STATUS AND TRENDS OF AEROENGINE POLLUTANT EMISSIONS

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Abstract

The Environmental effects issue of air traffic has been gaining increasing public attention. This has led to a considerable world-wide effort to reduce aircraft emissions. The task encompasses a broad variety of scientific and technological problems which are reviewed.

The concerns about atmospheric effects have been based largely on laboratory information and experience from weather and climatic simulations. Research carried out over the past few years will improve the understanding of physical and chemical interaction phenomena and will support regulatory activities. Operational changes of airline flight profiles would be of benefit to the reduction of NOx released into the stratosphere but would probably involve a major economic penalty. Emissions reductions through improved engine technology offer an overall potential of 10 % lower fuel burn but will also require a considerable component development effort and investment.

Combustion technology appears most promising and industry is concentrating research in this area. Over the past two decades smoke emissions have become negligible and oxides of nitrogen have been reduced by 50 %. Staged combustion and emerging lean premix and rich-burn quick-quench lean-burn technologies are potentially good for another 50 % reduction. Alternative gaseous fuels will become of interest only in the context of a necessity to generally replace crude oil fuels.

Symbols and Abbreviations

BPR		Bypass ratio
CIT	K	Combustor inlet equal to compressor exit total temperature
D	g	Emitted mass per ICAO LTO cycle
DLR		German Aerospace Research Establishment
EI	g/kg	Emission index, ratio of the emitted species mass flow to fuel mass flow
F	kN	Thrust
FAR		Fuel/air ratio, ratio of fuel to air mass flow
LPP		Lean premixed prevaporized
Pkm		Passenger kilometers
PR		Pressure ratio
RQL		Rich-burn, quick-quench, lean-burn
SFC	kg/Nh	Specific fuel consumption
SN		Smoke number
TET	K	Turbine entry equal to combustor exit total temperature
T.O.		Take Off
Φ		Equivalence ratio, ratio of actual FAR to stoichiometric FAR

Introduction

Pollutant emissions from commercial aircraft have been an environmental concern since the 1960s. The industrialized countries became sensitive to the issue with the Meadows Report to the Club of Rome in 1972 (1). Social sensitivity has grown ever since both due to the continuous world wide increase of environmental pollution as well as the advanced technologies which permit a better understanding of the global effects.

The concerns involve the toxicity of pollutants, the green house effect and the stratospheric ozone depletion phenomena.

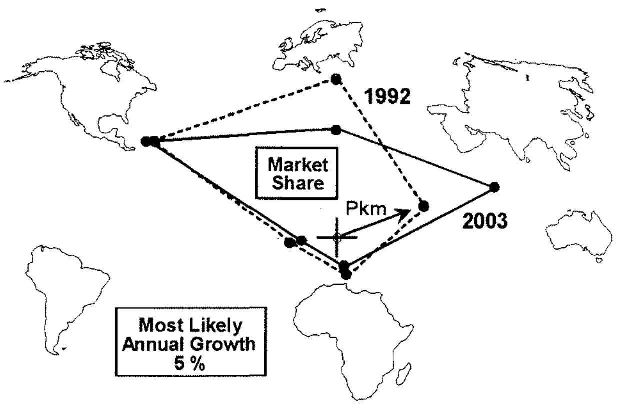


Fig. 1 Scheduled passenger traffic market share and growth forecast

Although air traffic only a minor contributor to the majority of these problems the exposure to the public is disproportionately high.

Jet aircraft accounted for less than 1 % of the total emissions in the USA in 1989 (2). Total carbon dioxide emissions at the Munich airport in 1993 were estimated to be 200000 t, oxides of nitrogen and carbon monoxide 800 t each. Summing up global emissions tends to generate incomprehensible numbers.

In view of these numbers and the ICAO projection that annual growth of passenger air traffic will be 5 % to the year 2003 (3), with a large shift in the market share of passenger km (Pkm) from Europe to the Far East (Fig. 1) it is obvious that government and industry must continue their efforts to reduce the impact of aviation on the environment. These efforts include atmospheric research, regulatory activities, aircraft design and operational aspects, thermodynamics of the engine, combustion technology and fuels. These problems will be reviewed and an attempt will be made to forecast near and long term developments.

Composition of the Engine Exhaust Environmental Impact on the Atmosphere

The engine exhaust consists of a variety of gaseous and particulate material with the following emission indices.

		EI g/kg fuel	
		T.O.	Idle
Nitrogen	N_2	32000	112000
Oxygen	O_2	6300	30000
Oxides of Nitrogen	NOx	40	4
Carbon Dioxide	CO_2	3100	3100
Water	H_2O	1300	1300
Carbon Monoxide	CO	1	40
Unburned Hydrocarbons	UHC	0,2	15
Soot (Smoke)	C	0,01	0,02
Oxides of Sulphur	SO_2	0,5	0,5

The first two constituents are the portion of air not participating in the combustion process. Oxides of nitrogen are by-products of the combustion reactions. Carbon dioxide and water are the final products from the release of chemical energy and are unavoidable when burning fossil fuels. The rest result from imperfect combustion. The last species is presently of little concern, since aviation fuels have a very low sulphur content.

CO and NOx are toxic, the latter contributes also to acid rain and to chemical smog in the atmosphere and is presently believed to participate in the depletion of ozone in the stratosphere. UHC and smoke contribute to urban smog and can cause respiratory diseases. CO_2 is a green house effect gas preventing infrared radiation from the surface of the earth from being emitted into outer space. Water forming ice particles should have a similar effect by reflecting such radiation back to earth.

The total amount of exhaust emissions is determined by the overall efficiency of the aircraft. This is both the thermodynamic cycle of the engine as well as the aerodynamic drag of the airframe. Ultra high bypass ratio engines with lower specific fuel consumption or wings with laminar flow control will benefit the reduction of all emissions.

The levels of the green house effect products CO_2 and H_2O depend also on the composition of the fuel. Alternative fuels may be of help.

The remaining constituents of the exhaust are directly affected by the quality of the combustion process. The aeroengine industry and researchers concentrate their activities on the improved control of fuel preparation and the burning process to reduce these emissions.

Environmental Research Activities

Larger scale research activities on exhaust emission environmental issues were initiated twenty five years ago. These included the *Climatic Impact Assessment Program* in the USA and the industrial development work by General Electric and Pratt & Whitney on staged combustion (4). The work was rather abruptly interrupted because of the *Oil Crisis* in the early 70's and priority was shifted to the reduction of fuel burn. This generated the *Energy Efficient Engine (E^3) Program* in the USA which accelerated the introduction of high bypass ratio engines into commercial aircraft with a major success on the reduction of fuel consumption and noise.

A revival of climatic concerns happened in the 80's, when continuous monitoring identified global warming, the rising of the carbon dioxide content of the atmosphere and the ozone layer depletion over the Antarctic. A large number of national and international research programms were launched and are still in progress or being planned.

The world wide research covers two main areas. The atmospheric and climatic response to pollutants and the technological potential of reducing exhaust emissions from aircraft (5). The atmospheric and climatic research includes investigation of the chemistry involved, atmospheric transport phenomena and global modelling, interactions between the troposphere and the stratosphere, aircraft exhaust effects on high density commercial aviation routs, local immission levels in the vicinity of airports and mapping of the immissions status.

International European research is organized in the Community's Environment and Aeronautics

Research Programms of the European Union. Atmospheric Research activities include four programms (6).

- *AERONOX*
  Integrates atmospheric science and engine technologies to assess the impact of aircraft emissions on the atmosphere.

- *MOZAIC*
  Collection of ozone and water vapour data over northern and southern hemisphere air-routes with automatic measuring units installed in five Airbus A340 aircraft of Lufthansa, Air France, Sabena and Austrian Airlines (7).

- *POLINAT*
  Measurement of the composition, distribution and chemistry dynamics of aircraft pollutants in the eastern part of the North Atlantic flight corridor.

- *STREAM*
  Development of an instrument package to measure the influence of aeroengine exhaust gases on the chemistry of the upper troposphere and the lower stratosphere.

The USA are engaged in very comprehensive similar programms integrated in the *Atmospheric Effects of Aviation Project (AEAP)* (8) including

- *AESA*
  Part of the NASA High-Speed Research programm to study supersonic transport technologies.

- *SASS*
  Complementing AESA by covering advanced subsonic transport issues.

AEAP is subdivided into six areas of work

- Emissions Characterization
- Near Field Interactions
- Operational Scenarios
- Laboratory Studies
- Atmospheric Observations
- Global Modelling

Several national programms complete the atmospheric research activities.

- Avion et ozone (France)
- Pollutants from Air traffic (Germany) (5),(9)
- Basics of the Impact of Air and Space Transport on the Atmosphere (Germany)
- Routine Whole Air Sampling Programm with Boeing 747-200 Aircraft (Japan) (10)
- Measurement of NO, NO_2 and O_3 from a Swissair Airliner (Switzerland) (11)

Combustion Research Activities

Combustion research activities are not as spectacular as atmospheric research, but they are just as intensive. Investment in engineering work is more industry oriented. Also because of the competitive aspect, results are not as visible in the public domain.

International research is practically organized internationally only within the European Union for the so called pre-competitive phase. This is also where most of the academic research is located. Combustion research is part of the BRITE EURAM overall programm and is centred about two major groups investigating the problems of small engines (helicopter, APU's) and large engines (commercial turbofans). Both tasks cover detailed research on performance and emissions improvement technologies as well as alternative combustor concepts(12). Involved are practically all EU countries grouping around the aeroengine industries of the United Kingdom, France, Germany and Italy.

The US have launched a major effort initiated by the activities within the High Speed Commercial Transport (HSCT) programm. Originally designed for the needs of supersonic transport, research has been extended to all aspects of combustion similar to the EU programm.

There is limited publicity on national programms which is partly due to the connection to military projects. Pre-competitive research in the United Kingdom is supported by the Civil Aircraft Research and Demonstration (CARAD) programm. Combustion has high priority within the propulsion systems work.

Germany has also launched a similar programm covering aeronautical research. Part of this is the Engine 3E (Environment, Efficiency, Economy) Programm with a major component in low emissions combustion. A parallel programm for high temperature turbines which has been in progress for some time now covers also environmental pollution aspects. Both these programms are collaborative among industry, academia and the DLR. Fundamental research beyond this at the universities is supported by the German Research Foundation.

National and International Regulations

Emissions regulations have been initiated by the Environmental Protection Agency (EPA) in the USA with the Clean Air Act in the 1970s. Specific regulations for aviation were developed by the International Civil Aviation Organization (ICAO), reporting to the United Nations. ICAO identifies emissions limits in Annex 16 Volume II (13) of the Chicago Convention. They are effectively mandatory for certification and production of aeroengines.

The widely quoted ICAO limits referred to Take Off thrust are defined for the so called Landing Take Off (LTO) cycle which accounts essentially for emissions in the vicinity of airports. For a short haul transport this is about 25 % of the total emissions (14). The presently valid limits, a time weighted sum D of emitted mass from four different operating conditions, which have to be demonstrated at certification are as follows.

- Smoke	SN	$< 83.6\ F_{TO}^{-0.274} < 50$
- UHC	D_{UHC}/F_{TO}	< 19.6 g/kN
- CO	D_{CO}/F_{TO}	< 118 g/kN
- NOx	D_{NOx}/F_{TO}	$< 32 + 1.6\ PR_{TO}$ g/kN

The overall pressure ratio of the engine appears in the nitrogen oxides limits, because it is the dominating parameter, as will be discussed later.

National legislation is usually more concerned with other sources of pollutant emissions. Special taxes apply in Sweden for aviation fuel consumption and UHC + NOx emissions.

Matching the Aircraft Design

Commercial aircraft are currently optimised for minimum direct operating Costs (DOC's). Since fuel consumption is a major contributor, this optimisation results in cruise altitudes at the tropopause level, partly because of the improved engine thermodynamic performance with decreasing ambient temperature. With the present understanding being that NOx emissions in these altitudes are detrimental to the stratospheric ozone layer, the question has arisen on the potential of reducing the effect by lower flying aircraft.

Extensive studies have been carried out in Germany on this issue and have given some interesting results (15),(16). Using the route from Berlin to Los Angeles, the flight profile was rematched to avoid cruising above the tropopause. For the aircraft currently in service this had a rather dramatic effect on performance reducing range by about 20 % respectively increasing CO_2 emissions by approximately the same amount. However, a large part of this penalty could be recovered, if the aircraft were optimised for the specific operational conditions, for example with a lower wing sweep. The engines were kept unchanged in this study so that some further improvement appears possible.

From these investigations it can be concluded that it is obviously possible to significantly reduce the effects of exhaust emissions in the stratosphere at some cost. However, more detailed studies are necessary to substantiate the results and particularly the impact on economics and higher CO_2 production. In any case, should this turn out to be a realistic solution to the problem, a complete new fleet of airliners would be required to take advantage of the optimised design.

Another interesting result from these studies is the extremely strong effect of ambient temperature on emissions. A temperature rise at a flight level because of a hot day effect of 10 K would increase NOx emissions by 10 to 20 %. This is caused by the adverse effect on the thermodynamic cycle of the engine and demonstrates clearly that the major effort needs to be directed towards improving the engine emissions characteristics.

Pollutant Generation Mechanisms

Carbon dioxide CO_2 and water H_2O may be undesirable exhaust emissions but are unavoidable as long as fossil fuel energy is used for propulsion. The amount emitted depends on the composition of the fuel and the efficiency of the thermodynamic cycle.

Unburned hydrocarbons UHC are typical of poor fuel preparation and incomplete combustion. They consist of species of small molecules from the thermal degradation chain of the fuel. They are emitted at low combustor inlet temperatures and pressures, conditions which also favour carbon monoxide CO formation. This pollutant develops in fuel-rich regions because of the lack of oxygen to complete the reaction to CO_2. In high temperature regions CO is produced owing to thermal dissociation of CO_2, in general, however, it is burned out in the cooler air-rich downstream zones, so that this latter mechanism is not of significance. The main generating process is the same as for the unburned hydrocarbons and dominates the idle and low power range.

Smoke consists of finely distributed soot particles which form in the fuel rich hot primary zone and are subsequently largely burned out. The mechanisms involved are both chemical and physical in nature and can be influenced by the fuel preparation. Modern burners and particularly air blast atomisers have effectively reduced smoke to negligible levels.

Nitrogen oxides NO and NO_2 are a special case because they are a side phenomenon not directly involved in the actual combustion process. Because of its toxicity and its potential effects on the stratospheric ozone layer, NO_x formation has been investigated quite thoroughly. Four main mechanisms of nitrogen oxide formation have been identified. (17),(18).

- Thermal NO

This is produced by oxidation of atmospheric nitrogen in the post flame gases. The reaction kinetics involved are represented quite accurately by the extended Zeldovich mechanism with the reactions

$$N_2 + O \leftrightarrow NO + N$$
$$N + O_2 \leftrightarrow NO + O$$
$$N + OH \leftrightarrow NO + H$$

These reactions are most active in the presence of the O and OH radicals. This is the case at high temperatures which also accelerate the forward reaction towards the right side products. High temperatures and residence times are therefore the parameters which determine thermal NO production (Fig. 2). Residence times in turbofan combustors are of the order of magnitude of 5 ms, thermal NO concentrations therefore are usually frozen in the dilution zone before equilibrium levels can be reached.

- The nitrous oxide mechanism
  This is another post combustion mechanism involving the formation of nitrous oxide N_2O (laughing-gas) and its reaction with other species like O, H and CO (17) to form NO. The contribution to total NO is usually not more than 1 % (19) However, for lean premixed combustion when thermal NOx contribution is extremely low the N_2O contribution becomes significant (20).

- Prompt NO
  This mechanism involves atmospheric N_2 reactions with low molecular products of the thermal decomposition of the fuel hydrocarbons. The main contributor is HCN, and NO is formed at the end of the reaction chain.

- Fuel NO
  This is formed from organic bound nitrogen in the fuel molecules. The amount generated depends on the N_2 content of the fuel.

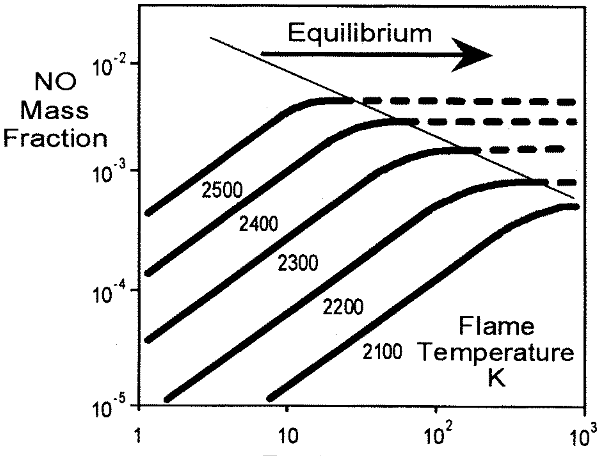


Fig. 2 Flame temperature and residence time effects on NOx formation in a combustor

Blazowski et al (21) assessed NOx emission indices to be dominated by thermal NOx for high combustor inlet temperatures, whereas prompt NO becomes a major contributor at lower temperatures, because of the limited thermal NO generation. Nicol et al (17) estimate 60 % thermal and 30 % prompt NO contributions for a 1900 K lean premixed flame. This is presently the accepted understanding of the problem (22),(23), efforts to reduce NOx emissions therefore have been concentrated on the thermal generation mechanism.

The Thermodynamic Cycle

The quality of the gas turbine thermodynamic cycle has two effects on emissions.

- An overall effect through the specific fuel consumption SFC and the weight.
- A direct effect on individual pollutants through the parameters temperature and pressure.

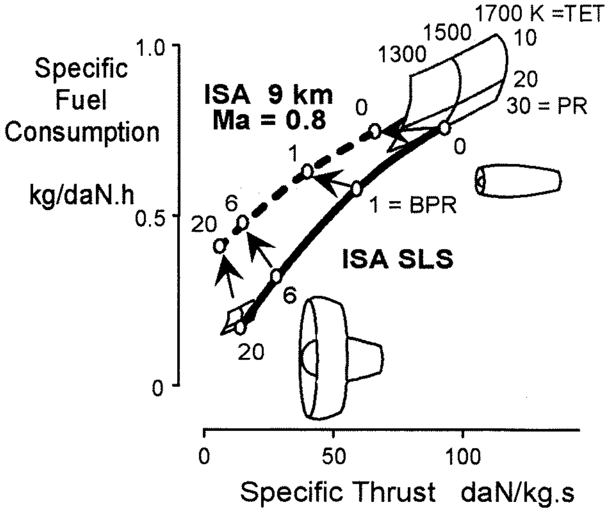


Fig. 3 Design space of turbofan engines

These effects are illustrated in Fig. 3 where specific fuel consumption is plotted against specific thrust for sea level static (ISA SLS) and altitude cruise conditions for varying bypass ratio BPR and the effects of turbine entry temperature TET and pressure ratio PR are shown in carpet form. The dramatic effect of bypass ratio on SFC at static conditions can be clearly recognised. Unfortunately it is considerably reduced at high subsonic Mach no. cruise. It can also be seen that the major part of the fuel consumption reduction potential has already been consumed by the latest generation of turbofan engines with bypass ratios of about 6.

Increasing bypass ratios lower the fuel burn through the improvement of the propulsive efficiency. This requires thrust to be generated by a low velocity high mass flow jet, which is exactly what the high bypass ratio engine does. This leads to a reduction of specific thrust and consequently to a larger and heavier engine, which has an adverse effect on aircraft take off weight. Optimum bypass pressure ratios for such ultra high bypass ratio (UHBR) turbofans become so low that they require variable geometry. The low speed of the large diameter fan makes a reduction gear box for the low pressure shaft necessary.

Also adverse is the drag rise owing to the increasing size of the nacelle. When this is accounted for into the specific fuel consumption the design range changes as shown in Fig. 4. Pressure ratio is plotted in the diagram versus bypass ratio with the parameter SFC. Optima of SFC develop at bypass ratios of approximately 13. They are quite close to those of about 9 which can be realised today without variable geometry. The potential SFC reduction between the two alternatives does not appear to be more than about 5 % , so that a major effort will be necessary to achieve worthwhile improvements with the projected ultra high bypass ratio UHBR engines.

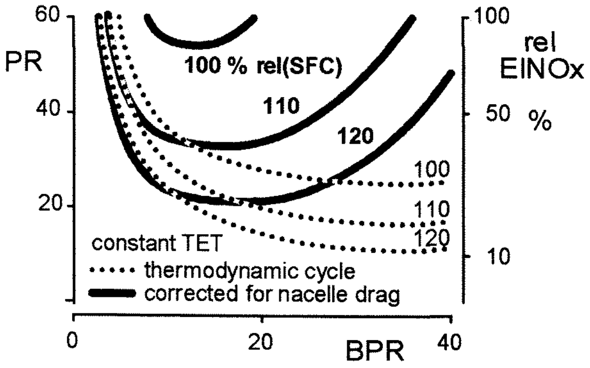


Fig.4 Nacelle size effects on turbofan design

The turbine entry temperature contributes primarily to an increase in specific thrust and thus to a reduction of size and weight. However, this is not very strong at higher bypass ratios. It has also a secondary effect in that optimum pressure ratios rise with TET. At present temperature levels optimum pressure ratios lie between 40 and 60. Besides the aerodynamic difficulties developing the necessary compressors, such engines would have very high NOx emissions (Fig. 4), if the alternative combustors discussed later do not become available.

Alternative thermodynamic cycles have been investigated extensively in the 1950s and 1960s, in the early days of the jet engine. Some of them have a considerable thermodynamic potential, but they do not appear to be feasible for practical commercial engines.

Schmidt (24) has discussed an intercooled UHBR turbofan with an exhaust heat exchanger. Light weight heat exchangers do not yet possess the necessary reliability for aircraft engines.

The principle of pressure rise combustion would improve the core engine cycle. However, the necessity for a large amplitude intermittent combustion has prohibited practical research to date. Kentfield and O'Blenes (25) review the potential alternatives of combustion-driven pressure-gain in gas turbines.

Summing up, only the conventional turbofan engine appears to offer potential improvements in the foreseeable future. This would require a major investment in component technology and could improve performance including size and weight by about 10 %.

The Emissions Problem of the Conventional Combustor

The combustor of a modern turbofan engine, in the configuration shown in Fig. 5, has to fulfil a variety of requirements.

- efficient combustion	thermodynamic cycle
- low pressure losses	thermodynamic cycle
- wall cooling	engine life
- exit temperature pattern	engine life
- adequate extinction limits	operational reliability
- relight capability	operational reliability
- resistance to rain and hail ingestion	operational reliability
- low pollutant emissions	environment

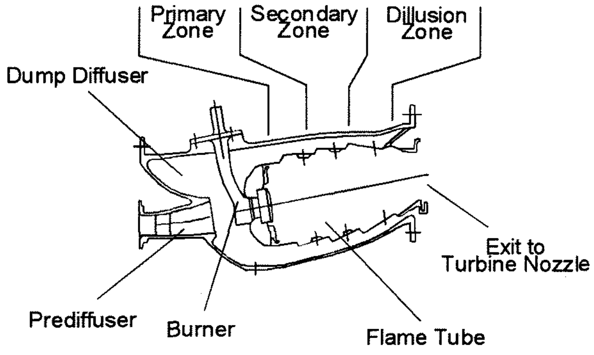


Fig. 5 Conventional Combustor

One severe requirement for the combustion is the extremely wide operating range. Gas turbine combustors have a rather low overall equivalence ratio Φ at maximum power of about 0.3 (Fig. 6) as opposed to 1.0 for reciprocating piston engines. This is due to the fact that the turbine is exposed continuously and not intermittently to the combustor exhaust temperatures. Thus the cooling capability of the turbine determines the allowable maximum overall equivalence ratio.

The idle condition, on the other end of the operating range, is at a very low equivalence ratio of about 0.1 and the weak extinction limit, encountered during deceleration transients at altitude with low pressure, is even at still lower values. In fact this range of overall equivalence ratios cannot be covered by any single combustor. The conventional approach is to use only part of the available air for combustion This amount of air is introduced into the primary zone (Fig. 5) where fuel is mainly burned. This results in equivalence ratios of approximately 1.0 (stoichiometric) at high power and acceptable low values at idle. In this concept the idle condition and the weak extinction limits prohibit lean flames at higher power settings because with fixed geometry the air split between the primary and the downstream secondary and dilution zone is constant over the operating range. Nevertheless the approach makes the gas turbine combustor feasible in the first place.

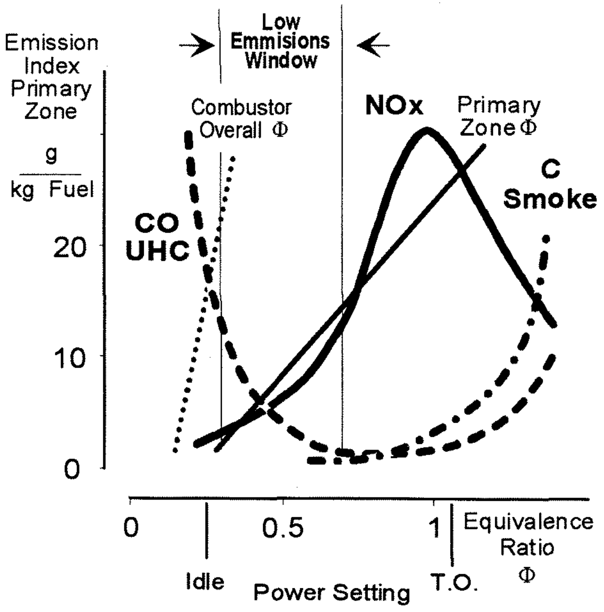


Fig. 6 Equivalence ratio and emissions in a conventional combustor

Fig. 6 shows the emissions characteristics. For the primary zone the emission indices are plotted versus equivalence ratio and the engine operating range indicated. High equivalence ratios, at high power settings, will enhance thermal NOx production. This is strongest at the take off rating. At cruise conditions NOx is already 65 % lower, in spite of the still relatively high temperatures(14). At the other end CO and unburned hydrocarbons dominate the idle condition. In fact there is a close correlation between the two as can be readily recognised from the ICAO data base (13) shown later in Fig. 10. Combustor designers try to put take off at as low an equivalence ratio as possible while keeping low idle and weak extinction limits at acceptable levels.

The conventional combustor burns liquid fuels. This requires a considerable effort in fuel preparation prior to combustion. The fuel needs to be dispersed in small droplets, vaporized and the vapour mixed with air. The quality of this process determines the residence time in the combustor necessary to burn out CO und UHC, and inversely the amount of thermal NOx generation.

Air blast atomisers, widely used to day, have proved to be quite efficient in this sense and have already contributed significantly to the reduction of pollutant emissions. The improved mixing reduces CO and UHC production and extends extinction limits at low power settings thus giving the engineer more design flexibility. Nevertheless the problem remains that the fuel preparation takes place in the hot environment of the primary zone and fuel burns immediately after vaporization close to the droplet at local equivalence ratios of about 1. Because of this effect local flame temperatures correspond to stoichiometric values and the conventional combustor cannot take full advantage of the overall lean primary zone design with lower flame temperatures.

The flame temperature is determined by the stoichiometric temperature rise added to the inlet temperature of the combustor. The latter is determined by the temperature rise for the compression and the engine inlet conditions. The temperature rise in the compressor is determined by the pressure ratio, thus resulting in the well known correlation between NOx emissions and pressure ratio which is also used by the ICAO for the definition of emission limits.

In spite of these difficulties, the development of the conventional combustor has been quite successful over the past thirty years. Exhaust smoke trails were reduced to near-invisibility by modifications to the combustor in the 1960s. Changes to the fuel injectors in the 1970s reduced CO and UHC emissions at idle to extremely low levels (14). Finally redistribution of air between the primary and the secondary zone and reduction of residence times has contributed to a significant reduction of NOx levels in the 1990s (22),(26).

Alternative Combustor Concepts

Alternative combustor concepts discussed today have been known for some time now (27),(28),(2),(18). Some of them have been investigated for several decades and staged combustion was introduced in airline service in 1995. The alternatives will be reviewed here, the problems to be solved will be discussed and potential research, development and introduction periods estimated.

Variable geometry

The main difficulty of the conventional combustor is that the fixed air split between the primary and the dilution zones does not permit any adaptation of the equivalence ratio to the operating condition. This could be overcome by variable geometry. The flow can be redistributed by opening and closing passages to the dilution air ports and changing the geometry of the burner. The necessary variation of flow in these devices would be about 1:5 which poses a severe problem on their aerodynamics. The main difficulty, however, which has prohibited any serious research up to now is the reliability of the system. Achieving satisfactory reliability and safety with such a complex system in the hottest region of the engine with the strongest temperature gradients presently does not appear feasible (18). Adkins and Elsaftawy (29) proposed a system that would need no moving parts in the hot section but this solution has not developed into a practical combustor.

Staged Combustion

A rather simple method to overcome the operating range problem of the conventional combustor is fuel staging. It is accomplished by turning off individual or groups of burners thus increasing fuel flow and equivalence ratio in the remaining burners. The principle, called circumferential staging, originally developed to achieve satisfactory lean extinction limits, has also been used to reduce pollutant emissions in conventional combustors (30).

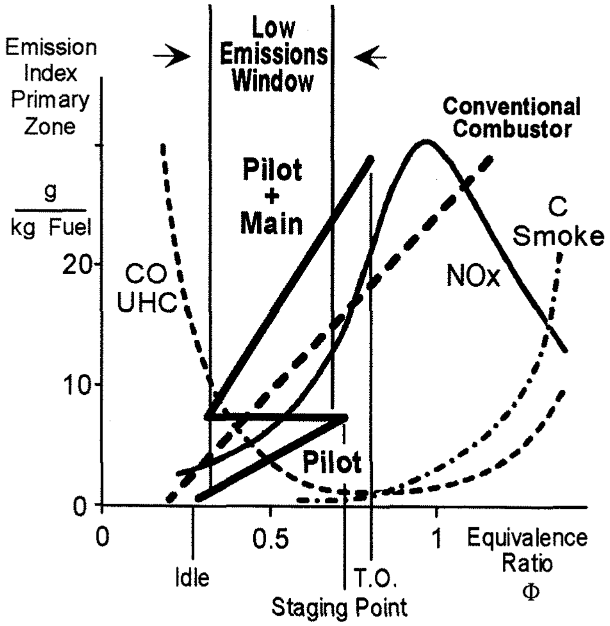
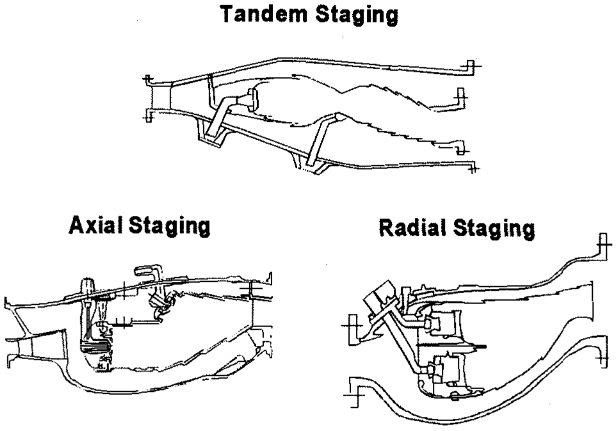


Fig. 7 Equivalence ratio and emissions in a staged combustor

However, what is called staged combustion today consists of two separate combustors integrated into one unit for aeroengine applications to reduce volume and weight. This concept was developed to exercise better control over the combustion processes than by turning on and off individual burners and is targeted at reducing NOx emissions. Research work on staged combustors started in the early 1970s at General Electric and Pratt & Whitney within the framework of the *Energy Efficient Engine (E^3)* Programm in the USA (31). The activities were run down after the first oil crisis and re-emerged in the late 1980s with the increasing environmental concerns. The first staged combustors to enter service have been developed by General Electric for the CFM 56 engines for the Airbus A320 and the GE 90 for the Boeing 777. Both were certified 1995. Pratt & Whitney prepared their version of the staged combustor for certification in the IAE V2500 (32) also for the Airbus A320 but the programm has not been launched yet. BMW Rolls-Royce in Germany is engaged in a research programm for its BR700 family of engines (33).

The operating principle is such that the airflow is distributed between two combustors with their own sets of burners, so that each one operates on about half of the total mass of air. At low power settings all fuel is fed to one combustor, the pilot, which can now burn at approximately double the equivalence ratio of the conventional combustor (Fig. 7), thus avoiding extinction problems and reducing CO and UHC emissions. With increasing power demand equivalence ratio and temperature rise in the pilot combustor. When critical levels for NOx production come close, the second, the main combustor, is turned on and the fuel is redistributed to achieve overall operation within the low emissions window of primary zone equivalence ratios.


Tandem Staging

Axial Staging

Radial Staging

Fig. 8 Staged combustors

Three principal configurations of such combustors have been considered (Fig. 8).

- Tandem staging where the main combustor is located directly downstream of the pilot (28) This concept has the disadvantage of having to be very long to accommodate both combustors.

- Axial staging which combines limited length with the smallest flame tube surface to cool, but requires two separate sets of burners. This configuration has been adopted by Pratt & Whitney and is investigated by BMW Rolls-Royce.

- Radial staging or double dome combustor, the configuration adopted by General Electric. Has the largest flame tube surface to cool, but the burners of the two stages can be integrated into one set.

These concepts represent a straight forward approach applying available technology to the separate combustors. Nevertheless several engineering problems had to be tackled. The increasing complexity of the fuel system requires a stronger effort to maintain reliability levels. The control system has to be redesigned to accommodate control of fuel split and the appropriate staging point. The two combustors in parallel pose new problems in achieving satisfactory temperature patterns at the turbine inlet. Although the surface to be cooled has increased, cooling air for the flame tube has to be reduced, so that sufficient air is available to control the combustion process in the pilot and the main zone.

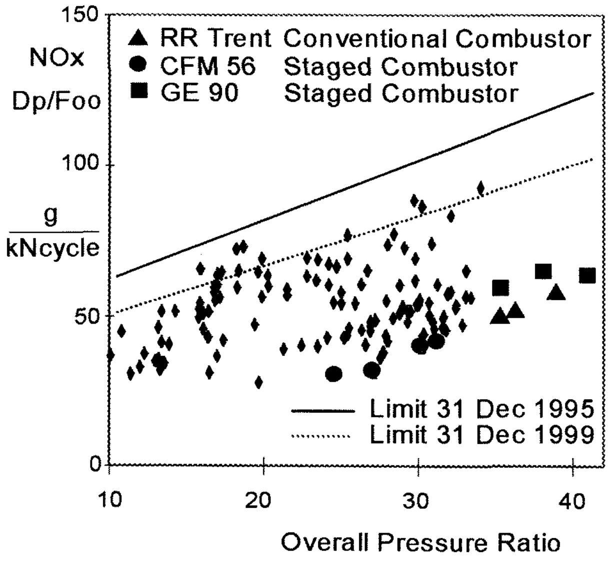


Fig. 9 NOx emissions from the ICAO data base

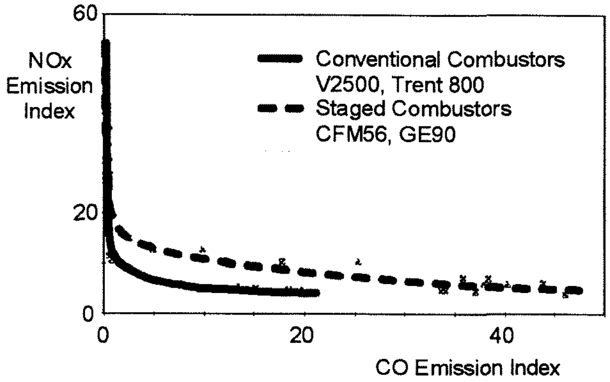


Fig. 10 NOx/CO correlation from the ICAO data base

The potential NOx reduction from the research results in the 1970s was estimated to be about 45 % in comparison to the conventional single annular combustor. Comparing the emissions data from the ICAO Data Base (Fig. 9) with Rolls-Royce Trent conventional combustor data looks disappointing. From the correlation of NOx with CO emissions (Fig. 10) it can be seen that the target of lean high power combustion has not been accomplished yet. This is probably due to the large cooling air requirements for the double dome combustor which reduce the air available for combustion control. It should be considered though that on the one hand annular combustor technology has improved since the 1970s, on the other hand General Electric, pioneering the industry, does not have a mature product yet. Considerable further reductions should therefore be expected in the near future.

Lean Premixed Combustion

As it was stated earlier gas turbine combustors have rather low overall equivalence ratios. This suggests the design of a combustor with a lean fuel/air mixture for high power settings with low flame temperatures and consequently limited formation of NOx. This can be accomplished by vaporizing and mixing the fuel prior to combustion. This is the lean, premix, prevaporize (LPP) concept with the ultimate target of providing a homogeneous mixture to the primary zone at an equivalence ratio close to the weak extinction limit, thus avoiding local fuel rich pockets. The limitation to leanness is given by the unburned CO at low temperatures, however, burn out will in general be achievable [(34)].

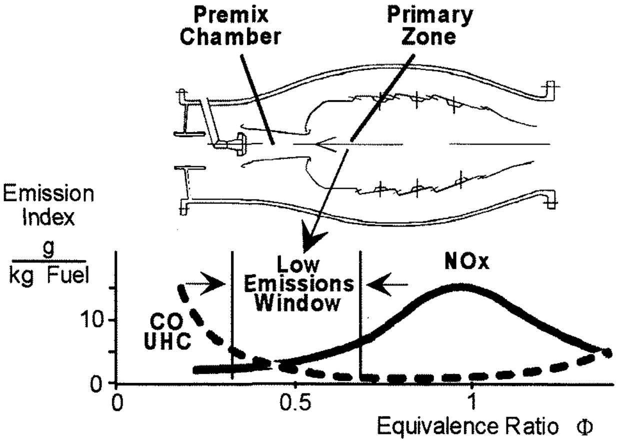


Fig. 11 Lean premix prevaporize combustor (LPP)

The principle is relatively easy to realise with gaseous fuels, which do not need the vaporization process and are already in use in industrial gas turbines [(35),(36)]. General Electric uses fuel staging and compressor variables in an aeroderivative gas turbine to keep flame temperatures and NOx emissions low over a wide power range [(37)]. Combustion of fluids, however, requires a more complex fuel preparation. Although also introduced in industrial applications [(38)], where no space and weight restrictions are posed, completely homogeneous mixtures can hardly be achieved in practical aeroengine combustors. Nevertheless the considerable potential of NOx emissions reduction inherent to the concept justifies the ongoing research.

Lean, premix, prevaporize combustion has two drawbacks. One is the risk of flash back into the fuel rich regions of the premixing and vaporizing zone at the high compressor exit temperatures of high power settings. The other is related to the same problem as for the conventional combustor. Owing to the wide operating range, lean combustion at high power is associated with low equivalence ratios at idle with the risk of flame extinction. Although special techniques like fuel injection into shear layers (39) can improve the situation, LPP combustors for aeroengines will probably require some kind of variable geometry or staging to overcome these problems.

Rich-Burn, Quick-Quench, Lean-Burn

The lean premix prevaporize concept relies on the low flame temperatures of low equivalence ratio combustion. Similar low temperatures are also reached at high equivalence ratios. This has led to the rich-burn, quick-quench, lean-burn (RQL) concept. A limited amount of air is introduced into the primary zone to give a fuel rich mixture with equivalence ratios between 1.2 and 1.6 (18). The exhaust of the rich-burn primary zone is rapidly mixed with more air in the quench zone to reduce the temperature and to generate a low equivalence ratio mixture for the subsequent combustion in the lean-burn zone.

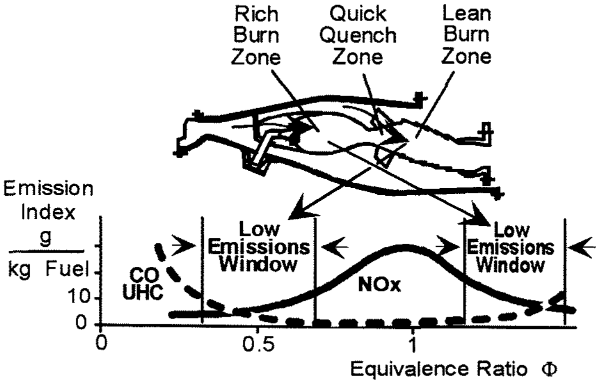


Fig. 12 Rich-burn quick-quench lean-burn combustor

The principle is automatically active in a conventional combustor when the primary zone reaches and exceeds stoichiometric conditions and unburned fuel spills over into the secondary zone to burn out fuel lean. This has been introduced successfully in practical conventional combustors for industrial applications and has contributed to the low emissions of the IAE V2500 engine (22)

The RQL principle, like the LPP concept, is very promising in reducing NOx emissions, but like every new technology poses problems for research to overcome. It looks simpler than staged combustion having only one set of burners. The rich-burn zone, however, requires special cooling techniques. Film cooling cannot be applied because cooling air would produce locally stoichiometric conditions with high temperatures and would counteract the low NOx target. The primary zone generates a large amount of soot which radiates heat to the walls aggravating the cooling problem. The quench zone requires a very fast mixing to minimise residence times near stoichiometric equivalence ratios and high temperatures. Finally the lean-burn zone needs to operate sufficiently hot to burn out soot, CO and UHC from the primary zone exhaust. This would limit minimum equivalence ratios about 0.5 to 0.7 (18).

Obviously a careful balance of the combustion split between the rich-burn and the lean-burn zones is necessary. The basic concept with a single set of burners offers little flexibility in this respect. Presently it is not clear what degree of complexity will be required to accomplish this balance over the full operating range of an aeroengine combustor.

Catalytic Combustion

Catalytic combustor research was initiated in the early 1970s (40). A considerable effort has been invested since then into the concept, but no applications in gas turbines have emerged yet, due to the complexity of the system.

Catalytic chemical reactions take place via an external partner who participates in the process but remains unchanged at the end of the reaction. In the case of catalytic combustion the fuel oxidation rate at low temperatures is increased considerably. This is achieved without the high flame temperatures of normal combustion. The physics and chemistry of the process, however, are such that a well premixed fuel / air flow is required. The principle therefore has presently a potential primarily for gaseous fuels. Accordingly research is concentrated on power generation gas turbines rather than on turbojet engines. Nevertheless with gaseous fuels being of medium or long term interest for aircraft applications this alternative is worth a closer look.

The reaction rate on the catalyst is diffusion controlled. The released heat raises the temperature of the catalyst substrate and is then transferred to the gas. This makes the catalyst sensitive to material failure at high temperatures, such as thermal sintering and vaporization of the precious metal active components and thermal shock fracture of ceramic parts. The process requires a large surface and heat capacity of the catalyst to limit material temperatures at high heat release rates. For aircraft applications low volume, weight and pressure losses are further requirements.

The catalyst needs inlet temperatures of about 700 to 800 K to „ignite“ (40),(41). With today's compressor pressure ratios this is available over most of the engine operating range, except for low power settings. Light up and low pressure ratio operation would require a preheater. Catalyst works best on an optimum equivalence ratio. Its activity is reduced with increasing temperatures so that a final combustion stage is necessary to achieve current turbine inlet temperature levels (42). Since a major part of the available oxygen has already been consumed at that stage, oxygen concentrations are low. It should be expected therefore that production via the Zeldovic mechanism is reduced further below that of the „cold“ lean premixed flame. A comparison with premixed flame data (43) , however, seems to indicate that there is no significant emissions advantage for the catalyst. Furthermore prompt NO generation is not affected by the catalytic process. An operational advantage exists at low flame temperatures where the lean premixed flame becomes unstable.

At part load conditions catalytic combustion becomes increasingly inefficient generating increasingly higher levels of CO and unburned hydrocarbons which have to be burned out in the final combustion stage (41). Over the extreme operating envelope of an aircraft engine this requires a certain amount of variability for the fuel and air flows to keep the fuel/air ratio in the catalyst at useful levels over the operating range. Engine transients pose another not yet resolved problem (28). The complexity of a catalytic combustor system and the potential reliability problems can be seen in the work of Kawasaki Heavy Industries (44) and Solar Turbines Inc. (45).

If any, catalytic combustion appears to have a long term potential only, requiring both a homogeneous fuel/air mixture as well as a complicated design and sophisticated control of the combustion process with variable geometry. Considerable development of materials technology for the catalyst and the substrate is also necessary. An application could be realistic in some kind of staged combustor architecture in combination with a lean premixed flame (18) .

Alternative Fuels

Commercial aviation lives in a kerosene world and will probably continue to do so for a few more decades to come. Living in a finite world, the end of oil reserves is foreseeable. At the time of the first oil crisis in the early 1970s this was estimated to be at the turn of the century. That crisis, however, stimulated energy conservation technologies and encouraged development of new oil fields thus prolonging the availability of kerosene fuel.

Traffic and energy projections indicate that the total aviation fuel demand will double from 1990 to 2015 and will also double its portion of the world wide consumption of crude oil. Oil production will have levelled off and started falling by then (46). Shell (47) estimates crude oil production to increase by about 50 % from 1990 to 2025 and then level off and drop. By that time oil will account for less than one third of the total primary energy consumption. Obviously early in the 21st century the competition for oil between fuel consumers and those using it as raw material for synthetic products will increase. This will probably lead to regulatory usage limitations and, in a free market world, to higher prices.

No matter which way the fossil oil market will develop, the time scales involved are by now coming within the life time of new airliners. Alternative fuels therefore need to be considered for economical as well as ecological reasons.

Natural gas and coal are the alternative fossil energy sources available. Allen et al (46) think that the next fifty years will see „Synker“, kerosene synthesised from natural gas, being introduced for aviation. Such a fuel could also be synthesised from coal, which is still available in large quantities, but production costs are presently prohibitive. The main argument for „Synker“ would be an economic one. The fuel handling infrastructure would not need to be changed.

Combustion of natural gas, consisting of 80% to 90% methane CH_4, in turbofan engines poses no problems. Direct usage therefore should be considered as an alternative. The necessary infrastructure for the distribution of natural gas is already largely installed so that investment would be mainly required for airports. Natural gas production would flatten out by 2025 but would remain constant well into the second half of the next century (47). The fuel would have to be liquefied (Liquid Natural Gas, LNG) and carried in special cooled tanks, making it a cryogenic fuel, and requiring 50 % more space in the aircraft than kerosene. The boiling temperature is 112 K (-161 °C) requiring a preheater. This solution is quite feasible. Dual operation of aircraft with kerosene and natural gas has been demonstrated in Russia (48),(49). From the point of view of exhaust emissions the Kuznetsov Bureau estimates an improvement of 30% to 40% because of the better mixing properties of the gasified LNG in the combustor.

Natural gas is also used for synthetic material and neither „Synker“ nor methane would eliminate CO_2 emissions at high altitudes. If pressure from these sides increases then hydrogen would emerge as the preferred alternative. It would also have to be used as cryogenic fuel and would require extremely well cooled tanks because boiling temperatures at atmospheric pressure lie at about 20 K (-253 °C). Volume requirement in the aircraft would be about four times that of kerosene. Hydrogen has the poorest energy density which may be slightly improved by employing a „slush“ of frozen solid with the liquid to increase it (50). The Cryoplane project of Airbus Industries (51) looks more like a Super Guppy than like the airliners we are used to today. Hydrogen has a heat value which is about three times that of kerosene. The weight of the fuel is therefore two thirds less than kerosene. This saving can be used for the structure of the tank offering the potential of keeping the take off weight constant (48).

From the emissions point of view hydrogen fuel would eliminate the release of CO_2 in flight but engines would emit larger amounts of water. Hydrogen burns with higher flame temperatures but since it is more prone to oxidation it can be burned in a very lean mixture. This would help hold low NOx emission levels.

There are several drawbacks to the introduction of hydrogen fuel. It is not a primary source of energy but only an energy carrier. It has to be produced using other energy sources like natural gas, nuclear or solar energy, with all the associated problems. There is no world wide infrastructure for the distribution available. Airports would require considerable investment also in consideration of safety issues. Engine fuel systems will have to be redesigned to accommodate some preheating device for the fuel. Finally a complete new generation of aircraft would have to be designed and developed. Because of these drawbacks hydrogen appears to be only a long term alternative and probably only in the context of its introduction as a fuel for general use in transportation and energy transformation.

Concluding Remarks and Forecast

The increasing effects of human activity on the environment have given rise to strong concerns over the exhaust emissions from combustion. This has a disproportionately strong impact on aircraft emissions although they contribute less than 1 % to the the total air pollutants. Governments and industry have responded with research and the introduction of new improved products.

A major concern is the release of carbon dioxide and nitrogen oxides in the upper atmopshere and the stratosphere. The chemistry and the atmospheric transport processes involved are not clearly understood yet. Comprehensive international research programms are now in progress. The results will soon provide a more sound background for legislative acitvities beyond the present ICAO regulations. Studies to improve the situation by reducing the cruise flight altitude do not appear to offer a viable alternative. Fuel burn would rise and matching the aircraft design to the requirement would have a major economical impact.

The turbofan, as the source of the aircraft exhaust, can contribute directly to a reduction of fuel burn and overall emissions by better cycle efficiency and lower weight. The improvement potential is about 10%. Development activities however are presently at a very low level due to the lack of an economic incentive. Alternative recuperated thermodynamic cycles or engines with pressure rise combustion do not appear to offer any improvements at satisfactory reliability to make the necessary effort worthwhile.

The major effort by industry and academia is presently invested in combustion research. Exploitation of the potential of the conventional combustor is accompanied by investigations on the following alternatives

- Staged combustion
- Lean premixed prevaporized combustion (LPP)
- Rich-burn, quick-quench, lean-burn combustion (RQL)
- Catalytic combustion
- Variable Geometry

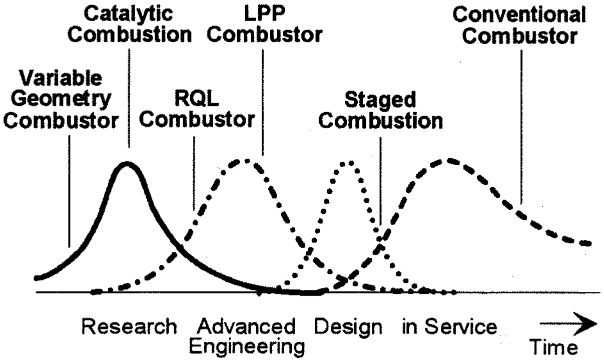


Fig. 13 Aeroengine Combustors Emissions Technology Status

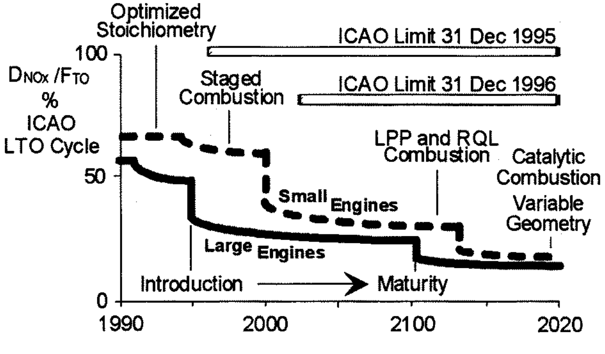


Fig. 14 Combustor Emissions Technology Forecast

The status of these activities is demonstrated in Fig. 13 in the four phases of development after E.

Koerner (52). Staged combustion is in the design and the in service phase. It has been introduced in production engines by General Electric in 1995. This technology however is not yet mature. Maturity has a potential of about 20% to 30% LTO cycle NOx reduction versus the conventional combustor (Fig. 14). The diagramm also shows that there is both a time and quality lag for smaller engines because of space and cost limitations.

The LPP and RQL concepts are still in the late research, early advanced engineering phase, the former having the advantage of application experience in the more favourable environment of industrial gas turbines with gaseous fuels. Practical devices for aeroengines should be available within the next fifteen years with a further NOx improvement of about 10%, which would be about 40% below the than mature staged combustion technology.

Catalytic combustion and variable geometry are still in the research phase and will probably have the heaviest complexity and reliability problems. New material and mechanical design technologies will be required to make them viable for aircraft applications. These are not expected to emerge for another twenty five years.

Alternative fuels are currently driven by economics rather than environmental issues. Natural gas would make the realisation of the LPP concept easier, however only hydrogen promisses reduction of carbon dioxide emissions to zero. Because of the necessary infrastructure development, it will not be available unless ground traffic also has to change over to this fuel. It should also be noted that hydrogen is not a primary energy source but only an energy carrier.

Summing up the engine aspects of this review, two main conclusions can be drawn.

- The engine can contribute about 10% to overall emissions reduction by better fuel burn. This includes carbon dioxide, water and oxides of nitrogen.
- Alternative combustors can contribute two thirds reduction of present technology NOx levels in two steps. The first is staged combustion, already in service. The second is LPP and/or RQL combustion within the next 15 years.

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