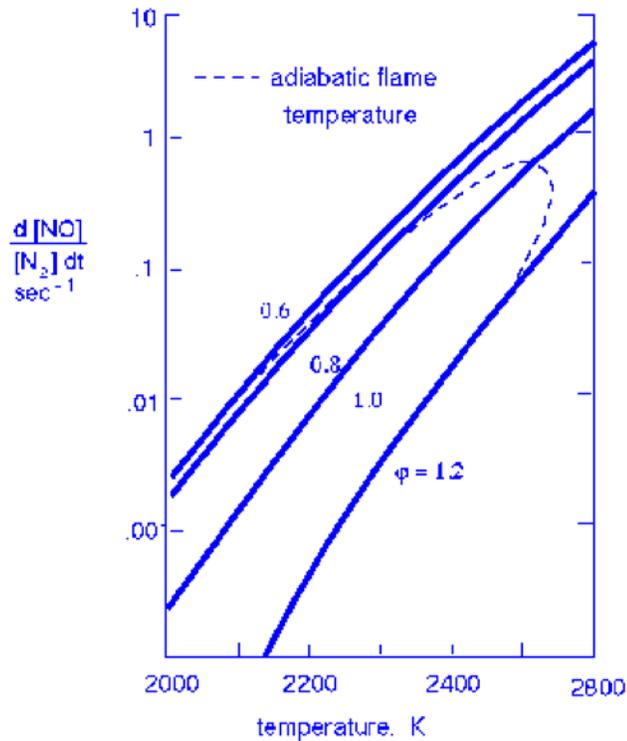
$$\frac{d\,[NO]}{[N_2]\,dt}\ sec^{-1}$$

adiabatic flame temperature

0.6

0.8

1.0

$\varphi = 1.2$

temperature, K

From Kerrebrock, Jack L. *Aircraft Engines and Gas Turbines*. 2nd edition. MIT Press, 1992. © Massachusetts Institute of Technology. Used with permission.

Strategies for reducing NO_x

    a) Premix and burn lean
    b) Burn rich and then dilute and cool quickly

Upper-Atmospheric Emissions:

Here the threat is to the O_3 in the upper atmosphere. No regulations are in place as yet for aircraft, although there is an international agreement limiting the manufacture and sale of fluorocarbons.
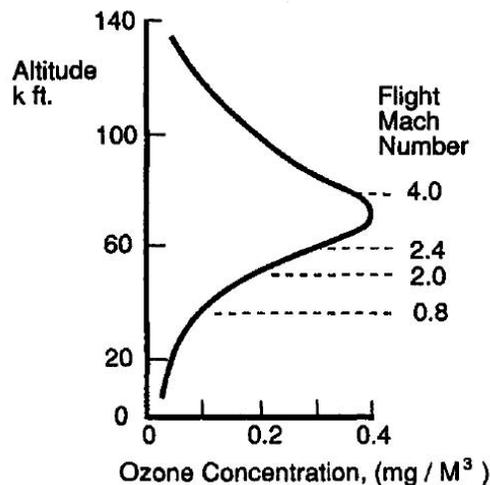
Altitude k ft.

Flight Mach Number

4.0
2.4
2.0
0.8

Ozone Concentration, (mg / M^3)

From Kerrebrock, Jack L. *Aircraft Engines and Gas Turbines*. 2nd edition. MIT Press, 1992. © Massachusetts Institute of Technology. Used with permission.

a) Formation of O_3 (the Chapman cycle):

Molecular oxygen provides a reservoir of O atoms through photodissociation by UV solar radiation:
$$O_2 + hv \rightarrow O + O$$
The atomic oxygen reacts rapidly in a three-body reactionwith molecular oxygen, to form ozone:
$$O + O_2 + M \rightarrow O_3 + M$$
The population of ozone is mainly controlled by its destruction though photodissociaation:
$$O_3 + hv \rightarrow O + O_2$$
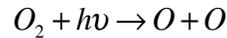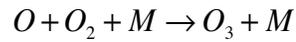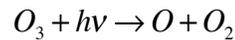
b) Effect of Nitrogen oxides:

The natural effect is the continuous upwards transport of NO_2 from the troposphere and its photodissociation to NO and O. This is followed by ozone destruction by

$$NO + O_3 \rightarrow NO_2 + O_2$$
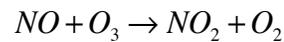
The natural transit time of NO_2 from the troposphere is as long as 100 years, so even a small amount of NO andNO$_2$ released in-situ by high-flying aircraft could potentially lead to a strong acceleration of the ozone destruction.

c) Other effects:

In addition to these NOx concerns, recent information suggests that the particulate content of the exhaust, largely sulfuric acid drops formed from the sulfur in the fuel, is a major factor in the overall effect on the atmosphere.

16.50 Introduction to Propulsion Systems
Spring 2012