M. Kroon, R. Smit and J. van Ham (Editors), Freight Transport and the Environment
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EMISSIONS FROM AIRCRAFT: STANDARDS AND POTENTIAL FOR IMPROVEMENT

D.M. Snape and M.T. Metcalfe
Combustion Department, Rolls-Royce plc, P.O. Box 31, Derby, DE2 8BJ United Kingdom

ABSTRACT

The paper will consider firstly the types of exhaust emissions produced by aircraft gas turbine engines and then attempt to put these into context in both global and local airport terms with particular emphasis on freight transport.

The basic operation of the gas turbine combustor and the need to maintain a high standard of airworthiness will be discussed and the various techniques which have been used to bring about emissions reductions described. This leads into consideration of the likely trends in emissions from aircraft sources as air traffic growth occurs and discussion of the need for future technological developments to bring about emissions reductions. Finally the various levels and types of technology which are associated with differing emission reductions will be considered.

AIRFREIGHT TRANSPORTATION

Aircraft engine emissions have mostly been considered in the context of passenger transportation. Before we can consider today's situation and the potential for improvement, it is necessary to understand the structure of airfreight and its relationship to other modes of transport.

A comparison of United Kingdom domestic freight transport (figure 1) shows that airfreight is insignificant on a

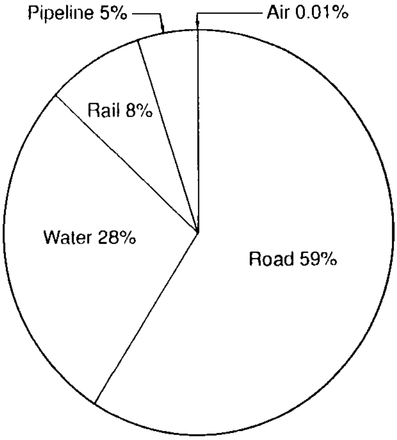


Fig 1. 1988 UK domestic freight transport, by tonne-km.

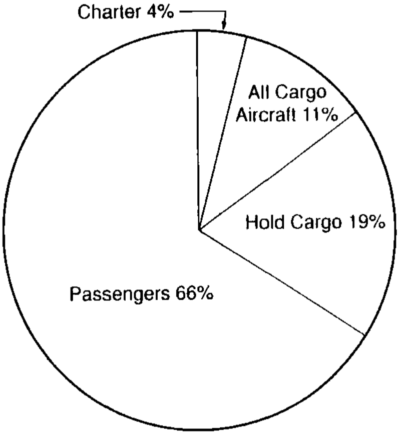


Fig 2. IATA air transport breakdown, by tonne-km.

tonne-kilometre basis. On a wider scale, comparison shows that total world airfreight (ICAO members, excluding the USSR and GDR) is equivalent to 25% of U.K. or 1% of U.S. domestic freight transport (1).

An analysis of the air transport market (figure 2) shows that freight accounts for 30% of all tonne-kilometres performed by IATA airlines (2). Approximately two-thirds of all freight is transported in the holds of passenger aircraft. This has resulted from the introduction of wide bodied passenger aircraft which have much larger cargo capacities compared with their older narrow bodied counter parts (3). This is important in the context of aircraft engine exhaust emissions since it implies that a large proportion of freight is carried in modern aircraft, rather than old converted passenger aircraft. The re-engining of older freighters, with modern fuel efficient engines, will also result in overall reductions in emissions from this sector of the fleet.

Airfreight has been predicted to grow annually until the turn of the century by 6-8% globally and 3-4% within Europe (3-5). It is expected that the distribution of airfreight between passenger aircraft holds and pure freighters will remain broadly similar.

Because the majority of freight is carried on passenger aircraft, there will be a great similarity in the emissions situation between passenger and freight transportation.

AIRCRAFT EMISSIONS IN CONTEXT

The problem of aircraft noise and the technology improvements which have brought about a dramatic reduction in noise levels are obvious to anyone living under an aircraft flight path. The improvements which have been made in exhaust emissions are less obvious, but have been continuing in parallel.

On initial reading a list of the exhaust emissions from an aircraft gas turbine, figure 3, looks formidable. It is important to see such a list in context.

There have been a number of studies on the contribution made by aircraft to both airport and global emissions (6-8). These studies have generally concluded that the contribution from aircraft gas turbines is negligible in both cases compared with other sources such as motor vehicles.

A comparison of aircraft and heavy goods vehicle (HGV) emissions on a grammes per tonne-kilometre basis is shown in

Fuel Venting - Raw Fuel Engine drains, etc (now prohibited)

Water vapour
Carbon Dioxide (CO_2)

Carbon Monoxide (CO)

Hydrocarbons (HC) - Olefins, paraffins, aromatics

Oxides of nitrogen (NOx) - NO, NO_2

Smoke - Carbon particles

Oxides of sulphur (SOx) - SO_2, SO_3

Fig 3. Exhaust emissions from aircraft gas turbine engines.

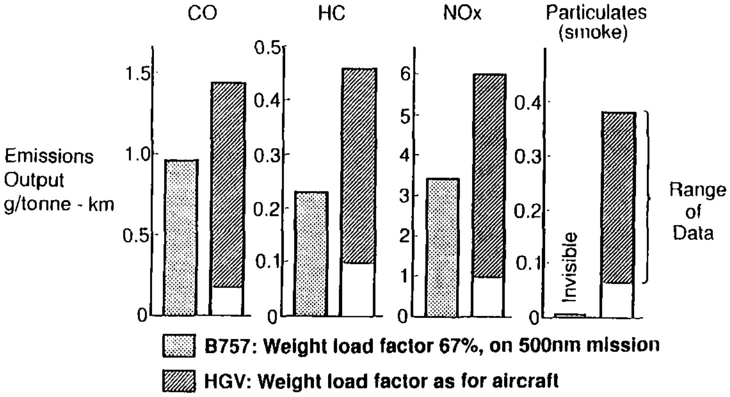
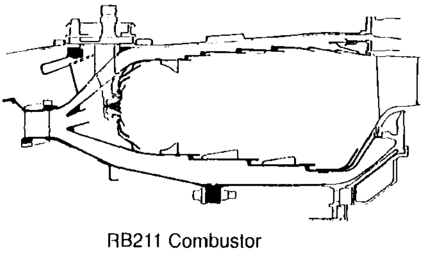


Fig 4. Comparison of aircraft and HGV emissions.

figure 4. The HGV emissions data (9) covers a range of vehicle weights and this leads to a wide variation in emissions. The aircraft emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) fall broadly within those for HGV vehicles. The particulate emissions of aircraft engines are much lower, and invisible throughout the flight cycle.

THE GAS TURBINE COMBUSTOR

A gas turbine combustor, figure 5, accepts air from the high pressure compressor at a temperature of typically 850K and a pressure of 3.5 MPa, at high power conditions. Fuel, aviation kerosene, is burnt at approximately 2500K, with typical heat release rates of 100 MW in a volume of 85 litres. The combustion designer must take into account a large number of requirements which are placed on the combustor, some of which are shown in figure 5. Paramount always amongst the requirements, are those which impact on airworthiness.



- Integrity - Reliability
- Exit temperature distribution-Turbine integrity
- Flame stability
- Relight at altitude
- Emissions
- Pressure loss-Fuel consumption
- High combustion efficiency
- Cold starting
- Weight, cost, length

Fig 5. The gas turbine combustor and its requirements.

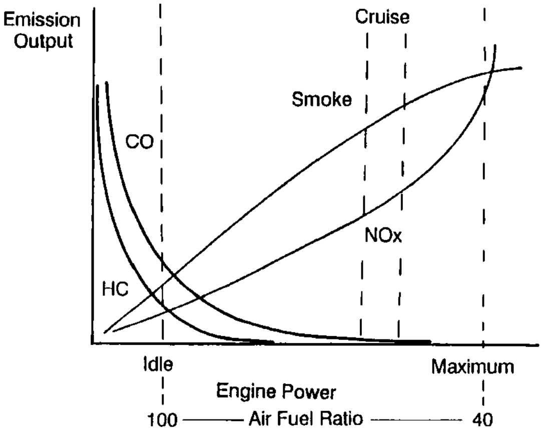


Fig 6. Gas turbine combustor emissions characteristics.

Typical emissions characteristics for a gas turbine combustor are shown in figure 6. It can be seen that the production rates of different species are dependent on engine power setting. At low power settings around idle, hydrocarbons and carbon monoxide can be produced in substantial quantities and the lack of complete oxidation of these represented an inefficiency which in the designs of the early 1960's amounted in some cases to 15%. As power increases and the combustor fuel air ratio becomes richer the nitrogen in the air is exposed for longer at high temperatures combining with oxygen to form oxides of nitrogen. Smoke also increases at higher powers due to the increased pressure levels and richer fuel air ratios. The shape of the emissions characteristics leads to a number of conflicts in designing low emissions combustors. As an example, if the combustor is designed to operate at a rich air fuel ratio at idle, to ensure complete oxidation of CO, this would lead to substantial NOx and smoke production at high power.

Despite the design difficulties substantial progress has been made in our understanding of the combustion process and this has led to large reductions in combustor emissions whilst maintaining or improving on other aspects of combustor performance (Fig 7). This has been achieved in the case of the Rolls-Royce Spey and Tay engines by the use of novel technology (10).

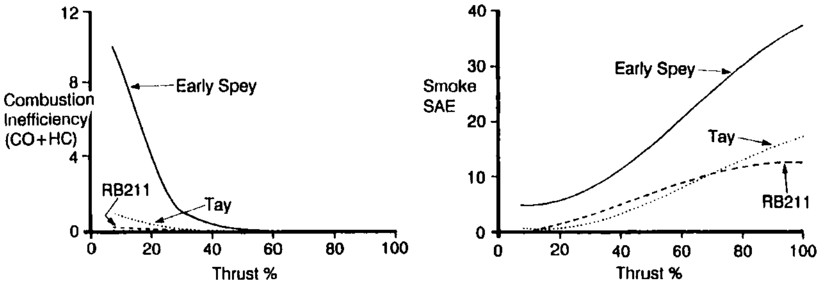


Fig 7. Achievements in reduced engine emissions.

THE CURRENT EMISSIONS SITUATION

The impetus for the improvements over the past decades, was initially driven by the requirement for improved combustion efficiency and, therefore, reduced fuel burn. This was soon followed by the introduction of emissions regulations which started with the passing of the US Clean Air Act and the formation of the US Environmental Protection Agency. The objective of the legislation was to achieve invisible exhaust plumes and to limit emissions in the vicinity of airports, for which a representative landing - take-off cycle was developed, as a basis for legislation and comparison (Fig 8).

Currently the US legislation covers HC and smoke emissions and this standard has also been adopted by the UK. ICAO have recommended the adoption of these HC and smoke standards along with ones covering CO and NOx. So far, only a few countries have adopted the full ICAO standards, but engine manufacturers ensure all modern civil engines comply with the ICAO recommendations.

More recently with the introduction of local air quality standards within the EEC, and other countries, the actual airport environment has become a more prominent issue.

The potential benefits from improvements in combustor technology have been assessed by Rolls-Royce (11). A complete inventory has been compiled, of all newly-manufactured western civil transport aircraft in three time periods. Data from the ICAO engine emissions data bank have been used to show how the mass of emission per passenger LTO cycle has changed with time as new technology has been developed (Fig 9). Since the majority of airfreight is carried by passenger aircraft, these trends will be equally applicable to freight transport. It can be seen that dramatic reductions have been achieved in HC and CO production whilst reductions in NOx are smaller. In the same time periods, however, the continuing drive for improved fuel consumption has led to an increase in engine pressure ratio which, had NOx control technology remained constant, would have led to a substantial increase in NOx emissions. The environmental benefits of improved emissions control technology will only be realised as engines incorporating new combustors are introduced into service. The actual position at the end of 1988 is one where the longevity of both airframes and engines has led to little fleet penetration.

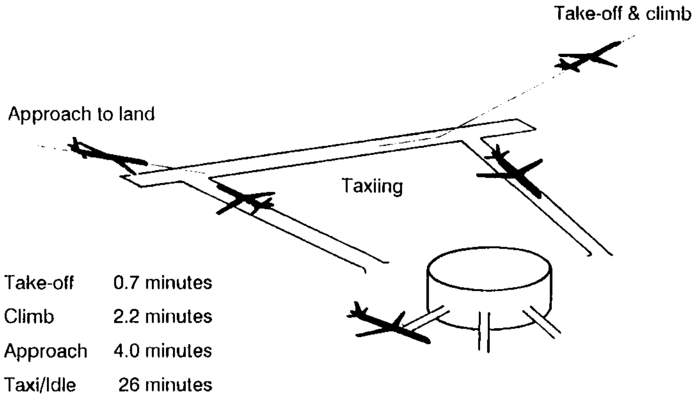


Fig 8. Landing-Take-off cycle for calculation of total emissions below 3000ft.

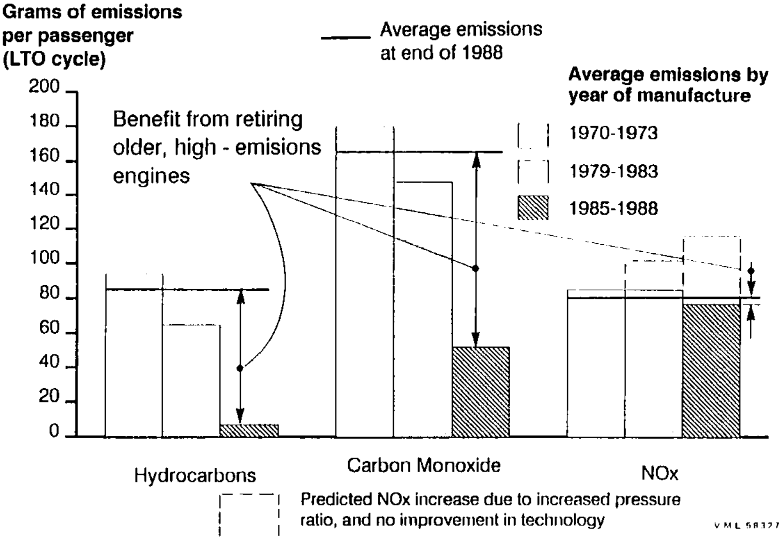


Fig 9. Current and potential improvements in aircraft emissions.

Thus it should be the case that as older airframe - engine combinations are replaced for noise reasons there will also be a beneficial side effect on emissions.

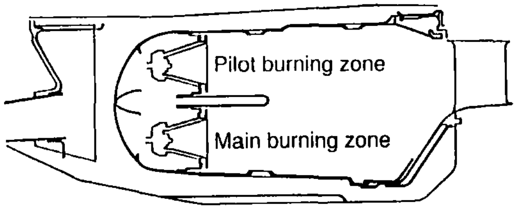
The pace of introduction of technology can, of course, be forced by government and Sweden is an example where government policy has made it economically attractive to airlines to introduce low emissions technology, in some cases by retro-fitting improved combustors to an existing fleet.

The current position is, that technological improvements have resulted in dramatic reductions in the smoke, hydrocarbon and carbon monoxide emissions of new engines. It is therefore difficult to justify economically the need for further work on these, however, further progress is desirable on oxides of nitrogen and possibly carbon dioxide and these will be considered in more detail.

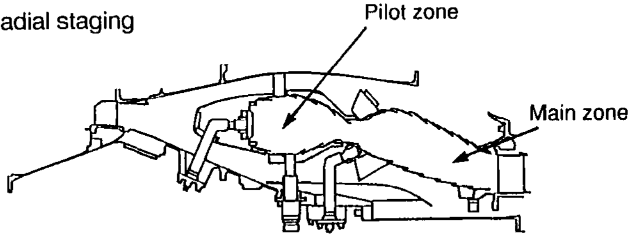
[Oxides of sulphur, whilst of major concern as an atmospheric pollutant from other sources, are not considered a problem in aircraft gas turbines since the closely controlled fuels specification permits a maximum of 0.3% sulphur].

OXIDES OF NITROGEN

The need to consider NOx comes about because of the continuing trend towards higher engine pressure ratios, for improved energy efficiency. Also, although small contributors on a global basis, aircraft concentrate their NOx at airports. These, combined with other high background sources (eg. motor vehicles) and under exceptionally adverse conditions, have been predicted to approach local air quality standards. A number of studies are in progress which should lead to a fuller understanding of the situation around airports. In addition, aircraft in flight are producing NOx directly at high altitude and, in the currently very limited case of supersonic transport, into the stratosphere where the effects are not understood (12).



Radial staging



Tandem staging

Fig 10. Staged combustor designs for reduced NOx.

Attempts to substantially reduce NOx production have tended to centre around the use of staged combustion systems which operated in either single or double burning mode depending on engine power (Fig 10). Rolls-Royce and other engine manufacturers have undertaken research on these complex combustor designs. The Rolls-Royce Radial Staged combustor (13), shown on the left hand side of figure 10, was tested in 1979, and required 72 fuel injectors and associated swirl modules, compared with 18 in the conventional design. These very complex combustors suffer from a number of inherent disadvantages, which must not be allowed to undermine airworthiness (14). Requirements include, lighting across rapidly and with complete reliability between the pilot and main zone for engine acceleration; in particular this is critically important were aircraft have to "go around" after an aborted landing. The complex fuel manifold and valve systems are potentially subject to blockage during destaging. Also the stability and water ingestion capability of the combustor when flying through rain storms is an unknown quantity. The radial staged design is also subject to exit temperature profile variations across the power range, which can adversely effect turbine component integrity.

Another potential means to reduce NOx, (Fig 11), is the use of variable geometry which, in theory, produces an infinite number of combustor variations to match engine conditions. There are many challenges to be faced before such a system could be considered for aircraft use. High control system reliability and the ability to fail safe, for example, would be essential as the consequences of failure could otherwise be to create a severe safety hazard. In industrial applications, which have fewer power excursions, it is currently possible to consider designs which include variable geometry. Figure 12 shows a Rolls-Royce proposal for a very low emissions combustor in the industrial RB211. It is clear that bulk and weight, quite apart from complexity and thus potential airworthiness concerns, would preclude the use of such a design in an aircraft application.

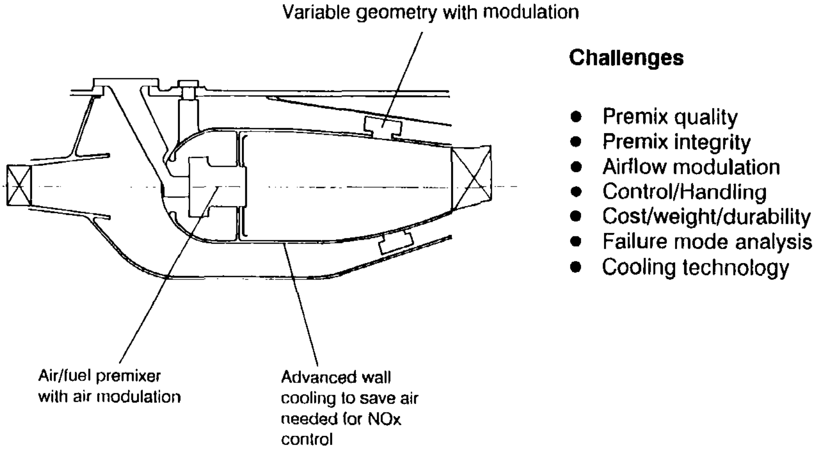


Fig 11. Variable geometry premixed combustor for low NOx emissions.

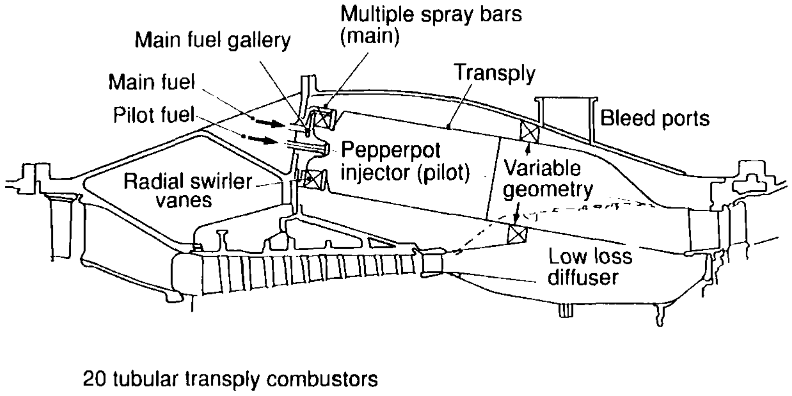


Fig 12. Industrial RB211 low NOx combustor.

CARBON DIOXIDE

It is becoming established that the burning of fossil fuels to form carbon dioxide is the major cause of the greenhouse effect. Various estimates exist which tend to show the contributions of aircraft to CO_2 production compared with other mobile and stationary sources to be of the order of 2%, (15) also the total contribution to CO_2 production from mobile and stationary sources is about on par with agricultural and natural sources.

There are a number of possible ways of reducing the contribution of aircraft to the greenhouse effect. The first is to burn less fuel by continuing the industry's quest for more efficient engines (Fig 13) and airframes (lower weight and less drag). As we have seen, this trend results in higher pressure ratio engines, and therefore potentially, increased NOx emissions. Also, reduced fuel burn can be achieved by improved aircraft load factors and, ultimately the imposition of controls to reduce air

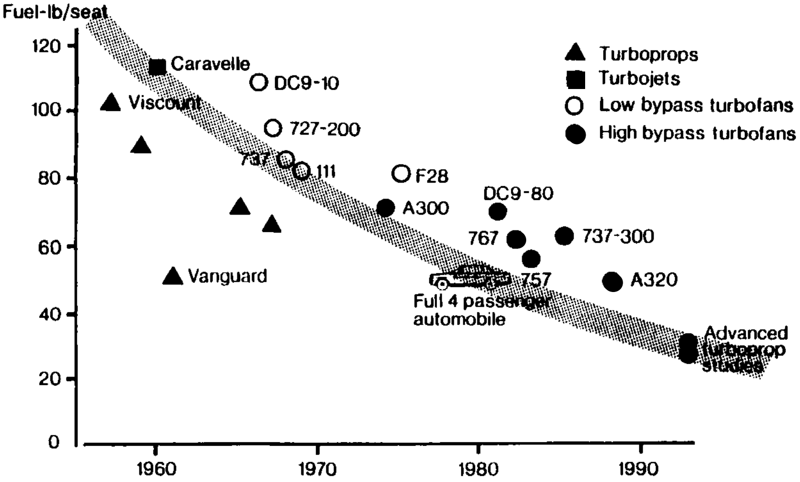


Fig 13. Aircraft fuel burn trend.

transport. Secondly, CO_2 emissions can be reduced by the utilisation of fuels with a lower carbon content. It would be technically feasible to do this from a combustion point of view, although hydrogen burning, for example, can produce more NOx due to the higher flame temperature. Another alternative is the use of biofuels where the CO_2 is continually recycled from the atmosphere. Currently, available biofuels do not have the required properties for use in the harsh environment of the aircraft engine and its operational requirements. Therefore, further work will be required to improve their properties before they can be considered.

The major problem with alternative fuels, however, comes in storage and handling both on the ground, where a large infra-structure has built up around provision of aviation kerosene, and in the air, where energy density considerations may affect aircraft range and where novel fuel handling and storage systems maybe needed, leading to new airframe designs.

CONCLUSIONS

Development in combustion technology has already brought about substantial reductions in exhaust emissions. It is clear, however, that engine manufacturers must continue to develop technology to bring about further reduction. But it is equally clear that this cannot be at the expense of safety considerations. In particular, great caution must be exercised in the introduction of complex, staged or variable geometry combustors. An EEC initiative in which Rolls-Royce will participate and which is funded under BRITE/EURAM, has commenced with the objective of discovering how far emissions levels can be safely reduced by 2000 AD, without compromise to airworthiness.

It may be that continued growth in airfreight and hence total emissions, will outstrip our ability to develop and put into service engines which incorporate low emissions technology. It must be clearly understood that whilst research and development will continue there will be no technological "magic wand".

We would like to thank the Directors of Rolls-Royce for permission to publish this paper, and add that the opinions expressed are ours and not necessarily those of Rolls-Royce plc.

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