Doc 9887

INTERNATIONAL CIVIL
AVIATION ORGANIZATION

REPORT OF THE INDEPENDENT EXPERTS ON THE LTTG NOx REVIEW AND MEDIUM AND LONG TERM TECHNOLOGY GOALS FOR NOx

REPORT

MONTRÉAL 2008

Published in English only by the International Civil Aviation Organization. All correspondence, except orders and subscriptions, should be addressed to the Secretary General.

Orders should be sent to one of the following addresses, together with the appropriate remittance in U.S. dollars or in the currency of the country in which the order is placed. Customers are encouraged to use credit cards (MasterCard, Visa or American Express) to avoid delivery delays. Information on payment by credit card and by other methods is available in the Ordering Information Section of the *Catalogue of ICAO Publications*.

International Civil Aviation Organization. Attention: Customer Services Unit, 999 University Street, Montréal, Quebec, Canada H3C 5H7
Telephone: +1 514-954-8022; Facsimile: +1 514-954-6769; Sitatex: YULCAYA; E-mail: sales@icao.int;
World Wide Web: http://www.icao.int

Botswana. Kags and Tsar Investments (PTY) Ltd., Private Bag 254/525, Gaborone
Telephone: +267 390 4384/8; Facsimile: +267 395 0004; E-mail: ops@kagsandtsar.co.bw

Cameroon. KnowHow, 1, Rue de la Chambre de Commerce-Bonanjo, B.P. 4676, Douala / Telephone: +237 343 98 42; Facsimile: +237 343 89 25;
E-mail: knowhow_doc@yahoo.fr

China. Glory Master International Limited, Room 434B, Hongshen Trade Centre, 428 Dong Fang Road, Pudong, Shanghai 200120
Telephone: +86 137 0177 4638; Facsimile: +86 21 5888 1629; E-mail: glorymaster@online.sh.cn

Egypt. ICAO Regional Director, Middle East Office, Egyptian Civil Aviation Complex, Cairo Airport Road, Heliopolis, Cairo 11776
Telephone: +20 2 267 4840; Facsimile: +20 2 267 4843; Sitatex: CAICAYA; E-mail: icaomid@cairo.icao.int

Germany. UNO-Verlag GmbH, August-Bebel-Allee 6, 53175 Bonn / Telephone: +49 0 228-94 90 2-0; Facsimile: +49 0 228-94 90 2-22;
E-mail: info@uno-verlag.de; World Wide Web: http://www.uno-verlag.de

India. Oxford Book and Stationery Co., 57, Medha Apartments, Mayur Vihar, Phase-1, New Delhi – 110 091
Telephone: +91 11 65659897; Facsimile: +91 11 22743532

India. Sterling Book House – SBH, 181, Dr. D. N. Road, Fort, Mumbai 400 001
Telephone: +91 22 2261 2521, 2265 9599; Facsimile: +91 22 2262 3551; E-mail: sbh@vsnl.com

India. The English Book Store, 17-L Connaught Circus, New Delhi 110001
Telephone: +91 11 2341-7936, 2341-7126; Facsimile: +91 11 2341-7731; E-mail: ebs@vsnl.com

Japan. Japan Civil Aviation Promotion Foundation, 15-12, 1-chome, Toranomon, Minato-Ku, Tokyo
Telephone: +81 3 3503-2686; Facsimile: +81 3 3503-2689

Kenya. ICAO Regional Director, Eastern and Southern African Office, United Nations Accommodation, P.O. Box 46294, Nairobi
Telephone: +254 20 7622 395; Facsimile: +254 20 7623 028; Sitatex: NBOCAYA; E-mail: icao@icao.unon.org

Mexico. Director Regional de la OACI, Oficina Norteamérica, Centroamérica y Caribe, Av. Presidente Masaryk No. 29, 3er Piso,
Col. Chapultepec Morales, C.P. 11570, México D.F. / Teléfono: +52 55 52 50 32 11; Facsímile: +52 55 52 03 27 57;
Correo-e: icao_nacc@mexico.icao.int

Nigeria. Landover Company, P.O. Box 3165, Ikeja, Lagos
Telephone: +234 1 4979780; Facsimile: +234 1 4979788; Sitatex: LOSLORK; E-mail: aviation@landovercompany.com

Peru. Director Regional de la OACI, Oficina Sudamérica, Av. Víctor Andrés Belaúnde No. 147, San Isidro, Lima (Centro Empresarial Real, Vía Principal No. 102, Edificio Real 4, Floor 4)
Teléfono: +51 1 611 8686; Facsímile: +51 1 611 8689; Correo-e: mail@lima.icao.int

Russian Federation. Aviaizdat, 48, Ivan Franko Street, Moscow 121351 / Telephone: +7 095 417-0405; Facsimile: +7 095 417-0254

Senegal. Directeur régional de l'OACI, Bureau Afrique occidentale et centrale, Boîte postale 2356, Dakar
Téléphone: +221 839 9393; Fax: +221 823 6926; Sitatex: DKRCAYA; Courriel: icaodkr@icao.sn

Slovakia. Letové prevádzkové služby Slovenskej Republiky, Štátny podnik, 823 07 Bratislava 21
Telephone: +421 2 4857 1111; Facsimile: +421 2 4857 2105; E-mail: sa.icao@lps.sk

South Africa. Avex Air Training (Pty) Ltd., Private Bag X102, Halfway House, 1685, Johannesburg
Telephone: +27 11 315-0003/4; Facsimile: +27 11 805-3649; E-mail: avex@iafrica.com

Spain. A.E.N.A. — Aeropuertos Españoles y Navegación Aérea, Calle Juan Ignacio Luca de Tena, 14, Planta Tercera, Despacho 3. 11,
28027 Madrid / Teléfono: +34 91 321-3148; Facsímile: +34 91 321-3157; Correo-e: sscc.ventasoaci@aena.es

Switzerland. Adeco-Editions van Diermen, Attn: Mr. Martin Richard Van Diermen, Chemin du Lacuez 41, CH-1807 Blonay
Telephone: +41 021 943 2673; Facsimile: +41 021 943 3605; E-mail: mvandiermen@adeco.org

Thailand. ICAO Regional Director, Asia and Pacific Office, P.O. Box 11, Samyaek Ladprao, Bangkok 10901
Telephone: +66 2 537 8189; Facsimile: +66 2 537 8199; Sitatex: BKKCAYA; E-mail: icao_apac@bangkok.icao.int

United Kingdom. Airplan Flight Equipment Ltd. (AFE), 1a Ringway Trading Estate, Shadowmoss Road, Manchester M22 5LH
Telephone: +44 161 499 0023; Facsimile: +44 161 499 0298; E-mail: enquiries@afeonline.com; World Wide Web: http://www.afeonline.com

3/08

Catalogue of ICAO Publications

Issued annually, the Catalogue lists all publications currently available. Supplements to the Catalogue announce new publications, amendments, supplements, etc. The Catalogue is accessible on the ICAO website at www.icao.int.

Report of the Independent Experts to the Long Term Technology Task Group on the 2006 LTTG NOx Review and the Establishment of Medium and Long Term Technology Goals for NOx

Contents of the Report

1. Executive Summary…………………………………………………………6

2. Introduction……………………………………………………………..15
2.1 Review Body…………………………………………………………..15

3. Scope of Review…………………………………………………………16

4. Policy Overview…………………………………………………………18

5. Science Overview………………………………………………………. 19
5.1 Introduction…………………………………………………………19
5.2 Local Air Quality Concerns……………………………………......21
5.3 Global Climate Concerns……………………………………….......22
5.4 Tradeoffs……………………………………………………………26
5.5 Summary……………………………………………………………27

6. Technology Review……………………………………………………….. 29
6.1 History………………………………………………………………... 29
6.2 Design and Requirements………………………………………….. 31
6.3 Addressing NO_x …………………………………………………... 32
6.4 Rate of technology change………………………………...…..32
6.5 Technology - Mid Term……………………………………….....33
6.6 Technology - Long Term ……………………………………......33
6.7 Noise……………………………………………………………...... 35

7. Academic Review…………………………………………………………36
7.1 Fundamentals…………………………………………...………..36
7.2 Contemporary practice and near term strategies……………………39
7.3 Mid and Long Term alternative technologies…………………….....39
7.4 Alternative Fuels……………………………………………………41
7.5 Alternative Engine Cycles……………………………………..... 43
7.6 Revolutionary Technologies…………………………………...... 44
7.7 Smoke Emissions……………………………………………….......46

8. Research Review……………………………………………………….. 47
8.1 Introduction…………………………………………………………47
8.2 History…………………………………………………………….... 47
8.3 Present………………………………………………………………50
8.4 Future Work………………………………………………………...52
8.5 Summary……………………………………………………………54

9. Discussion………………………………………………………………. 54
9.1 Review process.……………………………………………………. 54

9.2 Successive reductions in Certification NO_x and Long Term Trends. 55
9.3 Environmental Need LAQ & GCC…………………………….…. 57
9.4 Tradeoffs………………………………………………………… 63
9.5 MT (10yr) and LT (20yr) TECHNOLOGY GOALS……………… 66
9.5.1 Engine Goal Compliance Assumptions………………... 67
9.5.2 Technology Goals Different from Standard Stringency.. 67
9.5.3 Derived MT and LT Technology Goals………………...67
9.5.4 Uncertainty…………………………………………...72
9.5.5 Use of Uncertainty Bands……………………………… 72
9.6 Metric……………………………………………………….....73
9.7 In-Service Deterioration Rates……………………………….....73
9.8 Alternative Fuels…………………………………………..…..73
9.9 Affordability……………………………………….…………. 74
9.10 Small Engines…………………………………………...……. 75
9.11 Handling of Differences………………………………...……..75

10. Conclusions…………………………………………………………...75

11. Recommendations……………………………………………………....80

Appendix 1. Review Participants
1a. Terms of Reference for the Panel of Independent Experts
1b. Long Term Technology Group CAEP Remit

Appendix 2 NASA TRL Scale

Appendix 3 Notes from the LTTG Review 20-24 March, 2006

Appendix 4 List of Presentations

List of Figures

Figure 1: Review Structure 16
Figure 2: Bar charts of radiative forcing from aviation effects in 1992 (subsonic fleet) and subsequent modifications. Taken from David Lee Presentation 26
Figure 3: Relative pulse temperature response (K) for global fleet of NOx and CO_2 29
Figure 4: CAEP Stringencies 30
Figure 5: CAEP Certification Limits with Industry and Research Program Targets.. 34
Figure 6: NOx as a function of Combustor Air Entry Temperature 37
Figure 7: TVC cross section 45
Figure 8: A photograph of a quartz SPRF combustor in operation 46
Figure 9: FESG Passenger Retirement Curve.. 55
Figure 10: Illustration of Fleet Growth and Supply Pattern (indicative) 56
Figure 11: Aircraft Engine Combustor Development Key Requirements 63
Figure 12: Engine/Airframe Cycle Tradeoffs - Fuel Burn/NOx/Noise Carpet Plot Example 64
Figure 13: MT and LT Goal Bands.. 68
Figure 14: LTTG Goals and Industry NOx Performance Targets 69

List of Tables

Table 1: Radiative forcing (RFs) [mW/m^2] due to aviation emissions from historical operation of the subsonic fleet in the year 1992 as reported in by IPCC (1999). 25
Table 2: US Airport Contribution to Area and Non-Road NOx Inventory................ 60

List of Acronyms and Symbols

ACARE	Advisory Council for Aeronautics Research in Europe
CAEE	Committee on Aircraft Engine Emissions
CAEP	Committee on Aviation Environmental Protection is the committee of the ICAO responsible for environmental concerns and aviation.
CAEP/5	as above, 5th meeting
CAEP WG3	as above, Working Group 3 (Emissions)
Dp/F_{00}	The emissions regulatory parameter, defined as the mass of emissions (produced during a sea-level engine test for a simulated landing and take-off cycle) normalised against maximum engine thrust
EIS	Entry in to service (date)
FESG	Forecasting and Economic Support Group (of CAEP)
GCC	Global Climate Change
GHG	Green House Gases such as CO2, NOx (a GHG precursor) and Methane result from combustion of fossil fuels and are believed responsible for contributing to the “greenhouse” climate effect.
HAPS	Hazardous Air Pollutants (a subset of Hydrocarbons that can cause hazardous effects to human health)
HC	Hydrocarbons emitted due to incomplete fuel combustion (also referred to as volatile organic compounds (VOCs) and unburned hydrocarbons (UHC)).
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization is a body of the United Nations responsible for international aviation.
ICCAIA	International Co-ordinating Council of Aerospace Industries Associations
IPCC	Intergovernmental Panel on Climate Change.
ITH	Integration Time Horizon
LAQ	Local Air Quality
LDI	Lean Direct Injection
LPP	Lean Premixed Prevapourised combustor
LTO	Landing-take off cycle
LTTG	Long Term Technology Goals
NOx	Nitrogen oxides are produced as air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NOx.
OPR	Overall Pressure Ratio
PM	Particulate Matter refers to small particles that form as a result of incomplete combustion of fuel by aircraft (and other) engines and are small enough to be inhaled. PM10 and PM2.5 refer to particulate matter of less than 10 microns and 2.5 microns in diameter respectively.
RQL	Rich-burn/Quick-mix/Lean-burn combustor
Stringency	Successive tightening of CAEP environmental standards recommendations
SOx	Sulphur oxides are produced when small quantities of sulphur combine with oxygen from the air during combustion
TRL	Technology Readiness Level

UNFCC	United Nations Framework Convention on Climate
UHC	see HC
UEET	NASA's Ultra Efficient Engine Technology program
VOC	see HC

Report of the Independent Experts to the Long Term Technology Task Group on the 2006 LTTG NOx Review and the Establishment of Medium and Long Term Technology Goals for NOx

1 Executive Summary

1.1 Introduction

In support of the work programme agreed at CAEP/5 of the Long Term Technology Task Group (LTTG) of Working Group 3 (WG3) a Panel of Independent Experts (IEs) was tasked with leading a review of technologies for the control of oxides of nitrogen (NOx) culminating in the IEs recommendations for medium (10 year) and long term (20 year) goals for NOx control.

This Executive Summary of the report by the Panel of external Independent Experts (IEs) to the Long Term Technology Task Group (LTTG) records the key findings of the Review conducted in March 2006 in London together with the medium and long term goals for oxides of Nitrogen (NOx) recommended by the IE Panel.

This report has greatly benefited from comments received from the stakeholder groups and other participants in the Review and for which the Panel is greatly appreciative. The Panel's intention is for this report accurately to reflect any remaining differences of view.

A full list of Review attendees is provided in Appendix 1 of the Report.

1.2 Background

Civil aviation is an integral and essential part of modern society, is a wealth generating industry and a facilitator of industrial, commercial, and social developments globally. Civil aviation makes a relatively small but increasing contribution to global environmental problems (about 2% of CO_2 emissions and 3.5% of radiative forcing of all anthropogenic activities in 1992, according to the 1999 IPCC Special Report) and also affects local air quality and noise. Although a "small" contributor, it is one of the UNFCCC "key categories" as others are smaller. The predicted growth of aviation – around 5% p.a. for the next 25 years[1] – and its local air quality impact and unique atmospheric environmental impact continue to exert pressures for emissions mitigation. Studies suggest that given the growth potential for this industry and the likelihood that other industries will adopt cleaner fuels, these problems may increase over time. IPCC scenarios produced by CAEP for use by IPCC suggest that relative to the base year of 1992 aviation fuel consumption will have increased by a factor of 2.5 by 2015, and by around 4.0 by 2050. Corresponding estimates for NOx are for increases of 2.7 and 4.9 for these same years (IPCC Report 1999, Fa1 central scenario). It was frustrating for the Panel that more recent growth scenarios were not provided for the Review and particularly given that the 1999 IPCC study was based on data as old as 1992. It is questionable, therefore, whether the above figures represent current best estimates.

[1] FESG Global Emissions Model Report, CAEP/6-IP/13 App. A, 2-12 Feb. 2004, (figures taken from the FESG forecast of passenger demand for 2020, at an average of 4.3%, from 2.2% 2000-2005; 5.4% 2006-2010; 5% 2011-2015; 4.7%2016-2020).

1.3 Remit

The LTTG's remit for this task, as a pilot exercise, was agreed at CAEP/5 and revised at CAEP/6 and is summarised as follows:

> "To provide advice on long term technological practicability and feasibility to reduce aviation's emissions (both affecting local air quality and global climate change) taking into consideration the various national and international research programme builds and milestones, for the purpose of establishing long term and forward looking CAEP goals for aircraft emissions reductions."

The full terms of reference of the LTTG are available on the CAEP website and the Remit is given at Appendix 1b. NOx emissions were the primary focus of this technology Review.

As a means of pursuing its remit the LTTG recommended and the CAEP Steering Group appointed a Panel of Independent Experts (IEs) whom it charged with conducting a review of combustor technologies for the control of oxides of nitrogen (NOx) and using this to establish medium term (10 year) and long term (20 year) technology goals for NOx reduction. The Review comprised a Review Committee of the nominated Independent Experts together with industry representatives aided by two moderators drawn from ICCAIA. Wider Review participation comprised representatives from the aero engine industry, aircraft manufacturers, airlines, research community, regulators, NGOs, and the scientific community.

The terms of reference for the Panel of Independent Experts are provided in Appendix 1a and a more detailed description of the Review format can be found in Section 2.1 of the main report.

1.4 Scope of Review

In its environmental leadership role, CAEP periodically recommends changes to the stringency of environmental standards that apply to aviation. These recommendations result from a rigorous assessment of environmental need, achieved technological capability and cost implications. Technology goals are fundamentally different from stringency. Technology goals are not guarantees of future emissions performance. They are predicted levels of performance from future technology, based on the projected capability and foreseen (versus actually quantified) environmental need.

The terms of reference of the IE Panel dictated that the major elements of the Review were to include:

- The scientific understanding of climate effects
- Understanding of aircraft engine emissions effects on local and regional air quality
- The application of new (evolutionary) technologies to future products in the (10 year) middle (medium) term
- Focus and progress in development of revolutionary technologies for the (20 year) long term

Amongst other things, the IE Panel was asked to Report on:

- The status of technology developments for NOx emissions reduction in the 10 and 20 year periods
- To comment on the noise and emissions environmental tradeoffs resulting from such developments
- To report on the status of understanding of environmental impacts of aircraft engine emissions and identify where further research is needed
- To comment on the appropriateness of LTO emissions of NOx as the primary technology focus

The Review was evidence based. It considered information presented by industry and critically assessed their technology and research programmes. This information was presented to the Review Panel in as open a manner as possible given the commercial constraints that apply. In addition, the Review considered the theoretical performance limits that might exist for specific technologies, as well as the policy, NGO and airline industry perspectives, and the latest scientific understanding of the environmental effects of emissions that create the context for emissions reductions. All background information relating to the work of the LTTG in developing the technology review process is available from the CAEP website. An agreed note of the Review is provided as Appendix 3 and a full list of Review presentations is given as Appendix 4.

The Goals reported here are the product of the IE Panel and once adopted are not expected to require frequent change though they should be subject to periodic independent review and adjusted in the light of progress and technology development, improved understanding of environmental need, and improved understanding of interdependencies and tradeoffs amongst emissions and noise. For this first Review cost and benefits have been considered in a general sense only: no quantification of expected benefits resulting from the achievement of the goals has been conducted; no quantified cost benefit analyses or monetisation of benefits was possible. Goals have only a tenuous link with a future certification standard, but their metric was agreed by the Review as being the regulatory parameter, Dp/F_{00}. In addition there is a common basis in transitioning between the goal-setting and standard-setting process via the use of the Technology Readiness Level (TRL) scale to judge the progress of technology development through commercialization.

1.5 Technology Review

Figure 4 shows the history of CAEP certification limits along with some examples of recent certifications. It is noteworthy that the best of these examples (CFM56-7B and PW6122A), relative to CAEP/6 (effective from 2008), are 25-30% better than this most recent requirement, while using very different approaches (dual annular and single annular, respectively). Clearly, industry has made great strides in NOx reduction, as evidenced by the many models shown on Figure 4 that are below CAEP/6. It is also clear that the high thrust growth versions of product families are very close to CAEP/6, indicating that difficulty increases with increasing OPR. In this effort, the Panel looked to the best that could be done on a "new design" basis. Relief for growth within an existing design was determined to be an issue to be resolved in a debate regarding stringency, not technology. The fact that differing NOx control technologies has led to NOx levels significantly below CAEP/6 shows that today's technology base is broad and well positioned for further accomplishment.

1.6 Technology Goals

1.6.1 Compliance

For setting both the 10 and 20 year goals the Panel were asked to consider the levels of NOx performance thought likely to have been achieved by the due dates and refined to Technology Readiness Level 8 (TRL 8) – ready for service (see Appendix 2 of the main Report). However, it was evident to the Panel that further interpretation was needed as it was not stipulated whether this level of readiness was to apply, for example, only to the very best or to the average of all manufacturers or the average of a family of engines etc. The criterion adopted by the Panel was that a goal would be met when one or more manufacturers achieves a performance within the goal band (see below) judged against Technology Readiness Level 8 (TRL 8). Thus the goal bands are predicting the leading edge capability. Questions such as steep NOx development slopes for families of engines and considerations, for example, of other manufacturers' capabilities were considered by the IEs to be matters for resolution in debates about stringency and therefore outside the scope of this Review. Compliance is discussed in Section 9.5.1 of this report.

1.6.2 MT Technology Goal (10 year)

The Review concluded that an environmental and practical balance would require that NOx reductions should not be pursued at the expense of significantly worse fuel burn. Industry presentations on technology development programmes currently in hand suggested that within 10 years further reductions in NOx are likely to be delivered, but the outcome of those technology developments is not assured. The Review noted that engines better than the 2008 CAEP/6 recommendations have already been certificated.

The Panel positioned the MT technology goal at 45% below CAEP/6 (+/- 2.5%) calculated at 30 overall pressure ratio (OPR 30). The proposed goal band has a relatively shallow slope in comparison with the much steeper development slopes of engine families, and the "kink" at OPR 30 is absent. These differences are considered by the Panel to be matters for consideration under stringency rather than goal setting. The small band width indicates a reasonable degree of confidence of achievement from the leading edge technologies that would be expected to be ready for service at the end of this period. A fuller description of this MT NOx technology goal appears in Section 9.5 of the Report.

1.6.3 LT Technology Goal (20 year)

Presentations on research and longer-term development activity suggested that further significant reductions beyond MT technology goal outcomes are potentially possible, but will probably require major changes in NOx control technologies. Manufacturers are at the early stages of identifying possible technology routes, but these are not yet ready for down-selection. The IEs consensus positioned the LT technology goal at 60% below CAEP/6 (+/- 5%) and again calculated at OPR 30 (see para 9.5.3.2 for the goal band definition). The larger goal band width reflects the higher uncertainty of outcome. Again, Section 9.5 of the Report provides a fuller description of this goal and includes a section on the handling of uncertainty (9.5.3)

All presenting engine manufacturers showed prospective estimates for concepts that are either at, or near, the selected MT and LT goal bands set by the Panel. These include TAPS (GE), RR Lean Burn, TALON (PW) and Clean Combustor (SNECMA), and are presented on Figure 5. However, it must be realized that these levels are not guaranteed until TRL 8 'flight qualified' has been attained.

If achieved, the NOx reductions represent a large proportion of what is theoretically possible. Beyond this level further reductions may be possible, but scientific input would be required to determine the value of the possibly limited additional environmental benefit they might offer. The environmental need for such reductions, and particularly the advice on the ranking of pollutants, will be required to inform this issue, which will require impact assessment of the 20 year goal over suitably long time period projections – for example, the IPCC study considered 15 and 50 years, and P5 (of the Science Review, Summary Report, presented to the Review) notes 100 years as the current trading policy for long-lived green house gases (GHG). In addition, approaching the maximum theoretical possible NOx reduction implies in all likelihood growing difficulties (including with respect to environmental tradeoffs) and growing costs.

1.6.4 Goals Summary

Relative to mid term goals (CAEP/6 minus 45%, mid point) the best of today's products require a further reduction of 15% (of CAEP/6) and, relative to the long term goal (CAEP/6 minus 60%), yet another 15%, for a total of 30% (of CAEP/6) to meet the long-term goals. The technology to accomplish these reductions appears not to be limited to a single approach, much like the status of today's products. Dual annular, single annular, rich burn and lean burn concepts all continue to be pursued by industry. All presenting engine manufacturers showed prospective estimates for concepts that are either at, or near, the selected MT and LT goal bands set by the Panel. These include TAPS (GE), RR Lean Burn, TALON (PW) and Clean Combustor (SNECMA), and are presented on Figure 5.

The speed with which these technologies are brought to the certification process will be determined by a combination of "need" (yet to be determined) and funding. Concern regarding the absence of defined "need", as well as the lack of funding in place, was voiced during the Review.

1.7 Additional Review Findings and Comments

1.7.1 Scientific Perspective

A valuable input to the Review was provided by the Research and Science Focal Points from WG3 on their view on the latest understanding of the environmental impacts from aviation emissions. Their consensus view on the relative importance of various pollutants is reported in Section 5 of the Report – other views will and do exist and a clear “consensus” view across the entire scientific community on the environmental effects from aviation emissions is problematic. In summary, the Research and Science Focal Points advised:

1.7.1.1 Given current understanding on the environmental effects of aircraft emissions, the need remains to minimize aircraft NOx emissions and given projected growth in demand for aviation services mitigation pressure is expected to grow. NOx cannot be ignored from either a local air quality or global climate impact perspective.

1.7.1.2 From a global climate perspective SOx and PM emissions need to be minimised, but CO and HC are not a concern. The role of cirrus/contrails/PM on global climate effects is uncertain and it will be difficult to gain definitive scientific advice on any benefits of tradeoff mitigating the effects of cirrus/contrails/PM by possibly increasing other emissions (e.g., CO_2)..

1.7.1.3 From a local air quality perspective, NOx/NO_2 is the main concern, with PM next in importance, but more understanding of the effects of Hazardous Air Pollutants (HAPs) is needed. However, PM and UHC may grow in importance as the uncertainties surrounding their relative effects are addressed. CO does not pose any serious LAQ environmental concern now, and is unlikely to do so in the future.

1.7.1.4 The integration time adopted for the assessment of the impact of aviation emissions (for example, radiative forcing or global surface temperature response) is important. If the global surface temperature **instantaneous** forcing impact from NOx emission from a fleet is defined as 1 then the relative effect from CO2 will be 0.06. The use of **integrated** forcing changes this relation and suggests that in the integrated forcing from CO_2 emission is 8 times that from NOx. Figure 3 in the Report shows the relative surface temperature response to an annual pulse of NOx and CO_2 emissions from a fleet. Data presented indicated that over a 50 year timeframe NOx and CO_2 were approximately of equal importance for integrated global mean surface temperature response although this was based on an *indicative* calculation. Over longer timeframes, CO_2 will be of greater importance. Section 5, notably 5.5.1 and 5.5.2, and Section 9.5.3 provide further explanation.

1.8 Environmental Need

“Environmental need” – the primary driver for NOx reduction technology developments – relates both to LAQ and GCC. In neither case was there evidence presented to the Review to quantify the level of further aircraft NOx reductions required, in terms of either ceiling mass levels not to be exceeded, nor mass emission or concentration reductions needed to reduce environmental impact to an accepted level. There was evidence presented that air quality standards are being exceeded in the vicinity of airports, but the relative contribution of aircraft sources was not quantitatively presented. Nonetheless, the Panel was convinced that in the context of both LAQ and GCC, aircraft NOx ranked highly against other aircraft pollutants as a contributor to adverse environmental impacts. This, coupled with current airport pressures and expected traffic growth, led the Panel to conclude that significant pressure for further reductions must be assumed for the future. Continuing research is needed to better establish the aircraft contribution and quantify the costs and benefits of aviation NOx reductions. Given the absence of quantified environmental need, the Panel determined goals judged against the expected leading edge of technology capability at the two given goal time periods.

Once the technology goals are reached, the fleet will not be switched instantaneously to the new technology. Emissions from the fleet will change only slowly as new technology is introduced to newly certificated aircraft (i.e., not current production types) being phased into the fleet. The Panel recognized that evaluation of the environmental impacts would require evaluating the emissions of various scenarios to model this transition period. Once the annual emissions are determined, there still remains the question of what integration time horizon should be used for impact assessment. Based on information provided by the RFPs (see section 5), the Review concluded that the integrated effect of the annual NOx emissions from a fleet of aircraft was similar to that of CO_2 in terms of long term (~ 50 years) Global Climate Change (GCC), although as noted above there is a slight bias toward CO_2 over longer time periods. The choice of integration time has a large effect on pollutant weightings (as has been found to be the case for Global Warming Potentials). The integrating time frame for climate impacts is variable, instantaneous is viewed as inappropriate, and the integrating timeframe should be beyond 20-30 years (~ 1 generation), and 100 years may ultimately be the most appropriate, although difficult to implement from a policymaker's viewpoint. Some members of the Panel felt that 50 years appeared to be a good compromise time period because it was more consistent with the long lived nature of CO_2, aircraft type "life", and previous fleet/emissions modelling projections, e.g. CAEP FESG for IPCC. However, some Panel members questioned 50 year projections because of their high level of uncertainty and hence their questionable utility to inform decisions. All agreed that consensus models for future reviews would be helpful and further scientific understanding is required to reduce uncertainties, particularly in regard to long term impacts of aircraft emissions, on GCC and relative to other sources (e.g., ground transportation). Significant uncertainties remain with PM, H_2O and cirrus. From a global climate perspective both NOx and CO_2 are of approximately equal importance over an impact assessment 50 year timescale, but CO_2 tends to increase in importance over longer timescales. Technology goals for NOx are justified, but should be reviewed to assess their environmental relevance as the understanding of the effects of all emissions improves.

1.9 Tradeoffs

Aviation's contributions to both LAQ and GCC complicate emissions tradeoffs considerations. There appears to be no clear significant opportunities to trade one pollutant against another, other than possibly increasing CO beyond current levels achieved for certification to create tradeoff "headroom" to reduce NOx. With regard to CO_2 and NOx, given current understanding, it was concluded that both need to be minimised: reducing fuel burn also leads to a reduction in mass NOx emitted if the emissions index is unaltered. NOx emissions are a concern of both LAQ and GCC environmental issues and CO_2 is also a key GCC pollutant. Any medium term goal must recognise that pressure to reduce both these pollutants (CO_2 and NOx) will continue. Since CO and HC are generally well below certificated levels, then, in principle, they may be traded with NOx, but an associated worsening of fuel burn (CO_2) would be difficult to justify. Relatively high levels of uncertainty about the characterization of aircraft PM and HAPs (a subset of HCs), and resulting contribution to overall environmental effects, deny any realistic opportunity for assessment of significant tradeoffs.

Only limited noise tradeoff information was offered to the Review and it was concluded that the noise/NOx linkage is relatively weak for the NOx reduction technology presented by industry to the panel. This should be an area of further investigation in future reviews.

1.10 Alternative Fuels

The possible impact of fuels from alternative sources on NOx has been examined in this study. In the interests of safety and operability, for the lifetime of the current fleet, kerosene or fuel closely meeting the kerosene specification will need to be supplied. Of course, this does not preclude synthetic kerosene fuel stock of suitable quality, from a variety of sources including coal and Bio sources, entering the supply chain. The aviation fuel that results will have the similar calorific value as kerosene, will produce the similar combustor temperatures and therefore produce, essentially, the same NOx emissions. Alternative fuels with lower calorific values could reduce flame temperatures and NOx but would require a higher fuel load or would reduce range. Higher calorific value fuels, such as liquid hydrogen, would offer both reduced NOx and CO_2 (depending on the production route). However, the use of such fuels will require an entirely different aircraft fleet and will not be commercially practical for a considerable time (in all probability beyond the 20 year long term goal).

1.11 Economic Concerns

The Panel was not asked to conduct a full economic assessment of the consequences of its chosen Technology goals so it did not have sufficient information to draw any firm conclusions in this area. The Panel concluded that achieving the MT technology goal appeared affordable given that the required technologies were being actively pursued within existing long running projects. The higher relative uncertainty of the LT goals made any economic assessment more problematic. There is some concern in some quarters that changes to publicly funded research policies may result in less swift development of NOx control technologies than has occurred in recent years. However, the scale of funding required, when viewed as a proportion of total airline costs, was not thought by the Panel to be significant in absolute terms and funding appears to be continuing in the region of the EU. Nevertheless, reductions in publicly funded research, which tends to focus on high risk, high payoff, can have adverse consequences since the likelihood of revolutionary advances would diminish.

1.12 Review Process Issues

The Review process, used to develop evidence-based recommendations for medium and long term technology goals, appeared to work well during this pilot Review. The Panel found the process effective, but it might be improved by:

- More information on industry trends and medium term and long term forecasts and access to a suite of analytical tools for *ad hoc* benefits assessments;
- Presentation material being available ahead of time which would facilitate the preparation and giving notice of questions;
- Wider regional representation on the Panel, especially from the developing regions of the world;
- The ability for the IEs to request follow-up information was very useful and should form part of any future review while accommodating any concerns over both protecting commercial sensitivities and conducting them in full open session. This ability should extend beyond the Review itself to the report drafting period, if necessary.

1.13 Conclusions and Recommendations:

A full list of the main Conclusions of the IE Panel can be found at Section 10 of the Report. They number 31 in all and have been categorised under the headings: Process, Basis of Goals, MT Goal and LT Goal. The Recommendations numbering 18 in all can be found at Section 11.

Report of the Independent Experts to the Long Term Technology Task Group on the 2006 LTTG NOx Review and the Establishment of Medium and Long Term Technology Goals for NOx

2 Introduction

2.0.1 The Long Term Technology Task Group (LTTG) of CAEP Working Group 3 nominated a Panel of Independent Experts (IEs) appointed by the CAEP Steering Group, whom it charged with conducting a review of combustor technologies for the control of oxides of nitrogen (NOx) and using this to establish medium term (10 year) and long term (20 year) technology goals for NOx reduction. This report, written by the IEs, presents these goals together with other key findings from the first LTTG Review held in London during March 2006. The terms of reference of the IEs have been provided in Appendix 1a.

2.0.2 Technology goal-setting is a means to provide to CAEP members and stakeholders a forward view on what technology might be able to deliver in terms of emissions mitigation over the goal-setting period set against foreseen (or quantified) environmental need. Technology goals are not guaranteed to be achieved and they should not be regarded as alternatives to CAEP standard stringency given the fundamental difference in nature between the two (see Section 9.5.2). However there is a linkage between the goal-setting and standard-setting processes. This linkage is a common basis in transitioning between the goal-setting and standard-setting process via the use of the Technology Readiness Level (TRL) scale to judge the progress of technology development through commercialization.

2.0.3 Engine manufacturers have already produced successive reductions to NO_x emissions that have allowed certification standards to be tightened. Improved emissions performance has been demanded largely by the airport and airline industries, in response to increasing environmental concerns both locally and globally. ICAO’s CAEP makes recommendations on the level of certification standards after considering, in addition to technological feasibility, the environmental benefit and economic reasonableness of a prospective stringency increase. CAEP also takes into account the technological interrelationships between noise and emissions.

2.0.4 An agreed note of the Review prepared by the WG 3 LTTG Task Leader is provided at Appendix 3 together with short summaries of all of the papers presented. A list of all the presented papers is provided at Appendix 4. All of the presentations are available in full on the CAEP website.

2.1 Review Body

2.1.1 An important element of the Review process laid down by the LTTG was the use of a panel of Independent Experts with balanced backgrounds and perspectives, assisted by industry members, to provide an independent assessment of the prospects from technology for NOx emissions reductions. The IEs were provided from France, the UK and the US. Their names are listed in Appendix 1 along with those of all other Review attendees.

2.1.2 The IEs and the selected industry members constituted the Review Committee. The Review Committee along with presenters and observers constituted the Review Body. The organizational structure is illustrated in Figure 1.

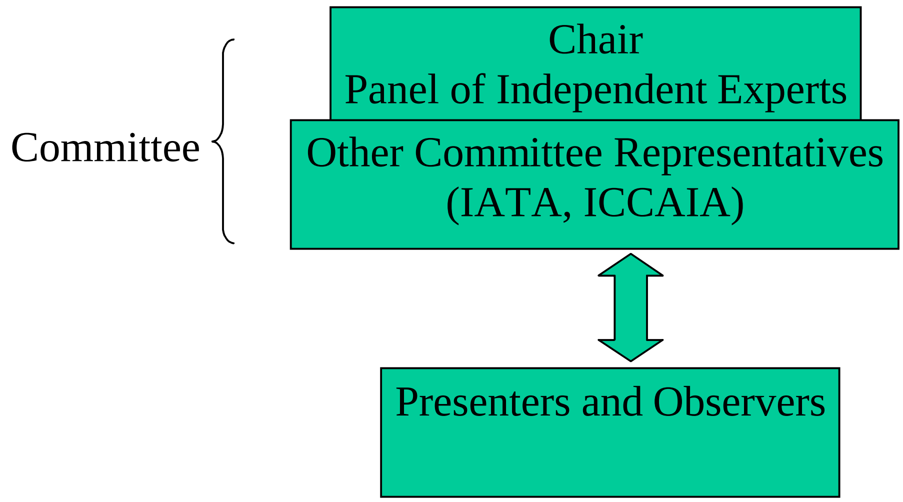


Figure 1: Review Structure

3 Scope of the Review

3.1 The review was asked to consider:

- Scientific understanding of climate effects of aircraft engine emissions;
- Understanding of the effects on local and regional air quality;
- New technologies for future products in the medium term;
- Prospects for development of revolutionary technologies for the long term.

Amongst other things, the IE Panel was asked to Report on:

- The status of technology developments for NOx emissions reduction in the 10 and 20 year periods
- To comment on the noise and emissions environmental tradeoffs resulting from such developments
- To report on the status of understanding of environmental impacts of aircraft engine emissions and identify where further research is needed
- To comment on the appropriateness of LTO emissions of NOx as the primary technology focus

The terms of reference of the independent experts is given at Appendix 1a of this Report

3.2 This Review was requested by the Long Term Technology Task Group, which had been charged by WG3 with providing advice on setting technology goals. The essence of the original remit for this task was agreed at CAEP/5 as follows:

> "To provide advice on long term technological practicability and feasibility to reduce aviation's emissions (both affecting local air quality and global climate change) taking into consideration the various national and international research

programme builds and milestones, for the purpose of establishing long term and forward looking CAEP goals for aircraft emissions reductions."

The full terms of reference of the LTTG are available on the CAEP website.

3.3 Further elements of the LTTG's remit require the support and development of methods for understanding the interrelationship of technology goals targeting individual emissions (in this case, NOx) performance improvements with other emissions, and noise, and developing the inputs appropriate for use with air quality, inventory and climate models to be used by CAEP to quantify the value of emissions reductions and to estimate the benefits from achievement of technology goals. CAEP agreed that the NO_x technology goal setting exercise should be used as a pilot to assess the goal-setting process and the extent to which goal setting on NOx could form useful advice for CAEP.

3.4 Key outcomes of this Review are the mid- and long-term technology goals - these being technology targets judged to be achievable within 10 and 20 years, respectively. They are not guarantees of future emissions performance, neither are they alternatives to CAEP standard stringency. Stringency provides the means to set a minimum environmental performance standard, whereas longterm technology goals offer predicted levels of performance based on projected capability rather than either being based on what might be technologically feasible (for all manufacturers) or economically justifiable.

3.5 The Technology Review was based on evidence and the combined judgment of the IEs. The industry had been asked to assess critically their own technology and research programmes and to present the information to the Review Panel in as open a manner as possible given the commercial restrictions that might apply. In order to respect sensitivities, technology conclusions have been reported largely without attribution to specific manufacturers. Technology "high water marks" (or best) regarding NOx were noted, and it was assumed that the industry could achieve these within reasonable cost expenditures. All participants were provided with detailed background information describing the work of LTTG in developing the technology review process. The goals reported here are the product of the IE Panel and, once adopted, are not expected to require frequent change though they should be subject to periodic independent review and adjusted in response to technology progress and development, improved understanding of environmental need, and improved understanding of interdependencies and tradeoffs amongst emissions and noise. This Review took account of both cost and benefits in a general sense only, as no means for performing quantified cost benefit analyses or monetisation of benefits was possible for this Review. In addition no quantification of environmental benefits that might result from achievement of the goals has been conducted.

3.6 While the Review had to identify an appropriate metric for the LT goals, the MT goal metric had been recommended by ICCAIA and agreed by LTTG as being the regulatory parameter, Dp/F_{00}.

3.7 The assessment of the status of technologies was based on the CAEP agreed TRL scale (See Appendix 2 and P12). This scale is already widely used to indicate the level of development of technologies as they progress from TRL 1 (Basic Principles) to TRL 9 (in service). For the purposes of this Review, the TRL range 6 to 8 was used for the medium term (10 year) goal and TRL 2 to 8 was used for the long term goal (P3 and 3.8 below). The Review was also presented with an academic overview of possible specific future technologies (P10).

The Review was provided with a presentation on the continuum that exists between the goal-setting and standard-setting processes. The presentation (P3) summarized that the TRL scale would be used as the primary mechanism for judging the state of development of technologies that are considered under both the goal and standard setting processes. The transition from medium term technology goals to considerations for further standard setting, based in-part upon the technologies shown to have achieved such goals, is defined by technologies that have matured to the point that TRL8 status has been demonstrated. The establishment of long term goals involves more uncertainty with regards to potential performance outcome and is farther removed from the standard-setting process. Standard setting will involve, amongst other things, consideration of economic reasonableness and competitive concerns. These factors are not relevant to technology goal setting and this demonstrates an additional distinction between goal-setting and standard-setting processes under CAEP. Section 9.5.2 of this Report provides further discussion of the philosophical differences between goal setting and consideration of stringency for standards.

4 Policy overview

4.1 The review was informed by a presentation of the UK government policy perspective to facilitate the growth of the aviation industry. The presentation (P2) stated that the UK, in addition to many other countries, is developing strategies to address these environmental concerns and the ability to have a robust forward view of the potential for environmental impact mitigation will assist these policy developments. The political necessity of providing a balance to permit the legitimate and advantageous growth of the aviation industry, whilst safeguarding the environment, can be addressed through a range of measures of which technology developments will be one of the most important. Moreover, the international context of civil aviation is a paramount consideration as change, should it be needed, will require international agreement.

4.2 Civil aviation is an integral and essential part of modern society, is a wealth generating industry and a facilitator of industrial, commercial, and social developments globally. Civil aviation makes a relatively small but significant and increasing contribution to the global environmental problems (ref. IPCC), both affecting global climate change and local air quality, and noise. Although technically small, it is one of the UNFCCC “key categories” – as others are smaller. Studies suggest that given the growth potential for this industry, and the likelihood that other industries will adopt cleaner fuels, these problems may increase over time.

4.3 In the absence of any other data offered to inform the IE’s of trends in aircraft emissions the 1999 IPCC report was used (Aviation and the Global Atmosphere, IPCC 1999) for this purpose. The CAEP FESG central scenario produced for the

IPCC suggest that relative to a base year 1992, aviation fuel consumption will have increased by a factor of 2.5 by 2015, and by around 4.0 by 2050. Corresponding forecasts for NOx are for increases by between 2.7 by 2015 and typically by 4.9 for 2050 (IPCC Report 1999, FESG Fa1 central scenario) and a range of scenario outcomes is discussed in para 9.2.5. It was frustrating for the Panel that more recent growth scenarios were not provided for the Review and particularly given that the 1999 IPCC study was based on data as old as 1992. It is questionable, therefore, whether the above figures represent current best estimates.

4.4 It was stated that (ref P2) climate impact assessments needs a longer viewpoint "50+ years" and the policymaker needs to know what technology may be able to offer under a variety of scenarios. The climate impact of long lived emissions e.g. CO_2 require assessment periods longer even than 100 years, but such time periods might be impractical from the policy standpoint. The more technology is able to deliver in terms of environmental improvements, the less pressure there is likely to be for other market instruments that could be considered to address aviation's future environmental problems. Technology gains will reduce the environmental impact of aviation growth and contribute towards CAEP's environmental objectives. The policymaker welcomed technology goals as a means to inform the extent to which environmental mitigation from future technologies might be effective.

4.5 This initial goal setting process has targeted NO_x emissions. However, setting goals for NO_x may influence the industry to focus on this emission rather than others, and the tradeoff issue needs to be addressed very clearly in any goal setting exercise. Moreover, the sustainability of the aviation industry will depend in part on the other emissions being addressed: the NGO presentation (ref P4) stated to the Review that long term goals needed to look beyond NO_x and address CO_2, PM and other global warming and climate change pollutants, and noise at the same time.

5 Aviation Environmental Science Overview

5.1 Introduction

5.1.1 The growth of air travel for the past several decades has been very rapid and has exceeded the growth of Gross Domestic Product (GDP). Global demand for travel services, both passenger travel and freight transportation, is increasing substantially, and is currently forecast to grow at around 5% per year for the next 25 years (ref. Boeing CMO, 2005, (4.8%)). Over the long term, the demand for air transportation will likely continue to grow rapidly. Whilst technology developments are likely to continue to reduce emissions per passenger kilometre, aviation emissions could grow against a background of reductions from other sources facilitated by adaptation of cleaner fuels, thus making aviation's relative contribution to the emissions burden potentially higher. Expected NOx reductions from other sources may reduce the need for required reductions from aviation, but this is unlikely to be the case with CO2 emissions, which the Independent Experts believe will likely grow from all sources.

5.1.2 Aircraft engine combustion products are roughly composed of about 70 percent CO_2, a little less than 30 percent H_2O, and less than 1 percent each of

NO_x, CO, SO_x, VOC, particulates, and other trace components including Hazardous Air Pollutants (HAPs).

5.1.3 Aircraft emissions, depending on whether they occur near the ground or at altitude, are primarily considered local air quality pollutants or are (or can affect) greenhouse gases, respectively. Water in the aircraft engine exhaust at altitude has a small greenhouse effect (positive radiative forcing), and water and particles may initiate contrails if environmental conditions favour their production and persistence. Contrails also have a positive radiative forcing, although the size of the effect is uncertain. The effect from contrail-derived cirrus is highly uncertain, and was stated as being from "small" to "very large". About 10 percent of aircraft emissions of all types, except hydrocarbons and CO, are produced during airport ground level operations and during landing and takeoff (i.e. in the atmosphere's boundary layer, up to about 1km). The bulk of aircraft emissions (90 percent) occur at higher altitudes. For hydrocarbons and CO, the split is closer to 30 percent local emissions and 70 percent at higher altitudes.[2]

Emissions from Combustion Processes

CO_2 – Carbon dioxide is the product of complete combustion of hydrocarbon fuels like gasoline, jet fuel, and diesel. Carbon in fuel combines with oxygen in the air to produce CO_2 .

H_2O – Water vapour is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produce H_2O.

1.1.1 NO_x – Nitrogen oxides are produced as air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x.

HC – Hydrocarbons are emitted due to incomplete fuel combustion. Also referred to as volatile organic compounds (VOCs). Many VOCs are also hazardous air pollutants.

CO – Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel.

SO_x – Sulfur oxides are produced when small quantities of sulfur, present in essentially all hydrocarbon fuels, combine with oxygen from the air during combustion.

Particulates – Small particles that form as a result of incomplete combustion and are small enough to be inhaled are referred to as particulates. Particulates can be solid or liquid.

5.1.4 To set long term technology goals, it is necessary to understand the relative impacts of various aviation emissions. The Technology Review sought advice on the degree of current scientific consensus concerning the understanding of the environmental impacts from engine emissions. Three major themes evolved: local impacts from emissions associated with operation in airports including landing and take-off (LTO emissions); global impacts associated with non-LTO emissions 1 kilometre (~3000 ft) above the ground; and tradeoffs amongst various emissions. It is likely that non-LTO emissions at cruise have only modest impacts on local air quality compared with local sources, and that emissions around specific airports do not

[2] Federal Aviation Administration, Aviation Emissions: A Primer, 2004.

affect global concentrations (Tarrason et al., 2004)[3]. This generally allows decoupling between local and global effects and reflects the reality of the situation where two distinct communities of practitioners study the two issues. However, the two issues cannot be really decoupled, as there are tradeoffs, which must be taken into account. Local air quality concerns, global climate concerns, and tradeoffs are each discussed below.

5.1.5 The discussion below is largely based on the input provided by the Research and Science Focal Points (RFPs), Malcolm Ko, Rick Miake-Lye David Lee and Claus Bruning (P5, 6, 7 and 8) as well as the IPCC report.

5.2 Local Air Quality Concerns

5.2.1 Aircraft engines are not the only source of local airport emissions. Airport access and ground support vehicles produce similar emissions. Such vehicles include traffic to and from the airport, ground equipment that services aircraft, and shuttle buses and vans serving passengers. Other emissions sources at the airport include auxiliary power units (which the review noted in some cases could account for 10% of aircraft sources) providing electricity and air conditioning to aircraft parked at airport terminal gates, stationary airport power sources, and construction equipment operating on the airport. The impacts of airport emissions on local and regional scales is also part of the broader problem of local and regional air quality monitoring and should be considered in the broader context of those environmental factors specific to the region's air quality problems. It is well known that the same emissions could cause different changes in ambient concentrations at different locations. In addition, the actual health impact will depend on the population exposure, which in turn depends on the population number and distribution in the region being considered. Nevertheless, some evidence was presented in the form of the difficulties encountered with adding a third runway at London's Heathrow airport (amongst other UK and European airports) and the large number of U.S. airports presently in non-attainment areas (areas exceeding air quality standards) for NOx as well as other pollutants to provide at least a qualitative need for long term NOx goals for aircraft.

5.2.2 **NO_x (NO and NO_2)** is a participant in ozone formation, and also contributes to nitric acid and acidification of aerosols (fog) and rain. Tracking NO_x serves multiple purposes as a criteria pollutant of NO_2, and as a precursor for ozone, and a minor precursor for PM2.5. The relative contribution from aviation NOx may become larger as other sources reduce NO_x through exhaust treatment. Quantification of and inventories for aviation NO_x local emissions are well in hand. Thus, additional work in further developing metrics for local NO_x emissions is not needed to inform long term goal setting.

5.2.3 Although there is no ICAO certification standard for particulate matter (PM), PM is also an important emerging issue. The air quality standards of many countries cover PM emissions, and inventories computed to show compliance must include PM emissions from aviation sources. Knowledge is lacking at

[3] Tarrason, L., J.E. Jonson, T.K. Berntsen, and K. Rypdal, Study on air quality impacts of non-LTO emissions from aviation, Final report prepared by the Norwegian Meteorological Institute for the European Commission. Available from http://europa.eu.int/comm/environment/air/future_ceilings.htm

present on how to measure aircraft engine particulate matter, how to calculate emissions factors and how aviation particles, both volatile and non-volatile, differ from those generated by other emission sources. There is significant recent and on-going research relating to how aircraft engine PM emissions depend on engine type, operating conditions and technology. Smoke emissions are defined by a Smoke Number, SN, developed in parallel with the various gaseous emission measurement approaches in the 1970s, to quantify the visible smoke trails behind airplanes. Only the maximum smoke emission level is regulated, irrespective of the engine power level that the maximum occurs. Thus, while visible smoke has been reduced significantly in the last decades and the application of the SN can be deemed a success, there is currently no reliable means of developing an inventory of aircraft particle emissions. To properly evaluate the influence of aviation growth on local air quality, uniformly consistent methodologies, both measurement technology and procedures (such as probe and sampling system designs) are critical. A subset of fine PM, generated by various sources, including aviation, has been recognized as hazardous to human health. It is well understood that the sulphur in fuels directly contributes to the gaseous emissions of sulphates and SO_2. What is less understood is how sulphates and SO_2 contribute to secondary fine PM generation, not only as individual contributors, but also in a heterogeneous mixture with other pollutants. In summary, there are many uncertainties surrounding aircraft PM and hence quantitative tradeoffs between NOx and PM are difficult.

5.2.4 For **Hydrocarbon (HC)** emissions, total inventories can be developed from the ICAO database. However, some HCs may be interrelated with volatile particles and, in addition, increased interest is arising in regard to specific hydrocarbons owing to their potential as Hazardous Air Pollutants (HAPs). As such, more detailed emissions characterization of HC may be required in the future. Some important initial work on speciation of HC emissions has begun, but dependences on engine and fuel properties are not well known at this time. Further research in characterizing HAPs and better understanding the interrelationships among the HC emissions is needed to produce a better understanding of these issues. Again, quantitative tradeoffs between NOx and HC are difficult given the uncertainties.

5.2.5 **CO** has a relatively long lifetime (~ weeks) and can affect the local hydroxyl concentration resulting in changes in concentrations of ozone and methane. However, CO from engine emission is generally very small. The IEs feel that there may be an opportunity to trade some increases in CO for benefits in NOx, but if fuel efficiency and CO_2 are worsened then this trade is not desirable.

5.3 Global Climate Concerns

5.3.1 Present commercial subsonic aircraft operate at cruise altitudes of 8-13 km (in the upper troposphere-lower stratosphere), where they release emissions and PM, thereby altering the atmospheric composition and changing the energy balance of the atmosphere-earth system. Aircraft global emissions lead to changes in ambient concentration of the emitted species (e.g. CO_2), and indirectly to changes in concentrations of other species through photochemical interactions (changes in concentration of O_3 and CH_4 as a result of NOx emissions). In addition, aircraft cause contrails under certain environmental conditions that may, in turn, enhance cirrus cloudiness.

5.3.2 The Intergovernmental Panel for Climate Change (IPCC) is the premier international organization that provides consensus policy-relevant scientific information for defining mitigation processes for global climate issues. The impact of aviation on climate has been analyzed by IPCC Special Report on Aviation (IPCC, 1999)[4] and the issues were revisited briefly in the IPCC' Third Assessment Report (IPCC, 2001)[5]. In the IPCC process, peer-reviewed results from top research groups are compared and reported, and opinions from an expert panel are offered. An individual chapter usually involves many authors and contributing authors and is twice reviewed by a wider scientific base, and finally by government representatives. However, it is important to note that as the process is consensus-driven, IPCC reports may not reflect leading edge research. Other, more cutting edge, sources may provide a more advanced view of the issues, but will be less likely to influence the policy perspective. The Research and Science Focal Points noted that the scientific community can provide some, but not complete, guidance on the formulation of tradeoff metrics to address aviation GHGs, and specifically cruise NOx. Defining metrics must also be informed by considering overall societal goals, potential tradeoffs between competing actions, and economic considerations that are clearly policy decisions.

5.3.3 The IPCC reports use radiative forcing (RF) to compare the climate impact of the different gases and particles. RF (here measured in milliWatts per square meter, mWm^{-2}) expresses an instantaneous change in the energy balance of the earth-atmospheric system resulting from a perturbation in concentrations of greenhouse gases (GHGs) in the atmosphere. A sustained positive radiative forcing imposes a warming effect, negative value a cooling one. Predicting the RF for a specific emission of a species depends on the ability to calculate the changes in species concentrations that result from the emission and the radiative efficiency (RE, forcing per unit change in concentration) of each of the perturbed species.

5.3.4 Well-mixed GHGs have long residence times (~ several decades or longer). The long residence time in the atmosphere means that it is straightforward to predict the change in concentration, as it is uniform over the globe independent of when and where the gas is emitted. Once emitted, the forcing will persist for decades or centuries even if emissions were to cease. For these long-lived GHGs the steady state surface temperature change from a sustained forcing is expected to be proportional to the RF, with approximately the same proportionality constant for all GHGs. Amongst emissions sources in the present day atmosphere, carbon dioxide is the most important well-mixed GHG because of the large quantities released and the long residence time of this gas in the atmosphere.

[4] IPCC, 1999: Aviation and the global atmosphere - A special report of IPCC working groups I and III. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 365 pp.

[5] IPCC, 2001: Climate Change 2001 - The Scientific Basis. Contributions of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 881 pp.

5.3.5 IPCC acknowledges that there are much larger uncertainties associated with evaluating the climate impacts from short-lived gases, and particulates. Once emitted, they typically remain in the atmosphere for less than a year. In addition, the spatial pattern of the change depends on where and when the emissions occur. For example, because only a small fraction of the NOx emitted at the ground is transported to the upper troposphere, NOx emitted at cruise altitudes has a much larger impact than the same amount emitted at ground level. Changes in concentrations will also be the largest near flight routes and therefore have a more regional effect on climate. Three–dimensional emission inventories for cruise are computed using fuel use and emission indices (g of pollutants emitted per kg of fuel use). It is unclear whether the global averaged temperature response to the global averaged forcing will bear the same relationship as the long-lived GHGs. For these reasons, there are conceptual difficulties in using a GWP[6] for NOx/O_3 as the chemical (and thus RF) effect varies in space (location, altitude). Finally, using a 100 year integrated effect approach would artificially minimize the short-term impacts because most of the effect really occurs in the first decade.

5.3.6 **Carbon Dioxide**: As explained above, CO_2 emitted by aircraft at cruise altitudes has the same effect as CO_2 emitted by a source at ground level. Fuel use for aviation is 2-3% of all combustion sources, and 15% of the transport sector. However, aviation is cited by the United Framework Convention on Climate Change as one of the major contributors to GHG inventories and the IPCC forecasts that fuel use from aviation may become 5% of all combustion sources by 2050.

5.3.7 **Water vapour**: emitted into the free troposphere by aircraft has little effects on RF because of the copious amount of water already in this part of the atmosphere. However, water vapour (and PM) emitted into the upper (cold) regions of the troposphere and often triggers the formation of line shaped contrails, which tend to warm the earth's surface. Persistent contrails may also disperse to form (optically thin) cirrus clouds (called contrail cirrus), which could have an additional warming effect. The direct RF of H_2O and the RF of linear contrails (for a given contrail coverage) is fairly well known, however, the RF associated with contrail cirrus is highly uncertain (noted as either "zero" or "very large"). In addition, prediction of contrail coverage and cirrus remain a challenge. The residence times of water and contrail in the upper troposphere are of the order of days and hours respectively and the relative importance of these effects versus CO_2 is difficult to interpret. The warming effect from water vapour injected into the naturally dry higher stratosphere may become more problematic with anticipated growth and should aircraft cruise altitudes increase from current levels.

5.3.8 **Sulphate and soot aerosols:** have a much smaller direct forcing effect compared with other aircraft emissions. Soot absorbs heat and has a warming effect; sulphate reflects radiation and has a small cooling effect. In addition,

[6] Global warming potentials (GWPs) are used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative efficiency (heat-absorbing ability) of each gas relative to that of carbon dioxide (CO_2), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of CO_2.

accumulation of sulphate and soot aerosols might influence the formation and the radiative properties of clouds. Direct RFs are fairly well known; however, indirect RF through changing cloud properties is highly uncertain. Addition uncertainties come from the emission indices of soot.

5.3.9 **Nitrogen oxides:** though not in themselves GHGs, produce an indirect radiative forcing by changing ozone and methane concentrations in the atmosphere. Nitrogen oxides are chemically reactive gases, which produce **ozone (O_3)** under the influence of sunlight**.** As a consequence of complex tropospheric chemistry, NO_x will also reduce the ambient atmospheric concentration of **methane (CH_4)**. The RF of ozone and methane are fairly well known, of similar magnitude but opposite sign.

5.3.10 Table 1 summarizes estimates of instantaneous RF and the uncertainties from changes in concentrations from historical aircraft emissions reported by IPCC (1999). A recent study by Sausen et al. (2005)[7] showed that the magnitude of the O_3 and CH_4 responses are 25% and 50% smaller. The results for soot and contrails are factor of 1.6 and 3 smaller respectively. The values given in the Table should NOT be used to compare forcing in trade-off studies for two reasons. First, the numbers are RFs from the changes in concentrations associated with cumulative emissions from the historical fleet, rather than annual emission. Second, they are instantaneous forcing values and do not account for the different future potential forcing effects between long-lived and short-lived GHGs. Radiative forcing from aviation effects is also illustrated in Figure 2.

Table 1: Instantaneous Radiative forcing (RFs) [mW/m^2] due to aviation emissions from historical operation of the subsonic fleet in the year 1992 as reported in by IPCC (1999).

<table>
<tr><td>Emission/concentration</td><td>RF
[mW/m^2]
Range*</td><td>Comment</td></tr>
<tr><td>CO_2/CO_2</td><td>18.0
13 to23</td><td>Instantaneous forcing due to a change in CO_2 concentration of 1 ppmv resulting from cumulative CO_2 emission from historical operation of the fleet to 1992. For comparison, the change in CO_2 concentration from 1992 emission is 0.07 ppmv.</td></tr>
<tr><td>NO_x/O_3</td><td>23.0
13 to 45</td><td rowspan="2">Instantaneous forcing from changes in concentration due to the steady state response of the atmosphere to a persistent operation of a fleet with 1992 emissions. Typical time to reach steady state is a few months for O_3, about 10 years from CH_4.</td></tr>
<tr><td>NO_x/CH_4</td><td>-14.0
-44 to -4</td></tr>
<tr><td>H_2O/ H_2O</td><td>1.5
1.5 to 3</td><td rowspan="2">Instantaneous forcing from changes in concentration due to the steady state response of the atmosphere to a persistent operation of a fleet with 1992 emissions. Typical time constant is weeks.</td></tr>
<tr><td>SO_x,PM/Sulphate</td><td>-3.0
-5.0 to 0</td></tr>
</table>

[7] Sausen, R., Isaksen I., Grewe V., Hauglustaine D., Lee D.S., Myhre G., Köhler M., Pitari, G., Schumann U., Stordal F. and Zerefos C., 2005: Aviation radiative Forcing in 2000: An Update on IPCC (1999); Meteorol. Z. 14, 2005.

Soot/ Soot	3.0 2 to 8	
H_2O, PM/ Contrails	20.0 5 to 60	

* The range represents a subjective estimate (as cited in the IPCC report) that there is a 67% probability that the true value falls within the range. The uncertainties arise from a combination of the uncertainties in predicting the change in concentration and in predicting the environmental impact from a given concentration change.

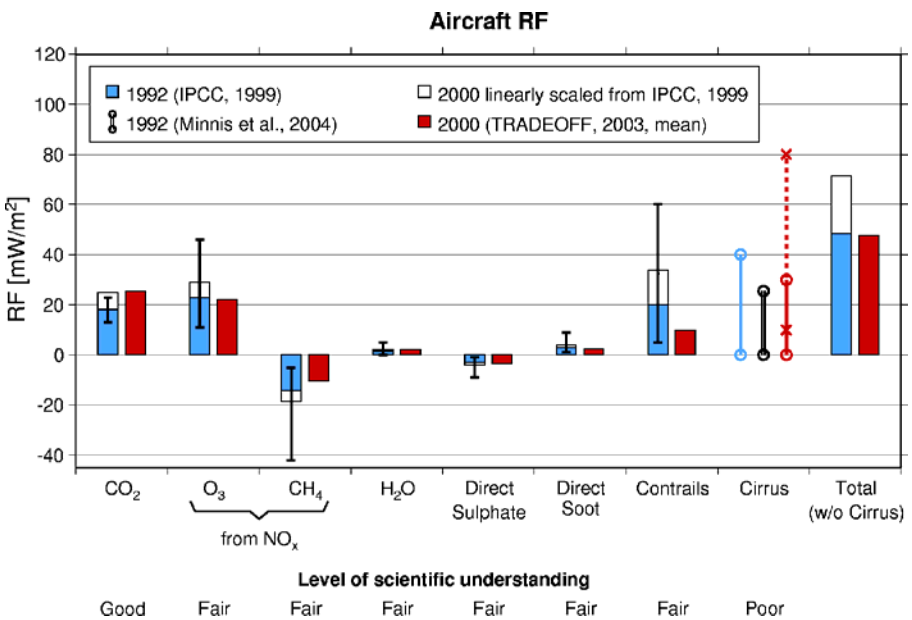


Figure 2: Bar charts of radiative forcing (using various integrating times) from aviation effects in 1992 (subsonic fleet) and subsequent modifications.[8]

5.4 Tradeoffs

5.4.1 Reducing emissions unilaterally is one approach to minimize a particular environmental impact. However, designs that reduce one engine emission may have negative impacts on other emissions or noise. This is the reason why tradeoffs must be considered in such designs. In the context of setting long term NOx goals, the following are important:

• trade space on global climate impacts from emissions at cruise
• trade space on local air quality (LAQ) and health (PM vs. ozone) from emissions at airports
• trade space between noise and LAQ at local level from airport operation
• trade space between air quality at local versus regional level

5.4.2 Uncertainties associated with estimating the environment impacts play an increasingly important role in trade studies as one includes more dissimilar environmental impacts in the trade space. The scientific consensus that warming

[8] ***Ibid***

from well-mixed GHGs is proportional to radiative forcing allows one to consider the tradeoff among well-mixed GHGs without having to specify the exact constant of proportionality. If one considers the tradeoffs among CO_2, NOx, H_2O and PM emissions at cruise, the outstanding science question is whether RF (instantaneous or cumulative) from short-lived emissions (NOx, H_2O, and PM emissions), and their effects on ozone and contrails, can be used as a proxy for temperature response in the same way as is done for well-mixed GHGs (CO_2). If this cannot be done the relevant policy question is whether a separate metric for short-lived GHGs is required and how this might relate to the long-lived GHG metric. This is one area where Science can provide critical input, but a clear answer is not available at this time.

5.4.3 The tradeoff at the local level between the effects of changes in ozone, PM and HCs presents a challenge because the issues will involve health impacts, crop damage, and visibility impairment.

5.4.4 Monetization of the costs and benefits of mitigation is beginning to be used to quantify these types of tradeoffs[9], and the scientific assessment of the impacts and their uncertainties are critical inputs to these analyses. Ultimately, however, policy makers will need to draw on the integration of the scientific inputs and the economic analyses, as well as the social costs and technological requirements, to make decisions on appropriate tradeoff requirement compromises for balancing the overall cost of emissions with the benefits that might reduce aviation's environmental contribution. Hence any goals recommended as a result of this review will need to be revisited.

5.5 Summary

5.5.1 The scientific experts charged with providing science input to the Review, namely the Research and Science Focal Points who advised CAEP WG3, were able to provide advice to guide long-term goal setting, but this was necessarily caveated given current uncertainties. The IEs noted that scientific uncertainties will always remain because the nature of science is to question. But focusing the advice of the scientific experts on some key questions helped elicit some useful advice. The specific questions were:

1) Is there still a need to consider further aircraft NOx reductions? Yes/No
2) If yes, is the need greater or less than previously?
3) What is the relative impact of aircraft NOx compared with other aircraft pollutants:
    a. LAQ
    b. Global warming
4) To what extent are these views consensus views?
5) How would you rank the relative importance of: CO_2, NOx, CO, UHC, SO_2, Soot, PM other (without quantification) in the next 20 years and 50 years out.

[9] Ian Waitz, "Benefit-Cost Analyses of Aviation and Environmental Impacts", 2006 University of California at Berkeley Aviation Noise and Air Quality Symposium, http://www.techtransfer.berkeley.edu/aviation06downloads/waitz.pdf

The replies were as follows:

1 and 2) was an emphatic “yes”. There is a need for further aircraft NOx reductions and this need is expected to grow given projected growth in demand for aviation services. NOx cannot be ignored from either a local air quality or global climate impact perspective.

3) The role of cirrus/contrails/PM on global climate effects is uncertain at this time and therefore difficult to relate to the effects of NOx emissions. It is advisable to limit SOx and PM, but from a global climate perspective CO and HC are not a concern. For local air quality NOx/NO_2 are the main concern, with PM next in importance (and its relative importance may exceed NOx/NO_2 after monetization). The importance of HAPs may increase with more understanding of their effects, and CO is not viewed as an important issue.

4) Whilst the Research and Science Focal Points offered their own consensus view on the relative importance of various pollutants, there is no clear “consensus” view across the entire scientific community since the community has not been charged with providing this since IPCC (1999).

5) From a local air quality perspective, NOx was noted as the most important pollutant. However, PM and UHC may grow in importance as the uncertainties surrounding their relative impact are addressed. CO is not a salient issue and is not projected to become one in the future. By contrast the process of ranking of various emissions for climate effects is conceptually difficult. Based on IPCC and other studies, the Research and Science Focal Points noted that using instantaneous forcing as the tradeoff metric, the climate impact from annual CO_2 emission is $1/15^{th}$ that of NOx. At the other extreme, using forcing integrated over 100 year as the tradeoff metric, the effect from annual CO_2 emission is 8 times larger. Figure 3 captures the relative temperature responses to a pulse emission (corresponding to the annual emissions for the global fleet) from of NOx and CO_2 for the global fleet (i.e. NOx and CO_2 in proportion to emissions). This clearly shows the importance of time frame considerations. This figure indicates that over a 50 year timeframe NOx and CO_2 were approximately of equal importance for integrated global mean surface temperature response although this is an *indicative* calculation. Over longer timeframes, CO_2 will be of greater importance.

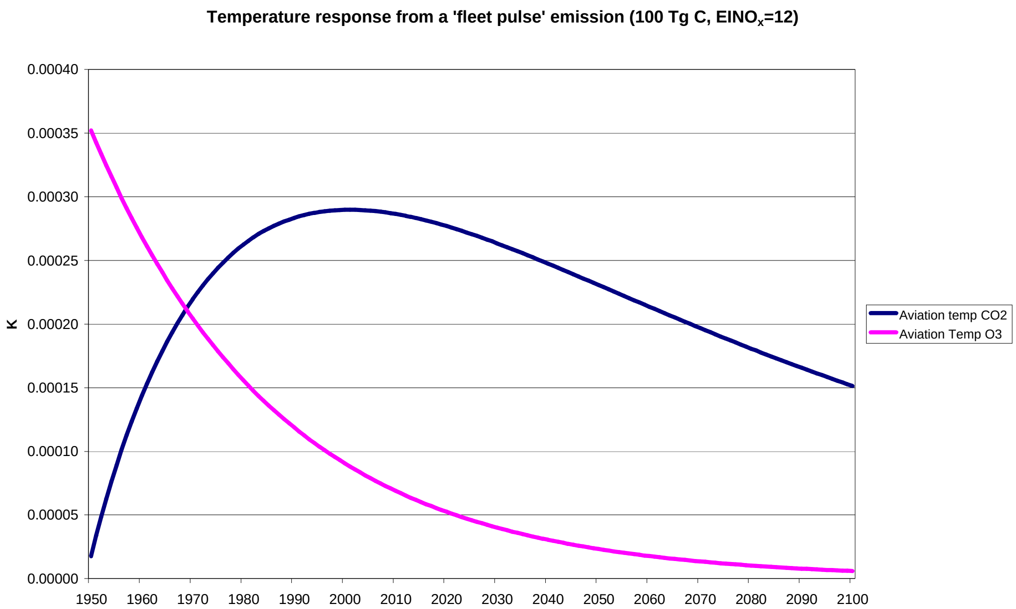


Figure 3: Relative pulse temperature response (K) for global fleet of NOx and CO_2

5.5.2 The integration timeframe (frequently referred to as the integration time horizon [ITH]) for climate impacts is somewhat arbitrary, but instantaneous is viewed as inappropriate. The IEs believe that the integrating time frame has to be beyond 20-30 years (~ 1 generation), and 100 years may ultimately be the most appropriate, although such a cross-generational response may be difficult to implement from a policymaker's viewpoint. However, P5 (of the Science Review, Summary Report, presented to the Review) notes 100 years as the current trading policy for long-lived green house gases (GHG).

5.5.3 Based on the evidence presented it appears that from a global climate perspective it is important to reduce both NOx and CO_2 and trading one for the other now is not advisable, although there is a slight bias toward reducing CO_2. The general conclusion from the scientific discussion is that the need for technology goals (for NOx) is to some extent justified but they must be reviewed at intervals, perhaps coinciding with the CAEP cycle, to both assess progress towards their achievement and their environmental relevance as the understanding of the effects of the other emissions improves.

6. Technology Review

6.1 History

6.1.1 The international regulation of NOx began with the ICAO CAEE limits of 1986 (year of certification compliance P3). Figure 4 below shows the current and historical CAEP certification standards for NOx. Using a takeoff OPR of 30, for convenience, to examine subsequent increases in the stringency of the NOx standards, we see that CAEP2 (1996 certification compliance) provided a 20%

reduction from the '86 level. CAEP4 (2004 certification compliance) is 16% below CAEP2, and CAEP6 (2008 certification compliance) reduced the requirement to 12% below the CAEP4 level (all levels quoted at 30 OPR for reference). Overall, from 1986 through the 2008 requirement, the NOx requirement was reduced by about 40% from the initial levels. This reduction is somewhat less at higher OPR levels due to the "kink" in the curve introduced in CAEP4. This "kink" at PR30 recognized the OPR increase required to increase thrust within existing engine programmes (wherein NOx increases more rapidly with OPR than when new system design is permitted). The figure shows some typical engine certification examples, plotted against the certification metric Dp/F_{00} and overall engine pressure ratio (OPR at sea level static test conditions). The emission parameter represents the characteristic mass of emissions produced during a simulated landing and takeoff cycle, Dp, normalised against the maximum engine thrust, F_{00}.

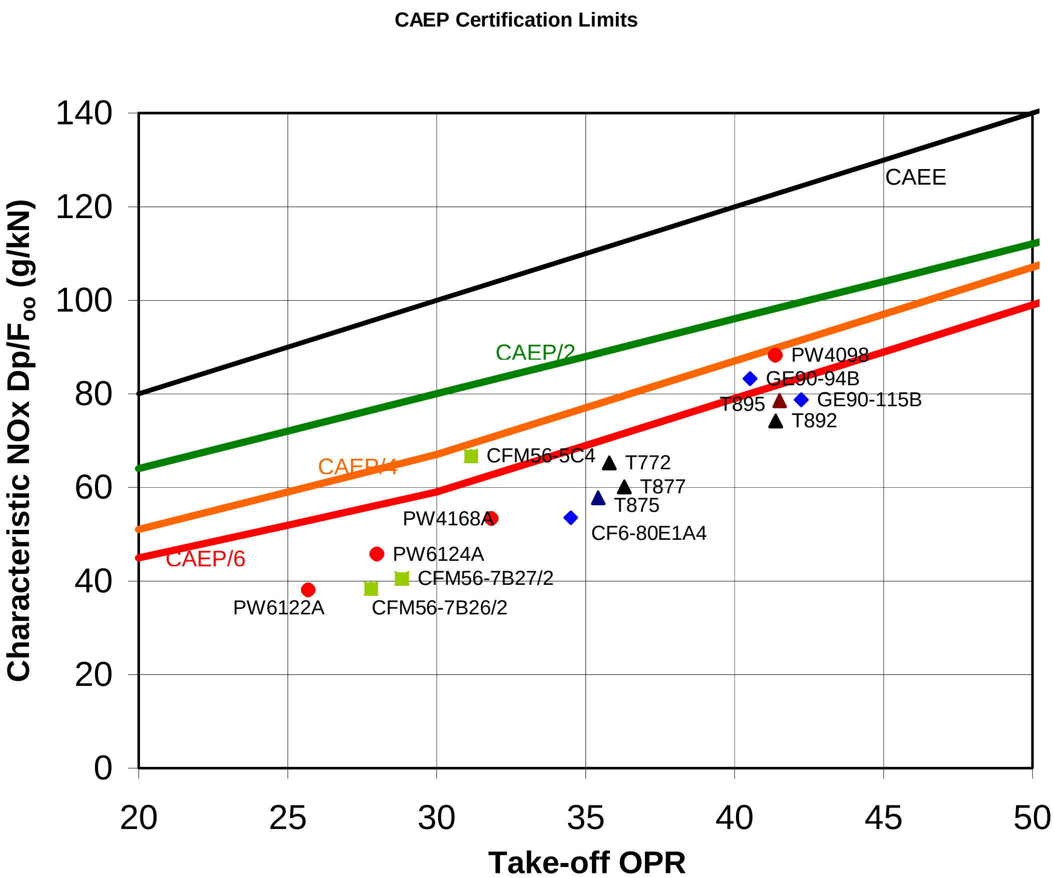


Figure 4: CAEP Stringencies

6.1.2 These stringency positions were determined *post hoc*, that is they were not "technology forcing". Capabilities for current and very near term products were understood before stringency was established. This process "locks in" gains from technology and ensures that all future efforts comply with best practice. This concept is evident from the most recent certifications, where most engines were certified 5 to 20% below CAEP6. External forces and market pressures have delivered lower NOx emissions. This most recent level of achievement will be captured in the next cycle along with demonstrated achievement in the interim. The chart above shows a sample of engine certifications for illustration.

6.2 Design and Requirements

6.2.1 The history of combustor design begins with the can combustor, a concept featured in about 12000 engines in service at the time of the 1986 ICAO regulations. These cans were individual, cylindrical combustors. They were relatively inexpensive, easy to test and develop and easy to replace when damaged while in service. On the negative side, they led to longer, heavier engines, and, due to large surface area, required more cooling flow. Cans reduced turbine life by creating discrete flow discontinuities and hot spots. NOx was more difficult to manage due to the high demands of cooling flow for the large surface areas.

6.2.2 The annular combustor came to commercial service with the wide-body aircraft of the early 70's. This design is more compact, lighter and has less surface area per unit of flow. This minimizes cooling flow and makes it easier to manage NOx.

6.2.3 Today's engines reflect 35 years of evolution of the annular combustor design. In that design cycle, the aircraft dictates the engine design. The aircraft is defined by market needs. The aircraft and engine design, then, determine CO_2 and H_2O emissions (fuel burned). NOx, CO, and HC are determined by the design of the combustor. There are options to trade these emissions within the combustor "design space", but the combustor faces a myriad of requirements that limit these options. It is these limits, mostly for safety and operability that separate the theoretical from the practical. These design requirements include:

- engine must have room for growth
- combustion system must also meet CO, HC and Smoke emission limits
- component efficiency goals
- flameout
- ground and altitude restart
- temperature profile for turbine life
- pressure drop for performance
- operability (adverse transients)
- burner noise/vibration
- cost
- weight
- other.

With these considerations, and there are more, the "design space" is now small given the need to achieve acceptable compromise and certificability on all the above.

6.3 Addressing NOx

6.3.1 NOx is produced by exposing air to high temperature. The longer the exposure time, the higher the temperature and pressure, the more NOx will be produced (see section 7 for more detail). Moreover, the need to address CO and HC emissions, which are products of incomplete combustion, and smoke which results from local high fuel levels, limits the "design space" when designing for low NOx emissions. The challenge of the last 30 years has been to limit the temperature and limit the time at high temperatures. This creates "tension" with fuel consumption, since low fuel burn is achieved by, for example, high OPR and by-pass ratio (BPR) and these require high combustor temperatures. Fuel burn performance is of paramount importance in an aircraft design and exerts a major influence on engine design. So, given temperatures are high, time at temperature must be kept at an absolute minimum to minimize NOx.

6.3.2 The reductions realized in NOx in modern combustors have come from advances in fluid mechanic science, and design tools (e.g. Computational Fluid Dynamics, CFD), and in fuel distribution systems, all supported by extensive experimentation and advanced instrumentation aimed at minimising exposure of air to high temperatures. These advances have been the result of research, development, test and evaluation by both government and industry. Heavy investment by all parties has been made to permit this progress.

6.4 Rate of Technology Improvement

6.4.1 History and judgment indicate that, on a rough scale, big steps (revolutionary) require on the order of 20 years from concept to product (TRL 2 to 8), e.g. GE DAC. In the case of evolutionary steps (TRL 5 to 8), as few as 5 and as many as 10 years can be required from concept to product. The pace of a technology up the TRL ladder is dependent on many factors including need, market forces, product success, regulatory pressure, funding, learning (often from the pursuit of what might transpire to be a bad idea), among others.

6.4.2 Heavy investment (during questioning at the review an example of $60 million for the TAPS combustor was noted) since the mid 90's has supplied technology for NOx reduction that will reach fruition in the next decade, consistent with the TRL pace mentioned. This cost at the lower TRL research levels is relatively small compared with clearing the technology through the higher TRLs. In addition emissions margin is often lost during transition to product. A number of candidate long-term technologies are being pursued and were presented to the Review, which could lead to improvements in the 20 year time frame.

6.4.3 Technology goals must recognize all the factors discussed above, in addition to the uncertainties in atmospheric science. Design decisions should be informed by the best scientific understanding to ensure design trades (e.g. choosing NOx over noise, or CO_2 or PM, or vice versa) do not produce unintended, undesirable, environmental performance.

6.5 Technology Status– Mid Term

6.5.1 The recently certificated engines incorporate optimized rich burn (Rich Quench Lean Burn – RQL) technologies, designed to meet/exceed CAEP6 NOx levels, with room to allow for thrust growth. The A380 powerplants, the most recent certifications, use RQL approaches in an aircraft that will be in service throughout the first half of this century. From the certificated numbers the range of NOx emitted from these engines was from 5% to more than 20% below CAEP6.

6.5.2 The next large commercial products on the horizon (2008 to 2012 certification) are the Boeing 787 and Airbus A350 and the next significant new narrow-body aircraft are expected to be the 737/A320 replacements. The technologies for the 787 are already committed to development and certification. These are the RR Trent 1000 Phase 5 (RQL) and the General Electric (GE) TAPS (LDI), combustors. The Pratt and Whitney (P&W) TALON X is an RQL approach and is targeted at the new narrowbody market. Today, TALON X is at TRL 5-6, while the 787 applications are at TRL 7. All of these products show promise of significant NOx reduction, with all three manufacturers showing challenging targets. Rolls Royce (RR), for example, states company goal and Trent 1000 prediction at 50% below CAEP2, or about 40% below CAEP6. Both GE and P&W noted similar levels of performance for this time frame. The small engine SaM146 developed by Snecma in collaboration with NPO-Saturn and Avio (P19), to be certified in 2008, relies on optimised conventional technology (rich combustion) and similar level of NOx reduction is foreseen.

6.5.3 The A350, 787, and the anticipated future new narrow-body aircraft set the boundaries for mid term technologies. They are in place, gathering investment and rapidly climbing the TRL scale. These aircraft could dominate the fleet past 2050.

6.6 Technology – Long Term

6.6.1 Looking beyond the 10 year, mid-term time frame to a 20 year horizon is made difficult in part due to the uncertainty of atmospheric science (what is the need for NOx reduction? what are the proper trades?) and, the increasing pressure on economics of operation (fuel burned, maintenance, reliability). Today, economic pressures (very high fuel price) suggest that fuel burned, and, hence CO_2, will dominate preliminary designs of products that will comprise the majority of the fleet in the second half of the century. Economic and regulatory pressures can have a powerful effect on design, and have played a strong role in determining the successful configurations in service today. Examples were noted during the review. The answer to NOx reduction beyond the mid-term will lie in the establishment of atmospheric needs in conjunction with economic drivers.

6.6.2 Today, OPR growth appears to have been slowed down by materials technology limitations, and that, coupled with the desire to reduce fuel burned and noise, leads to high BPR without higher burner inlet temperature (T3). Therefore, some NOx relief comes from a slowing of the trend to higher OPR, and an absolute reduction in fuel consumption. Alternative concepts are a possible longer term solution. They are presented in section 7, but show no real promise for flight

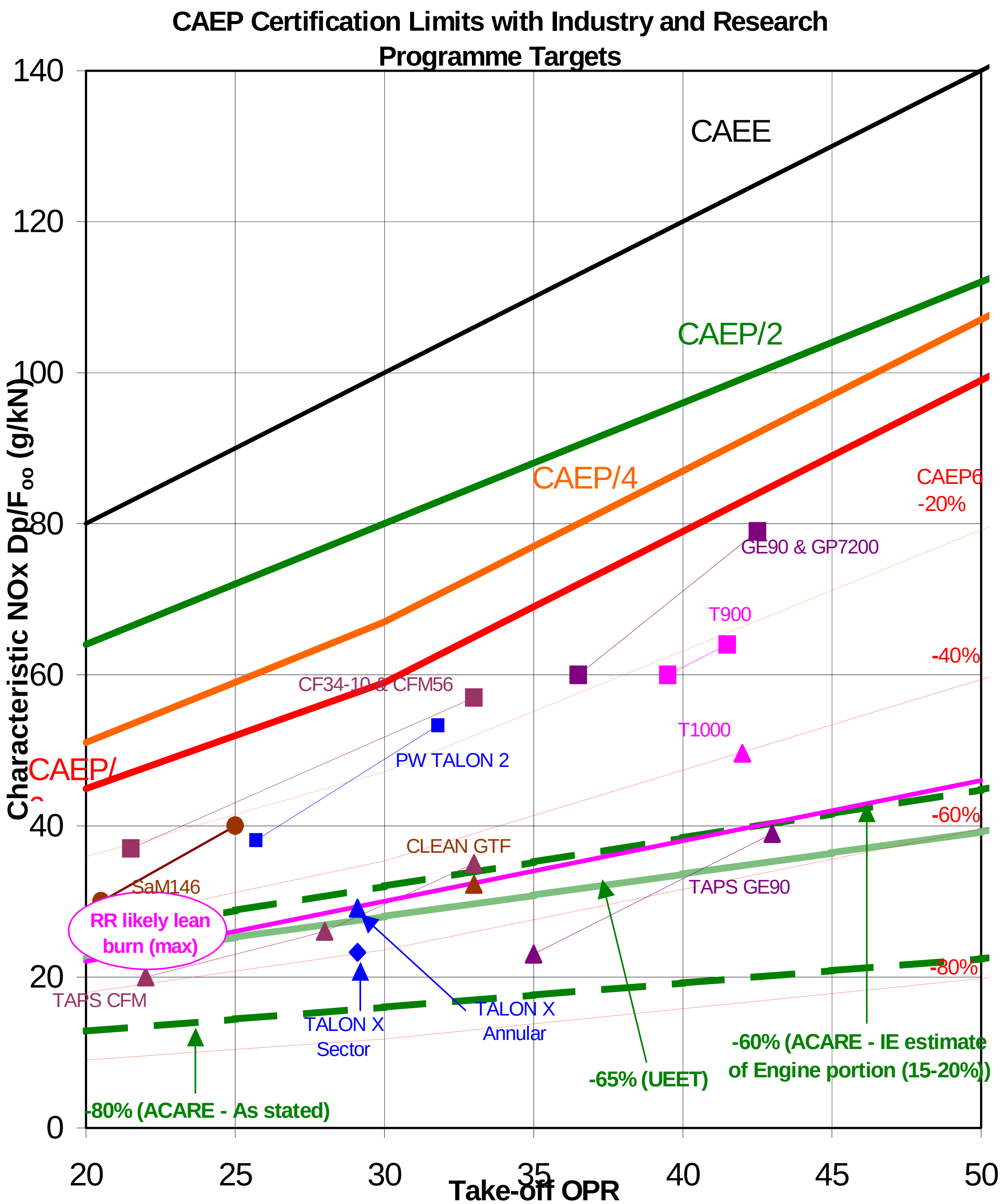


Figure 5: CAEP Certification Limits with Industry and Research Programme Targets

systems in the 20 year time frame. Figure 5 shows the industry predictions of NOx emissions performance against US and European technology targets (UEET and ACARE) plotted against the certification requirement.

6.6.3 The ACARE goal of 80% reduction is not targeted at the engine alone, but represents contributions from the engine, airframe and operational strategies. Because the CO_2 reduction goal was 50% (engine portion 15-20%), the IEs assumed the engine combustor contribution to NOx reduction is 60%. This assumption is supported by ACARE's Strategic Research Agenda (SRA1), see para. 8.3. There are considerations regarding how the CO_2 reduction is realized (e.g., at what OPR?) that will have a secondary effect on the split between engine and aircraft. These considerations are recognized, but deemed small for our purposes.

6.6.4 Relative to mid-term goals, P&W, GE and RR show significant potential from concepts currently under study for the longer term. P&W shows (P21 page 23) for a 30 OPR TALON X single annular combustor long term performance goals to be at 20-30% of CAEP/2. This corresponds to NOx values ranging from 16-24 g/kN (see Fig. 5). This is approximately 30%-40% of CAEP/6. The GE goal for TAPS3 (P20, page 8) is to be at 15% of CAEP2, this relative to TAPS2 at 30% of CAEP2. GE, on page 10, states a concern regarding funding levels required to support this technology. With allowances for design margin and correction from average to single engine this translates into NOx values of 40 g/kN (TAPS2) and 20 g/kN (TAPS3) at OPR 40 for both. This is approximately 50% of CAEP6 for TAPS2 and 25% of CAEP6 for TAPS3. RR showed (P18) its 2020 target to be 20% of CAEP2 somewhat consistent with the ACARE goal). This compares to the stated RR target and Trent 1000 emissions prediction of 50% of CAEP2 in the 2010 time frame. This implies, on a CAEP6 basis, a 35% improvement from the Trent 1000 to the 2020 RR target. Between GE and RR, at OPR 40-43, the long term goals look to be 60-70% below CAEP6, as defined by TAPS3 and the RR 2020 target. TAPS3 is at TRL 2-3, whereas the RR 2020 target was not yet characterised against this scale. The developments in the frame of European programmes (P11), in particular by Snecma on multi-point injection, although still at level TRL3-4, could be also considered in a long term goal perspective. The target is ACARE.

6.6.5 Based on the presentations by all the engine manufacturers, it would appear that both rich and lean burn concepts will be candidates for addressing low NOx goals in both the 10 and 20 year time frames. The IEs will not seek to identify product or manufacturer superiority.

6.7 Noise Implications

Noise has generally benefited from the pressure to reduce fuel burned. High BPR engines in the early 70's reduced the jet noise that dominated the fleet in the 60's. This jet noise associated with the early low BPR (BPR about 1.0) engines was produced because the hot stream producing the thrust was not transferred to the low spool (fan) to produce thrust at low velocity. This was due to turbine temperatures limited by materials technology (high BPR requires high temperature for engines of acceptable weight). Materials technologies led the way to high BPR, reduced fuel burned and lower noise. The new noise technology problem shifted to fan noise, but as the noise performance of newer aircraft began to improve, the acceptability of noise became the new issue. Pressure for noise reductions continues. Local as well as national and international noise pressures are intense. Though ICAO standards for noise are international in scope, the local noise rules in effect at some airports (e.g. Heathrow, Orange County) have created pressures for manufacturers to design to those rules, in some cases at the expense of fuel efficiency or other engine performance measures. This drives aircraft and engine designs, and NOx performance has to be taken into account within the competing influences from noise, although the manufacturers did not raise this as a serious issue at the Review. A chart presented by ICCAIA (P30) indicated that for one aircraft/engine combination, minimum noise led to a 1.5% NOx penalty. The IEs understands that different relationships will apply for other aircraft/engine combinations. The IATA presentation (P9) specifically highlighted the negative impact that local noise restrictions have on design practices. The IEs believe that this is an issue that needs to be examined in future review.

7. Academic Review

The aim of this section is to allow the recognition and evaluation of NOx reduction possibilities that lie outside of the mainstream technologies of immediate interest to aero engine manufacturers. The later half of the section addresses these more speculative technologies.

The first section outlines some basic explanation of NOx production theory and includes a description of NOx production in combustors that did not feature NOx reduction technology. This also illustrates where NOx levels would go to in higher pressure ratio engines without the existing NOx reduction designs. The increasing challenge of maintaining this NOx control as pressure ratios rise is also shown. Some of the material summarized below (particularly Sections 7.1, 7.4 and 7.6) was not discussed at the review or commented on by ICCAIA. However, as the IEs considered this material to inform their views on the long term goals, it is included here for reference.

7.1 Fundamentals

7.1.1 The rate of the combustion reaction governs the time interval between the ignition of a homogeneous fuel/air mixture until the achievement of, effectively, completely burned products of combustion. Approximately, the rate of reaction will be proportional to the system pressure [P^2] and exponentially to the compressor exit air temperature [exp ($-T_{E1}T_A$)]. Under low pressure, low temperature combustor conditions, such as those at ground and flight idle, the rate of the combustion reaction will be low and the time available for the combustion process (residence time) will be limited, leading to some emissions of carbon monoxide and unburned fuel. At high power, the rate of reaction will be high and the combustion process will, very closely, approach 100% completion. In fact very few reactions go to 100% completion, including combustion reactions. These arrive at an equilibrium state that includes minor concentrations of species such as CO and NOx.

7.1.2 In comparison with hydrocarbon oxidation the NOx production reactions are slow – at least at moderate temperatures and pressures. Approximately, the rate of reaction is proportional to combustion pressure $P^{0.5}$. However it is also exponentially proportional to the temperature of the flame where the NOx is produced [exp($-T_{E2/}T_F$)]. Therefore there is a very high dependency on the stoichiometry of the combustion process in conjunction with compressor exit temperature and pressure. Like the combustion process the NOx production reactions arrive at an equilibrium state. Although this is well short of reacting all the available nitrogen and oxygen, NOx concentrations can be created given modest reaction times. Evidence of this can be seen, for example, in low speed diesel engines where compressions ratios are very high and combustion times are long.

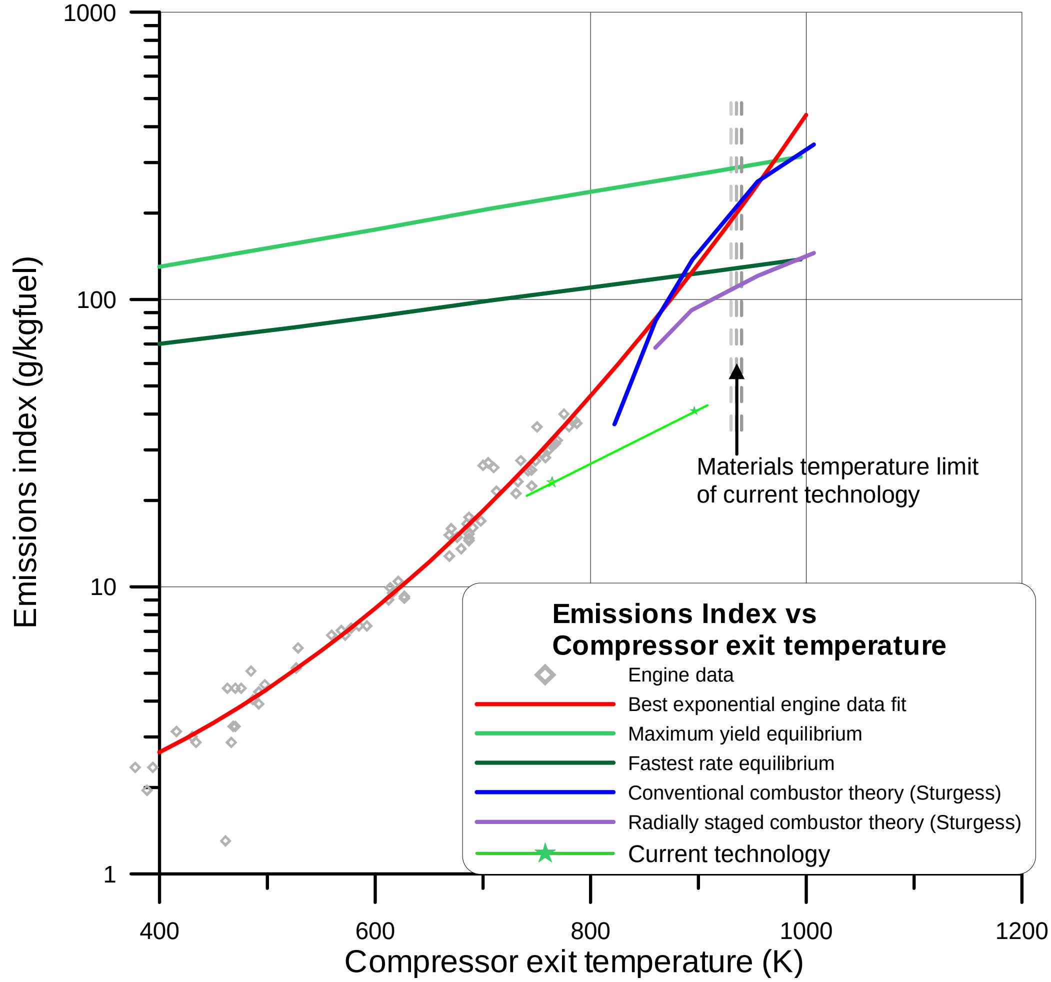


Figure 6: NOx as a function of Combustor Air Entry Temperature

7.1.3 Figure 6 shows NOx Emissions Index (EI) as a function of combustor air entry temperature (compressor exit temperature). The NOx production is also a function of pressure that is taken account in the data since the pressure is a function of the temperature (any effects of variations in compressor efficiency will be lost in the scatter). Two theoretical, NOx characteristics are shown.[10] The line 'maximum yield equilibrium' shows the NOx that could be generated by the most effective air/fuel ratio given 'infinite' reaction time. However 'infinite' in this context can be measured in unit milliseconds. The line 'Fastest rate equilibrium' shows the NOx that could be produced at a fuel/air ratio that generates NOx at the fastest possible rate. These two equilibrium lines together with all the intermediate possible levels are produced at similar air fuel ratios and temperatures close to the

[10] J R Tilston, EU 'Cypress' project Publishable Report 2002 UK.

maximum flame temperature that will be present in the primary zones of all 'conventional' and RQL combustors.

7.1.4 The difference between 'conventional' and RQL is that RQL deliberately aims to control the time (residence or stay time) the combustion process spends at the critical air/fuel ratios in order to limit the NOx production. All the NOx data shown on the graph are derived from production and research engines employing combustors that featured no form of NOx control. The 'Lipfert' data[11] was collected in the early 70's and these are shown as the lower half of the range of points (grey diamonds) on the chart. The additional data was collected through the 80's and 90's from a variety of engines to re-enforce the Lipfert database.

7.1.5 As temperatures and pressures (and therefore reaction rates) increase it is to be expected that the engine NOx will increase and, at some point, merge with the equilibrium values. The data titled G Sturgess, 'conventional' and 'radially staged', derived from theoretical studies in the 90's aimed at exploring the possible NOx production at high OPRs for these two styles of combustor. Unsurprisingly, because the combustion process is allowed 'unlimited' time to form NOx, the 'conventional' combustor runs into the 'max yield' characteristic. Again, unsurprisingly, the staged combustor reduces NOx because the combustor has been optimised for high power NOx emissions by minimising the time spent at the peak production conditions. However the characteristic of this design is unable to defeat the 'fastest rate' chemistry.

7.1.6 Logically, an extrapolation of the combined engine data set to higher OPRs should show a convergence with the 'maximum yield' characteristic and this is true for the extrapolated best-fit exponential. Overall the graph indicates the great difficulty of controlling NOx production at high OPRs by relying on reducing residence time if the combustion starts rich and passes through peak flame temperatures. Nonetheless, current RQL technology has made considerable reductions of NOx in spite of huge opposition from the combustion chemistry. However, in the future, to reduce NOx emissions further, and if CO_2 reductions are achieved by increasing OPR, lean burn technology that avoids peak NOx production air/fuel ratios will, theoretically, be much more successful.

7.1.7 Future trends in sea level engine OPR are constrained by the need to limit compressor exit temperatures due to materials limitations at compressor exit. Therefore sea level pressure ratios are likely to be limited to the upper 40s, low 50's, certainly in the medium term and possibly in the 20 year time frame as well. Design OPRs increase with altitude so the numbers quoted are at take-off.

7.1.8 In summary, most alternative NOx reduction technologies are either at a very early TRL or present considerable operating difficulty even in land based, non-safety critical plant. However the drive to reduce fuel burn may encourage exploration of new engine cycles for aero application. As might be expected the combustion technologies of choice employed by aero engine manufacturers are fully appropriate to the engine mission and seem likely to remain appropriate.

[11] Lipfert, F W, Correlation of Gas Turbine Emission Data. ASME 72-GT-68, 1972,.

Evolution of engine cycles to higher OPRs are likely to force combustor designs that feature lean burn technology in order to avoid very high NOx production rates.

7.2 Contemporary practice and near term strategies

7.2.1 The RQL process has been the norm throughout the 'life' of the aero gas turbine combustor. Originally it was a convenient format to deliver excellent handle-ability together with suitable turbine entry temperatures. Additionally the sequential zoning principle was used to complete the combustion of CO and smoke.

7.2.2 More recently the RQL process has been employed expressly to control NOx with considerable success. The designs have evolved from the initial empirical bases through to the sophisticated knowledge based systems shown by the manufacturers at this Review. This technology is clearly capable of very significant reductions for the medium term, and for at least one manufacturer remains the path to long term goals.

7.2.3 While RQL has been strongly and successfully evolved to date, it is significant that some manufacturers are revealing pursuing lean burn direct injection, lean burn technology that shows current NOx reduction and potential reduction beyond that of their own RQL designs. This technology relies on direct injection of the bulk of the fuel spray into a lean zone where, in principle, stoichiometric peak flame temperatures are never achieved. A smaller flow of additional fuel is placed in a parallel 'rich' zone to provide low power emissions performance and stability. Ultimately, as with lean premixed-prevaporised (LPP), this 'piloting' fuel will limit the NOx reduction that can be achieved especially in the LTO cycle. To a significant extent the two combustion zones interact and vary in size and location throughout the engine operating condition. The optimisation of this interaction demands excellent control of fuel spray preparation and placement in the combustor. The ability to design and manage the overall process is very heavily dependent on the advanced numerical design and modelling techniques that have been produced in recent decades. Overall the 'twin zone' format should allow smoother, more flexible fuelling staging than could be achieved with separate combustion spaces as with double annular combustor (DAC). In the medium (and, with evolution in the longer term) direct lean injection may give NOx reductions of the order of 80% i.e. comparable with LPP combustion with fewer technical challenges.

7.3 Medium and Long-term alternative technologies

The medium and long-term alternative technologies discussed below are largely based on the academic input provided to the Review (P10).

7.3.1 **Water injection.**

Water injection has been demonstrated to reduce take-off and climb-out NOx by ~80%[12] . However it presents a serious weight problem not in the mass of water

[12] Daggett, David L.; and Hendricks, Robert C.: Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NOx. NASA/CR-2004-212957, 2004.

(which is used in take-off and climb-out) but in tankage, pumping and pipework (which is a permanent parasitic penalty). There are additional logistic problems of supply, chemical purity issues, as well as protection against freezing since anti-freeze additives could produce additional airfield contamination. Water injection is unlikely to provide a market acceptable solution even in difficult LAQ situations.

7.3.2 **Lean premixed Prevapourised (LPP)**

Lean Premixed Prevapourised combustion has been researched throughout several decades and, using kerosene fuel, in a number of research programmes, has demonstrated NOx reductions in the region of 97% (un-piloted) at an OPR of 32 at TRL 3[13]. However, the addition of piloting, needed to provide safe handling, reduced this to ~75%. There was no attempt to manoeuvre the combustor to different flight conditions. The effect of an engine surge and occasional unprovoked, destructive auto-ignitions in premix ducts remains a severe problem, as do damaging combustion resonance problems that usually appear. There is likely to be an impact of combustor length leading to increased engine/aircraft weight. These and other issues (identified in the Academic Input) remain largely unsolved problems even in methane burning land-based gas turbines where agile handling is not required. LPP is unlikely to be a contending technology even in the long term.

7.3.3 **FLOX combustion**

'Flameless oxidation' has been demonstrated in furnaces (gaseous fuel) to produce NOx reductions >> 90% in atmospheric furnaces (P10). It relies on massive recirculation of combustion products that have been cooled to some extent in the application during the recirculation. In effect it removes much of the available oxygen from the combustion.

Problems of application in the aero-engine environment include the size of the combustor (increased engine mass), the pressure drop across the combustor (reduced SFC), means to heat exchange and cool combustion products.

Problems of application in the aero-engine environment include the size of the combustor (increased engine mass), the pressure drop across the combustor (reduced SFC), means to heat exchange and cool combustion products. Ideally this technology needs an uncooled, adiabatic wall.

This technology is unlikely to find application as an aero engine combustion system in the 20 year long term.

7.3.4 Catalytic Combustion

Very high NOx reductions have been achieved in experiments at TRL3 using gaseous fuels. Much the same disadvantages apply as for LPP combustion i.e. prevapourising liquid fuel, flashback and auto-ignition. In addition catalytic combustion is heavier and demands larger, longer combustion systems that would have a serious negative impact on engine/aircraft weight and fuel burn. The

---

[13] Final Publishable Reports. EU projects LOWNOX II, 1992-1996 (MTU coordinators) and LOWNOXIII 1997-2002 (SNECMA coordinators)

material presented by Hans-Jörg Bauer (P10) noted that severe technical problems of engine start and relight also need to be overcome because the catalyst temperature needs to be raised to ~ 500-600K before it begins to function, which is a serious safety concern. Moreover catalysts have short life and are subject to coking and poisoning in the presence of substances such as sulphur.

Very high NOx reductions have been achieved in experiments at TRL3 using gaseous fuels. Much the same disadvantages apply as for LPP combustion i.e. prevapourising liquid fuel, flashback and auto-ignition. In addition catalytic combustion is heavier and demands larger, longer combustion systems that would have a serious negative impact on engine/aircraft weight and fuel burn. Overall, it has not been possible to produce competitive catalytic combustion even for gas fuelled, land based gas turbines. This technology is unlikely to be viable even in the long term.

7.4 Alternative Fuels

Information presented at the Review on alternative fuels was limited. The IEs felt that alternative fuels were important due to future supply and cost considerations and because of potential environmental benefits, as well as burden, these fuels might present. The IEs have supplemented the discussion below with reference material and their own expertise.

7.4.1 Hydrogen and methane fuels

The UK project "The Potential for Renewable Energy Sources in Aviation ("Presav")" (2003)[14] produced by Imperial College Centre for Energy, Policy and Technology in 2003, studied the options for potential renewable fuels for civil aviation, including hydrogen and methane. Both hydrogen and methane fuels could give significant NOx reductions (as demonstrated in studies at TRL2) because they have a wider flammable range that allows operation at less than peak flame temperature whilst maintaining at leaner air fuel ratios than would be possible with kerosene. They have advantages of reduced CO_2 emission (depending, of course, on the manufacturing route of the hydrogen; hydrogen produces no CO_2 only if made using renewable energy sources. The processes to produce hydrogen from sources such as coal or natural gas may lead to a relative production of CO_2 higher than that of oil derived kerosene). Whatever source is used the current energy cost for production and liquefaction is very high. Hydrogen and methane also have advantages of thermal stability and cooling capacity that could be used to advantage in advanced engines. Modern studies suggest that the hydrogen-fuelled aircraft may have much the same take-off weight as a conventional aircraft though will face tankage/design issues. However, given that sufficient power source is available to produce the hydrogen it would probably be preferable to synthesize methane and the Fischer-Tropsch kerosene. Both hydrogen and methane would increase emissions of water vapour at altitude that may or may not turn out to be significant to radiative forcing. The use of either one would require a massive conversion of airport fuelling logistics and infrastructure. Overall, these alternative fuels are possible, but not thought to be in the 20 year future.

[14] Potential for Renewable Energy Sources in Aviation (PRESAV) study (www.iccept.ic.ac.uk), 2003.

7.4.2 Other alternative fuels

7.4.2.1 The "Presav" study[15] also examined bio diesel, ethanol, methanol, Fischer-Tropsch synthetic kerosene, and nuclear energy. Methanol, ethanol and bio-methane, along with nuclear energy, were considered to be inherently unsuitable for civil aviation. Of the remainder, bio-diesel was regarded as a potential kerosene extender, but further research was required in order to understand its cold weather performance (wax solidification) although these were not seen to be insuperable for the future. Between 1980 and 1984 Brazil developed PROSENE®, an alternative combustible lipofuel (vegetable oil) used as an alternative to aviation kerosene. Pure biokerosene was used to power EMBRAER turbo-prop aircraft, between the cities of São José dos Campos and Brasília. In 1984, however, Brazil stopped efforts to go forward with the National Biodiesel and Biokerosene Program because of lack of interest by energy and economic authorities. But, driven by the recent rise in fuel prices, this concept is once more receiving attention.

7.4.2.2 A large number of hydrocarbon based fuels have been produced from a variety of sources. These have included fuels derived from coal, tar sands and shale oil amongst others. Those derived from coal, using the Fischer Tropsch synthesis, (SASOL) have sometimes been marginally competitive in price with oil-based kerosene. The embargo to end apartheid in South Africa provided the impetus for the adoption of Sasol, which is a 50-50 blend of petroleum derived and synthetic kerosene still in use today. Engine manufacturers are pursuing efforts to qualify pure Sasol for operational use.

7.4.2.3 ICCAIA provided information noting that the Qatar Synthetic fuels FT kerosenes are already studied and produced in small-scale plant in countries such as Sweden, China, France/Italy. Qatar is presently building a large facility. At present 'freeze point' appears to be problematic although it is believed that this can be improved. Combustor testing (TRL 2/3) has often shown these alternative fuels to have a variety of problematic characteristics that would not be acceptable in the existing kerosene specification and which, therefore, would not be acceptable for aircraft use. This is because, on cost grounds, the supplier would like to offer a fuel produced by simple distillation, like kerosene. Normally, however, kerosene from non-oil sources requires additional processing in order to meet the kerosene specification. However, the best alternative fuels have properties comparable to or better than oil-based kerosene itself. Producers of alternative fuels that do not meet the kerosene specification generally suggest that the specification is unreasonably restrictive. In fact the opposite is true; the kerosene specification is performance based and has been overhauled many times in attempts to increase the availability of jet fuel. Changes to the feedstock would require careful monitoring to ensure no performance degradation via a property not controlled by the current specification but nevertheless inherent in petroleum derived jet fuel. The most obvious advantages of the best synthetics are the

[15] Potential for Renewable Energy Sources in Aviation (PRESAV) study (www.iccept.ic.ac.uk), 2003.

reduced sulphur and aromatics contents that, particularly in the case of sulphur, which would result in lower PM emissions.

7.4.2.4 All of these alternative fuels would have calorific values comparable to kerosene, would produce comparable flame temperatures and therefore comparable NOx and CO_2 emissions. Reduced flame temperatures and NOx could be achieved by using alternative fuels such as alcohols for example. However this would be at the expense of a considerable reduction in calorific value that would require more fuel to be burned. These fuels could be more expensive than the cost of conventional aviation kerosene. In comparative terms, conventional aviation kerosene costs $4.6 per gigajoule (GJ) whereas the cost of bio diesel, FT kerosene and H_2 would be in the respective ranges of $33.5 - $52.6, $5.8 - $31.7, $21.5 - $53.8 per GJ. The difference in fuel price, along with the need to ensure compliance with the current safety and air worthiness regulations that apply to conventional kerosene result in the report's conclusion that for the foreseeable future the use of alternative or renewable fuels would be pursued for other transport modes before being made available for civil aviation. However, the cost of energy has changed significantly since the Presav study was performed, and the engine company Pratt and Whitney noted in a presentation[16] that synthetic aviation kerosene could be "economically viable when crude prices reach (up to) $59 a barrel" – in 2006 crude reached $70 per barrel.

7.4.2.5 In conclusion, acceptable alternative, liquid, hydrocarbon fuels, meeting the kerosene specification can be produced from a number of non oil sources. These could have advantages of low aromatics and sulphur compared to present day oil based kerosene. Equally however oil based kerosene could similarly have lower aromatics and sulphur give additional processing. Alternative fuels meeting the kerosene specification are likely to be used as components of the existing fuel supply as and when supply pressures demand additional sources of supply. Ultimately, the use of alternative fuels in aviation may also be driven by energy security and independence considerations (since the review the U.S. Department of Defense has initiated an effort to advance the introduction of alternative fuels for aviation use). Alternative fuels may provide environmental benefits and could become an element of a total environmental strategy where the industry may be able to use alternative fuels to deal with some local air quality issues, allowing manufacturers to focus engine design to reduce noise or other environmental issues such as NOx.

7.5 Alternative engine cycles

Very significant improvements in specific fuel consumption can be achieved by use of more complex engine cycles, such as the inter-cooled regenerative cycle (ICR), and these are increasingly being deployed in power raising and marine gas turbines. At first sight the cycles offer NOx reductions comparable to the reductions in fuel burn. However both reductions can easily be cancelled out, especially in aero-engine applications by factors such as the weight and parasitic losses due to the heat exchangers. Improving the integrity of the heat exchangers also represents a considerable challenge. Overall, these cycles offer very significant emissions

[16] Biddle, T. Syn Fuels TRB 1-23-06.ppt 23 Jan 2006

reduction although much work will be required to mitigate the penalties associated with the weight and complexity. These cycles are unlikely to be employed in the 20 year future and may take more than the traditional commercial competitive pressures to be researched adequately.

7.6 Revolutionary Technologies

Additional alternative technologies have been identified by the EIs as follows:

7.6.1 Variable geometry engines and/or combustors.

The variable geometry may be used to modify the stoichiometry of the combustor as a whole by means of variable engine features or of individual combustion zones using flow control techniques applied to the combustor or fuel injector. These variables could take the form of air or fuel staging or modulation. Some variables can be devised that have a benign or neutral effect on other aspects of engine performance (i.e. such as surge margin or combustor pressure loss). However factors such as weight, complexity and reliability also need to be taken into account. Normally some stage of the LTO/flight cycle presents combustion 'difficulty' that tends to compromise the best combustion solution elsewhere. In such an instance variable geometry may provide a tool that could be used to make useful adjustments to combustor or emissions performance. This technology is likely to have been evaluated at TRL 3 to 4. If required it could be exploited in the long term. (References – AIAA 2002-0073 and Cypress (EU project), Future Engine Cycle Prediction and Emissions Study, 2001-2003) and elsewhere).

7.6.2 Trapped Vortex Combustion

The TVC concept is a revolutionary technology with potential payoffs in almost every category of gas turbine combustor performance including heat release rate, operability, weight, and even cost. High-pressure testing results of a prototype TVC sector indicate it can help meet the performance requirements for military applications while reducing overall emissions. The TVC departs from conventional gas turbine combustion in several ways, but the most substantial is the mechanism that stabilizes the flame. A conventional combustor has a primary recirculation zone established by air swirlers located around the fuel injector as shown in Figure 7. This recirculation zone transports some of the hot combustion products back toward the combustor face and ignites the incoming fuel and air as it is mixed in the combustion chamber. TVC stabilizes the flame by trapping a vortex in cavities located in the walls of the combustor as shown in Figure 7. Strategically placed air and fuel injection points in the forward and aft walls of the cavity drives the vortex in the cavities. The created vortex recirculates the hot combustion gases within the cavity, then the gases are exhausted out of the cavities and transported along the face of the combustor. Technology level is probably about 3.

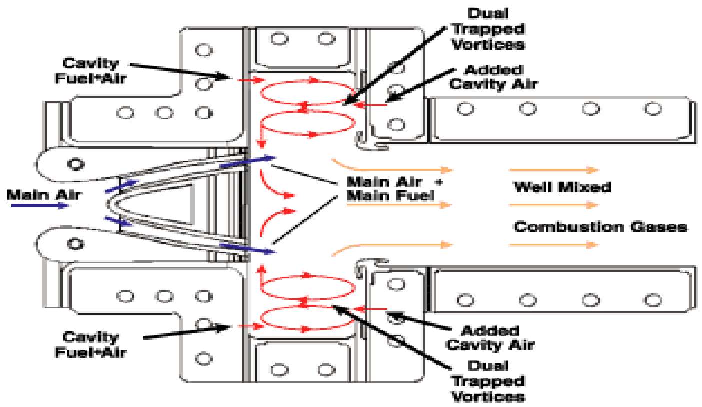


Figure 7: TVC cross section[17]

7.6.3 Stagnation Point Reverse Flow (SPRF) Combustor.

The Stagnation Point Reverse Flow (SPRF) combustor, shown in Figure 8 below, can burn gaseous or liquid fuels in premixed or non-premixed modes of combustion with ultra low NOx emissions (NOx~1 and CO<10 ppm at 15% O_2). The combustor consists of a tube with open and closed ends. Contrary to most combustors, the reactants and products enter and leave this combustor at the same (open) end. In the investigated configuration, the reactants are injected along the combustor centre line, moving towards the closed end, where the flow velocity must be zero. This creates a low velocity region towards the closed end of the combustor that helps stabilize the combustion process. Furthermore, the presence of a closed end forces the generated combustion products and burning gas pockets to reverse their flow direction and move towards the open (exhaust) end of the combustor. Thus, a portion of the hot products, laden with radicals, is entrained back into the incoming reactants to form a more chemically reactive mixture. The presence of radicals in the mixture lowers its ignition temperature and, thus, the lean blowout limit of the combustor. Thus, the SPRF combustor's geometry produces a combination of stagnation region and reverse flow entrainment that allows this combustor to operate stably at very low temperatures with ultra low NOx emission in the 1 ppm range and below. It has been also shown that these low NOx emissions can be attained with premixed or non-premixed modes of combustion. Finally, it has been shown that the developed combustor can operate with high combustion intensities without experiencing combustion instabilities. Technology level is probably about 2.

[17] Journal of Engineering for Gas Turbines and Power -- January 2005 -- Volume 127, Issue 1, pp. 36-41, Assessment of Rich-Burn, Quick-Mix, Lean-Burn Trapped Vortex Combustor for Stationary Gas Turbines. Douglas L. Straub, Kent H. Casleton, Robie E. Lewis, Todd G. Sidwell, Daniel J. Maloney, and George A. Richards, *U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV 26507*

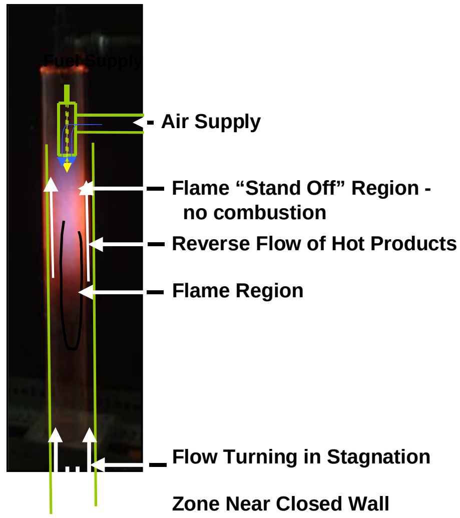


Figure 8: A photograph of a quartz SPRF combustor in operation

7.6.4 Plasma combustion Enhancement.

Lifted flames and oscillatory flames are a common feature of lean combustion systems and combustion downstream of high velocity flows. Typically these separations may occur during fuel or air transients. The separation can lead to a loss of flame holding or destructive oscillations as well as a severe degradation of emissions performance. Experiments at ONERA have demonstrated that injection of small concentrations of ‘cold’ air plasma is extremely effective in stabilizing combustion at its designed location on the burner. This technology is at TRL2.

7.7 Smoke emissions (solid carbonaceous particulates)

7.7.1 In RQL combustors smoke emissions are always likely to be highest at high thrust, sea level conditions where combustor primary zone conditions are richest and pressure levels are highest – both of which conditions favour smoke production. There is a tension between the requirements of NOx reduction and smoke reduction. This is because the primary zone fuel air mixture is critically designed to be richer than stoichiometric to avoid the high temperature conditions with free oxygen that produce NOx. On the other hand conditions must not be so rich that smoke generation is produced. In practice a balance is made where although the combustion is rich the maximum smoke generation conditions have been avoided and the fuel air ratio has begun to favour smoke burnout. At cruise conditions, apart from low combustor pressure, combustion conditions favour high combustion efficiency and low smoke emissions.

7.7.2 In contrast with lean burn, direct injection technology, at high power, the primary combustion zone is operated with an excess of oxygen and at temperatures that are judged to control NOX production. Under these conditions smoke is likely to be very low. However a tension now exists between the NOx control at high power and combustion efficiency, combustion stability and possibly unburned fuel particulates at low power and at cruise.

8 Research Review:

8.1 Introduction

U.S. and European representatives provided detailed presentations on U.S. government and European Commission funded research programmes. These programmes are generally conducted in close collaboration with industry and academia. The presentation (P12) provided by the U.S. National Aeronautics and Space Administration (NASA) reported on NASA's past research and technology development for low emission combustors and engines. It gave an insight into NASA aeronautics' current efforts to re-shape its Aeronautics program and provide a pre-decisional view of the program content that might be relevant to LTTG. The European representatives provided two briefings. One described the European Low Emissions Combustion Technology in Aero Engines (ELECT - AE) coordination action from the 6th Framework Program (P11) being pursued in Europe. The second focused on the ACARE (Advisory Council for Aeronautics Research in Europe) (P29) objectives through the CLEAN (Component validator for environmentally friendly aero-engine) and VITAL (Environmentally Friendly Aero Engine) research projects on emissions reduction technologies. Similarities were noted between Europe's current programs and the NASA programs of the last twenty years. By contrast, NASA currently does not have clear environmental goals that support LTTG. Details on the history, present status and future outlook for Government sponsored research projects are provided below

8.2 History

The US:

8.2.1 NASA programs have historically focused on TRL 1-6, with the engine industry expected to mature and introduce technologies into products. As such, the programs featured a strong collaboration with industry.

8.2.2 In the late 1970s, NASA started its first major combustor emissions technology development effort - the Experimental Clean Combustor Program (ECCP). NASA worked with the General Electric Company (GE) and Pratt and Whitney (P&W) to develop and test advanced clean combustors for industry's future product commercial engines. Clean combustor concepts were developed and successfully engine tested in the CF6-50 and JT9-D and GE's Energy Efficient Engine (EEE). These advanced multi-zone combustor concepts featured radially or axially spaced pilot combustion zone and a main combustion zone, shingle metallic liner construction, and advanced airblast fuel air atomizers/mixers. The rich burning pilot combustion zone provided stable combustion over the complete flight envelope, and the main combustion with fuel staging or variation at the higher power conditions provided low emission combustion. These multi-zone combustor concepts with advanced liners and fuel injectors reduced NOx levels by 40 to 50 percent relative to the original very rich burning first generation annular combustors of the CF6–50 and JT9D engines, over the LTO portions of a flight. CO and unburned hydrocarbon levels were also reduced, and visible smoke was eliminated.

8.2.3 In the early- 80s, NASA initiated its first major engine fuel efficiency technology development effort - the Energy Efficient Engine (EEE) Program. NASA worked with General Electric Company and Pratt and Whitney to develop fuel-efficient engines and test advanced clean combustors for industry's future product commercial engines. Noteworthy among these early-80s clean combustor concepts was the General Electric Company's dual annular combustor. GE implemented the NASA developed technology in their dual annular combustor with staging of the fuel to the lean burning main zone at various lower power setting and continuous fuelling of the rich burning pilot zone at all power conditions. Because of the requirement for an advanced digital electronic control system and advanced combustor liner materials and cooling concepts, the dual annular combustor was not introduced into commercial service until 1995 in the higher pressure ratio CFM56 engine. General Electric Company's fuel efficient engine was introduced in 1995 as the GE90 and Pratt and Whitney's fuel efficient engine technologies were introduced into the PW 4000 and PW 2000 engine families.

8.2.4 In the early- 90's, NASA started it's second major engine technology development effort – the High Speed Research (HSR) Program involved teaming with GE and P&W to develop technology for a fuel efficient engine with ultra-low cruise NOx combustors to enable an environmentally acceptable Supersonic Commercial Aircraft. Lean premixed prevapourised (LPP) and rich-burn/quick-quench/ lean-burn (RQL) combustors were developed with low cruise NOx emission levels as measured in a subscale sector rig (TRL 4).

8.2.5 In the mid-90's, NASA started it's third major engine technology development effort as part of the Advanced Subsonic Technology (AST) Propulsion Project. NASA teamed with industry to develop fuel efficient engines with low emission combustors for both large and regional engines. The AST Program's engine and emissions technology activities were conducted to develop fuel efficient engines and low emissions NOx combustors. The goals of the AST program were:

- Fuel efficiency improvements of at least 8-10% and reduction of at least 3-10% in direct operating cost of air travel of next generation commercial engines.
- Demonstrate by 1999 reductions in LTO NOx emissions of at least 50% based on the 1996 ICAO limits for future large and regional engine combustors with corresponding reductions in cruise NOx levels and no increase in other emission constituents while exhibiting comparable operability and maintainability.
- Begin to address new emission concerns to understand the emission levels of particles and particle precursors coming from low emission combustors.

8.2.6 These AST activities culminated in a 1999 demonstration test of the AST 50% NOx Reduction Combustor operating in a PW 4000 engine over the normal operating envelope (based on average measured emissions compared with the regulations), and limited combustor operability and durability were also assessed in this engine test.

8.2.7 In the 2000s NASA initiated the fourth major engine technology development effort - the Ultra Efficient Engine Technology (UEET) Program. NASA continued working with industry to develop technology and reduce risk for fuel efficient engines and low emission combustors aimed at large and regional engines. The goals of the UEET program were:

- Propulsion technologies to enable increases in system efficiency and, therefore fuel burn reductions of up to 15 % (equivalent reductions in CO and CO_2)
- Combustor technologies (configuration and materials) which will enable reductions in LTO NOx of 70% relative to 1996 ICAO standards.
- Emission levels of aerosols and particulates coming from low emission combustors to be assessed and reduced if possible.
- Improve and validate the combustor design codes to reduce the design and
- Development cycle time by 50 percent for low emission combustors.

8.2.8 UEET as a formal program was ended in 2005, prior to the completion of all the planned work. However, UEET goals were met in TRL 4 demonstrations. NASA and industry plan to complete RQL demonstration work at TRL 5 in 2006.

EUROPE:

8.2.9 European aero-engine manufacturers, Rolls-Royce (RR plc & RR Deutschland), Snecma (Safran group), Turbomeca (Safran group), MTU and Avio have been working on low emission combustors in the past, either in the frame of national programs or in collaboration through European programmes (FP4 from 1995 to 1998, and FP5 from 1999 to 2002). The current European programs are the follow-up of previous initiatives. The European achievements can be described as follows:

- Many advanced concepts have been tested at TRL5, exceptionally at TRL6. Work has been devoted to the control of flashback for LPP concepts. Thus far the achieved results are confidential to the project partners due to their industrial sensitivity.

- Improvements have been significant in two areas. First, numerical simulation: coupling between a complex aerodynamics and a very detailed chemical scheme. For the NO formation, NO being later oxidised into NO2, the main mechanisms are the "prompt" NO and the "thermal NO" (Zeldovich's mechanisms). To approach this detailed chemistry, a minimum is to use a semi-global scheme, for instance those proposed by Kundu et al. (16 chemical species and radicals, 23 chemical reactions). Demonstration computation has been carried out with very large CPU time, and an obstacle remains the detailed validation of this prediction, validation which required very detailed measurement in realistic conditions. Another issue is the two-phase turbulent combustion and the prediction of droplets formation remains the less predictable phenomena. Secondly, advanced optical diagnostics focused on measurement of nitrogen oxides concentrations.

- Coupling between environmental issues and combustion technologies has been enhanced: Onera performed its first campaign last year of air quality measurements at CDG airport (AIRPUR project); this campaign involved also different French and German laboratories, ADP (Aéroports De Paris, P27) and Air France; data processing is in progress.

8.3 Present

The US:

8.3.1 NASA recently announced its decision to cease its applied R & D of the past three decades and focus on "fundamental" research. A few final technology development efforts are still being completed, for example NASA continues to work with Pratt and Whitney to complete the technology development for the TALON X full annular combustor through engine testing (TRL 6), to further establish the operability and viability (P21). This is a rich quick-quench lean burning (RQL) combustor concept for both low emissions, stable combustion with good operability. General Electric Aircraft Engines' Twin Annular Premixing Swirler (TAPS) combustion concept, has successfully completed sector testing (TRL 4) and will be brought into commercial engine service when the GEnx engine is introduced on Boeing's 787 aircraft (P20). Rolls-Royce North America developed through successful sector testing (TRL 4), a lean burning combustion concept that may be introduced in their AE 3007 regional engine family.

8.3.2 Based on the progress in work sponsored by UEET, NASA is continuing measurement campaigns in collaboration with the U.S. Federal Aviation Administration and Environmental Protection Agencies as well as other academic, State government and private sector collaborators to assess and understand emission levels of particles and particle precursors emitted from engines in commercial service, as well as low emission combustors. Particle/precursor projects were initiated in 2004 with the Aircraft Particle Emissions eXperiment (APEX) series. However, NASA has no present technology development goals.

EUROPE:

8.3.3 The common priorities for the European contributors are those defined by the ACARE, (ref P29) the Advisory Council for Aeronautics Research in Europe. This was created after the report "European Aeronautics: a Vision for 2020" was issued in January 2001. This document proposed, among others, the following ambitious Environmental Challenge for air transport: a reduction of perceived noise to one half of current average levels; a 50% cut in CO_2 emissions per passenger kilometre (which means a 50% cut in fuel consumption in new aircraft in service in 2020); an 80% cut in nitrogen oxides emissions. ACARE's first Strategic Research Agenda "SRA1" was issued in October 2002, and "SRA2" was issued in October 2004. SRA1 provided clarification and more details on the previous goals. In particular, the three previous goals on Noise, CO_2 and NOx, concern the technology of Aircrafts and Engines as well as ATM and refer to the 2020 entry into service (EIS) level compared to that of 2000.

8.3.4 The reference is the state of the art in 2000 and the time target is 2020. The fuel burn is defined as the mass of kerosene burned per passenger for 100km. The expected improvements will come from aerodynamics, structures, ATM and engines; the specific target for the engine is a reduction of fuel burn of 15-20% (mass of kerosene divided by thrust and time, da/N h). The reduction of NOx emissions in relation to climate change has been interpreted as the reduction of the mass of NOx produced per passenger-100km. If the mission fuel burn reduction is taken into account (reduction of fuel burn by 15-20%), the NOx target for the engine itself is a reduction of NOx emission (by units of thrust and time or by kg of kerosene burned) by around 60%.

8.3.5 The national European targets, even if they address the ACARE targets, are specific, depending on different parameters such as the objectives of the national manufacturers, the strategic analysis, the available funding, etc. For instance, the French Research is focused on injection phenomena and numerical simulation.

8.3.6 The European projects are organized through FPs (Framework Programmes. The 7th FP is in preparation and will be divided into 9 themes, one of which includes aeronautics (3). A characteristic of European projects is that they can gather several objectives, depending of the interest of the partners. For instance, the EEFAE (Efficient and Environmentally Friendly Aero-Engine) project of the FP5 comprises two sub-projects: CLEAN (Component vaLidation for Environmentally Friendly Aero-eNgine), and ANTLE (Affordable Near Term Low Emission Engine). In CLEAN the research tasks relate to the intercooled recuperative engine (MTU), the control of stall margin (Snecma) and a task devoted to NOx reduction (Snecma and Avio). In ANTLE (RR), the main task is a demonstration around a modified Trent 500. In FP6 EEFAE will be followed by VITAL (Snecma) and NEWAC (P11, 29).

8.3.7 Since 1998 the following FP5 and FP6 European projects have been indirectly related to the issues being addressed by LTTG:

a) Combustion technology.
LOWNOX I (Low Emissions Combustor Technology I) 1990 to1992
AERONOX 1992 to 1994
LOWNOX II (Low Emissions Combustor Technology II) 1992 to 1996
LOWNOX III (Low Emissions Combustor Technology III Pt I) 1996 to 2001
LOWNOX III (Low Emissions Combustor Technology III Pt II) 1997 to 2002
ICLEAC 2000 to 2004
CYPRESS (Future Engine Cycle Prediction and Emissions Study) 2001 to 2003
LOPOCOTEP (Low Pollution Combustor Technology Programme) 2001 to 2005
INTELLECT-DM (Integrated Lean Low Emission Design Methodology) 2004 to 2007
ELECT-AE (European Low Emission Combustion technology Aero-Engine) 2005 to 2009
NEWAC (NEW Aero Concept)

b) Modelling
LES4LPP (Large Eddy Simulation for Lean Premixed Prevapourised combustion) 1996 to 1998
CFD4C (CFD for Combustion) 2000 to 2003

c) Emissions, environment
Partemis
SIA-TEAM 2005 to 2006

ECATS (Environmentally Compatible Air Transport System) 2005 to 2009
AERONET III

8.3.8 All the main European nations have, in parallel to the European projects, national programmes. For instance, in France, and since 2002, the research is performed in a framework called INCA (Advanced Combustion Initiative) joining Snecma, Onera and CNRS (Centre National de la Recherche Scientifique); the funding is provided by the DGA (Ministry of Defense) and DPAC (Ministry of Transport). Onera has also its own research program (mainly code development and validation tests up to TRL5).

8.4 Future work

The US:

8.4.1 NASA’s future plan was not yet defined at the time of the Review and hence the NASA representative presented (ref P12) a view of possibilities. NASA is now a re-shaping its Aeronautics Programs to assess long-term research needs and goals and establish technical roadmaps to accomplish these goals. For LTTG, the relevant research areas are Subsonics Fixed Wing (SFW) and Supersonics in the Fundamental Aeronautics Program (the remaining thrusts are Subsonics Rotary Wing and Hypersonics). In responding to LTTG for priorities within the relevant SFW and Supersonics thrusts, the following list of research areas were defined as pre-decisional, since the proposal process is not complete.

8.4.2 Key technologies/tools that will aid in the advancement of low emissions combustion technology are listed below:

- Increase the predictive accuracy, relative to current State-of-the-Art (SOA) combustion Computational Fluid Dynamics (CFD) with “no tuning”, of the emissions indices and combustor performance metrics

- Develop fundamental databases on emissions production using advanced diagnostics to provide accurate, non-intrusive measurement at realistic operating conditions

- Conduct particulates research in sampling methodology development and validation, emissions database development and particle transport and transformation model development and validation. Perform experiments that elucidate soot inception and growth as functions of combustor design/operation and fuel type

- Investigate low cost, MEMS-based fuel-air injectors with high speed, micro-actuators embedded in the assembly

- Develop quantitative high accuracy chemical kinetic mechanisms for alternative and current hydrocarbon fuels

8.4.3 In responding to LTTG request for targets, the assessment is less clear yet, and the following are described as “notional”:

- Progress in the projects will be measured through a well-structured set of milestones beginning at level 1 and integrating sets to achieve successive levels, culminating in level 4 multi-disciplinary analysis and optimization milestones.

- Notional targets will be for example, improving the prediction accuracy of a model predicting emission species by xx%, or the ability to predict species to +/- YY%. Included in the prediction will be: CO, NOx, unburned HC, SO_2, as well as particle and precursor growth and size distribution.

- Diagnostic instrumentation will be improved to more accurately temporally and spatially measure species, velocity, temperature, pressure, particle sizes and distribution.

EUROPE:

8.4.4 The European future long term research & technology developments respond to "ACARE Goals" for CO_2, NOx and Noise emissions. Focusing on NOx, Vision 2020 80% cut is to be considered in term of total mass emitted either during LTO cycle (for Air Quality) or during the whole mission (for Climate Change). Combined with the ACARE fuel consumption reduction goal of 50%, it is estimated at the engine level, that the average cruise emission index should be reduced by 60% and that the LTO NOx D_P/F00 parameter should be reduced by 60% to 80% depending on the aircraft take-off weight reduction from the 50% fuel burn reduction.

8.4.5 The **VITAL** project, initiated in 2005, is a major European on-going engine program not directly concerned by combustor technology, but more dedicated to delivering low pressure technology (with assessment of new engine architectures) in order to reduce noise (by 6dB) and CO_2 (or fuel burn) by 7%. This fuel burn improvement would contribute also to total NOx reduction. Therefore, VITAL will be a step towards ACARE CO_2 and NOx goals.

8.4.6 The FP7 budget will be less than anticipated and the distribution of the global budget between the nine themes may not favour aeronautics, at least at the level of expectation. The European projects are dominated by the manufacturers, and therefore the selected objectives are expected to be conservative, with near term applications and an usual balance between RRD, Snecma, MTU and AVIO (with also a part of the budget oriented towards the new European Community nations like Poland, Czech Republic.

8.4.7 The increasing environmental pressure will influence research towards "propulsion and environment". In France, a reduced civil aviation budget for research is anticipated since a large part of the budget will be required for other aerospace developments.

8.4.8 Priority will be probably given to developing a better knowledge of the impact of aviation on the environment (LAQ and global warming), and this could reduce funding for combustion research and technologies.

8.4.9 On the part of their budgets and resources which is not used for the European and national programmes, the research establishments will focus on the fundamental aspects of the general issues. In France, Onera intends to give greater importance to:

- Code development (two phase LES approach) and code validation;
- Environmental impact;
- Breakthrough technologies for long term innovative concepts.

8.5 Summary
The evidence presented in the Review showed that programmes supported by governments in the U.S. and Europe from the 1970s to the early 2000s have yielded technologies that can be transitioned into products to support 10-year LTTGs. Europe continues to invest in programs that heavily engage industry and have clearly defined goals. However, NASA has shifted its investment philosophy and it has been argued this is likely to affect the achievement of 20-year goals.

9 Discussion

9.1 Review Process

9.1.1 In the view of the Review Panel the Review process and format worked generally well. Presentations were comprehensive and reflected the importance the industry and other contributors placed on the Review. The panel is grateful to all presenters and contributors for their cooperation. Access to material ahead of time was patchy and this lack did adversely affect the efficiency with which the IEs could perform their role. The Review format developed as the Review got under way, and lessons were learned. In particular, the IEs regarded the follow-up Q and A sessions as being very helpful – but *post hoc* there is an issue as to whether these should be open sessions: the advance notice by written questions worked well and this approach would be greatly facilitated by earlier access to presentational material. The Review was dominated by US and European representatives, and for the future the Panel believes other regions should be engaged in the process. Airport representation was also lacking and would be helpful for the future, especially given the importance of LAQ issues. The mixed Committee, comprising IEs and industry personnel, appeared to be a successful combination, and the IE Panel is grateful for the support received from the industry members. Consensus among the IEs was achieved on this report and its findings.

9.1.2 The process had some limitations. A quantification of the benefits projected to result from achievement of the goals was not conducted under the Review. Likewise, no cost–benefit (c/b) analysis was possible and is likely to be ambitious even for future Reviews. However c/b monetization will be needed for policy making and should ideally be considered in future Reviews. More background data and projections from a consensus source such as ICAO of fleet emissions for 10 years, 20 years, and beyond would have been useful when assessing environmental need. Access to a suite of modelling tools would have been useful, but for this initial Review it was recognised that such work would have been too ambitious.

9.1.3 The question of tradeoffs could not be dealt with in a particularly structured manner, partly a recognition that significant gaps remain in scientific understanding. It is recognised that by its nature this is a complicated topic with numerous inter-related reactions and trades associated with differing future technology proposals (P30). The means to make this a more structured and quantitative exercise for future reviews should be considered.

9.2 Successive Reductions in Certification NOx and Long Term Trends

9.2.1 As a backdrop to setting NOx LT technology goals the Panel were conscious of the successive reductions in permitted certification levels. These have been described in detail in Section 6 and illustrated in Figure 4 where it can be seen that significant reductions in certification NOx levels have already been adopted or agreed for newly certificated engine types. On the other hand, it was recognised that changes to aircraft standards of this kind impact the total fleet NOx production very slowly as newly certificated types progressively enter the fleet - the long production lives of specific models (15 + years), coupled with long in-service lives (typically 30+ years for passenger aircraft, 45 years for cargo aircraft) and infrequent opportunities for airlines to introduce new fleet types, slow the introduction of the benefits on offer. Figure 9 illustrates this in respect of retirements; CAEP's FESG found that 60% of passenger aircraft were still in service at 30 years of age[18].

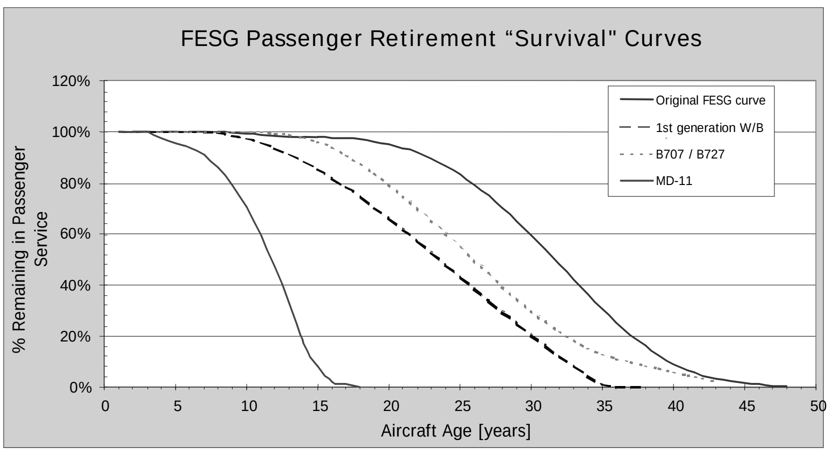


Figure 9: FESG Passenger Retirement Curve

9.2.2 Looking forward from any point in the future the total commercial fleet will comprise: a progressively declining proportion of the in-service fleet as gradual retirement takes place; an increasing proportion of current production types entering service to satisfy growth and retirement of older types currently in service; and finally a small but slowly increasing proportion of newly certificated types. It is this last category that delivers the benefit of the very latest certification standards. Figure 10 taken from Airbus' Global Market Forecast is typical of the fleet growth and supply pattern. What such a figure does not show is that even the majority of the new aircraft supplied will be of current certification types continuing in production for many years in to the forecast and

[18] Wickrama U. CAEP/5-IP/11, 8-17 January 2001, Montreal

therefore new certification types will only gradually constitute a rising and eventually significant share of the total fleet. On the plus side where aeroengines are concerned (as opposed to airframes), there is a tendency for a somewhat more rapid introduction of newly certificated types resulting from the opportunities to change engines at airframe mid-life developments (e.g. A340-300 to A340-500/600 and 747/400 to 747-8). In respect of in-service aircraft, it is an historical fact that re-engining of existing in-service aircraft has rarely been a viable economic option, though in circumstances of very high fuel prices, the IEs believe this might become at least a more theoretically attractive possibility.

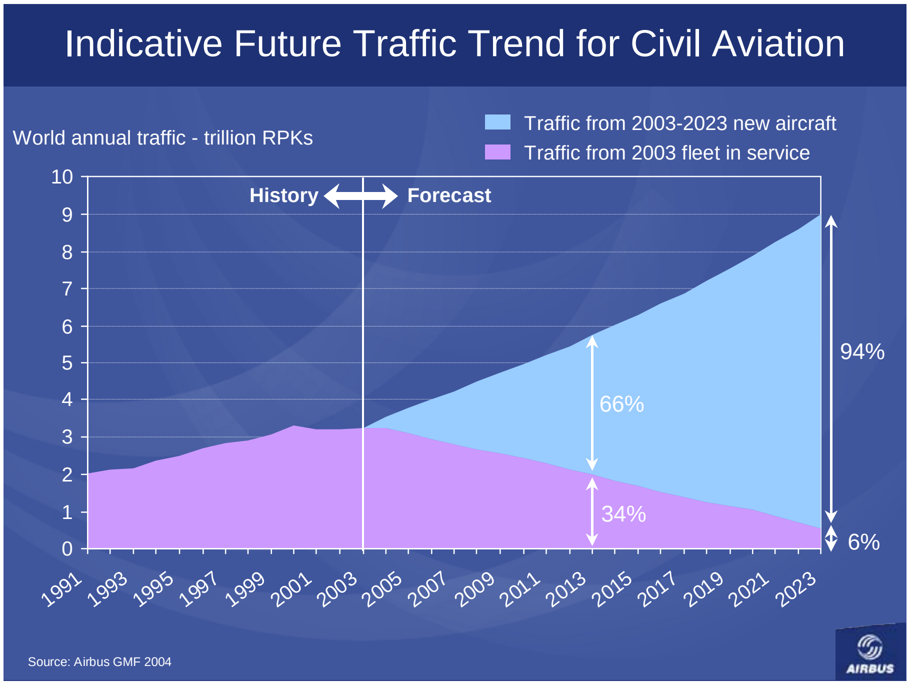


Figure 10: Illustration of Fleet Growth and Supply Pattern (indicative)

9.2.3 All forecasts of air traffic predict growth over the next 10 and 20 year periods and beyond. For example, in the near and medium term a generally agreed worldwide figure of around 5% per year is expected thus indicating a doubling of today's air traffic in about 15 years' time (ICAO, Boeing, Airbus forecasts, 2006). To help put the scale of growth in perspective, the incremental annual growth in 2005 was equal to the total industry traffic in 1967 (ICAO World Traffic Statistics and 2005 Provisional Figures). This growth, coupled with the relatively slowly applied impact of new standards and technologies described above, suggests there will be significant upward pressure on aircraft emissions. Advice from the WG3 Research and Science Focal Points (See section 5) confirmed that from the climate science perspective very long timescales should be considered. As a consequence, and in the context of addressing 'need' the IEs requested information about forecast long term emissions trends. Advice from the WG3 Research and Science Focal Points (see section 5) was that there were two issues that need to be considered: firstly, the overall modelling and assessment timeframe and secondly, the climate impacts ITH. Previously, the science and technology research communities have used a 50 years timeframe for modelling and assessment of various scenarios (IPCC, 1999). Climate impacts ITHs tend to suggest that 50 to 100 years is a suitable timeframe. None more recent than the 1999 IPCC referenced scenarios were found to be available within the CAEP system.

9.2.4 During the report drafting stage the Panel was informed that some work had begun to model the long term commercial aviation emissions inventories trends and also account for the likely impact on emissions inventories if the MT and LT goals of this report were to be achieved. Some very preliminary results from US and UK-sponsored analyses were presented to the Panel during the Atlanta meeting. Even if fully worked results of the potential effects of the goals were to be made available within the reporting timescale, it had been questioned as to whether they fell within the Terms of Reference of the Panel. Given the very preliminary nature of this work the IEs felt that before use is made of such results modelling methods and input assumptions should be carefully reviewed and such activity would be beyond the timescale of this Report. Nonetheless, the Panel was grateful for being made aware of this work in progress and encouraged the production of consensus long term aviation emissions trend curves as it was felt that these were needed to better inform environmental need, impact studies and the assessment of tradeoffs

9.2.5 Long term forecast scenarios do vary. It is regrettable that no recent projections were made available to the Review. The Panel made use of the IPCC report (1999) quoted scenarios produced by FESG, NASA, ANCAT and DTI, but these were largely based on 1992 data. These scenarios indicate that aviation fuel consumption will have increased by a factor of 2.5 by 2015, and by 4.0 by 2050 (for the typical FESG mid-case scenario, Fa1). Corresponding estimates for NOx increases were factors of 2.7 by 2015 and 4.9 by 2050. The 2050 scenario range considered by FESG (Fc1, Fe1) gave a range of factor increases of between 2.2 and 6.4, and between 2.7 and 7.9 for fuel and NOx respectively. Some other forecasts, notably the EDF, were also reported with much higher levels of increase. It is questionable whether the above figures represent current best estimates

9.3 Environmental Need

9.3.1 Section 5 provides the Panel's detailed report on the level of scientific understanding. The presentations (P5,6,7 and 8) by the WG3 Research and Science Focal Points were followed by written questions from the Panel, which were answered in a question and answer session held on the fourth day of the Review. The Panel sought advice on the impacts of individual aircraft pollutants on both LAQ (local air quality) and GCC (global climate change).

9.3.2 When considering environmental impacts, ideally, these impacts should be known with a reasonable degree of accuracy that enables CAEP and other bodies to recommend appropriate action and, when considering LT technology goals, have informed an agreed set of requirements, such as a permitted ceiling level of emissions. For GCC, the level of debate has not reached anywhere near an agreed level of, for example, an acceptable level of aircraft emissions. With this in mind the Review was informed (P24) that there were moves within the EU signalling the first signs of sectoral attribution of emissions. In the area of LAQ, it was noted that the debate about impact appears to have been taken further and has led to local emissions concentration limits within the EU which are already affecting the air transport industry, and in the US there are concerns about AQ non-attainment areas which are impacting capacity enhancements at airports located in these areas.

9.3.3 In summary, the Panel noted that with respect to GCC there is genuine continuing (though possibly reducing) uncertainty about emissions impacts on atmospheric chemistry and the related climate response. Considerable uncertainty remains about the contribution of some individual pollutants, though there appears reasonable confidence on the effects of CO_2 and NOx. Work is continuing and updated views would need to be considered in future Reviews. In the area of LAQ it was noted that the key issues were much more related to questions of attributing emissions to competing sources rather than the impact of NOx *per se*. There were significant uncertainties noted on the impact of PM and HAPs (P5), but much more systematic efforts than those aimed at GCC are underway to address these. Whatever the uncertainties, the clear conclusion was reached that at this time there is still an imperative to reduce aircraft NOx emissions for both LAQ and GCC.

9.3.4 LAQ (See also Section 5.2)

The clear advice received was that for LAQ NOx is the current priority, though PM (particulate matter) and toxic substances (hazardous air pollutants of HAPs) cannot be ignored, as interest is growing in their potential effects and some research notes that their impacts may rival those of NOx (P25). The Panel noted particularly the existence of the EU Directive (legally binding on member states) set to come into force in 2010 with NO_2 limited to 40 μg per m^3. Several UK and EU airports were said to already exceed this figure today, and in the case of Heathrow was the major reason for a delayed runway development (P4 and P24). And in the US also a considerable number of airports lie in non-attainment areas (25% of total airports and 80% of the top 50) and air quality concerns delay capacity expansion.

9.3.4.1 The Panel faced a number of difficulties when trying to understand the impact of aircraft emissions and the potential for technology goals to address LAQ related issues. Firstly, issues of variability in local circumstances e.g. large local land based sources and variations in the size of land areas under scrutiny. Secondly it was not clear from the presentations what was the specific contribution to local exceedence from aircraft emissions alone as compared with, for example, motor traffic or other airport sources. During the review, ICCAIA referred to a U.S. EPA report (P26), which showed that even though the sum of aircraft NOx emissions from ten large U.S. airports was predicted to increase with traffic growth between 1990 and 2001, total regional NOx emissions for the same ten airports were predicted to decrease by nearly one half. Even with this trend, by 2010, aircraft NOx emissions (based on the variable mixing height assumption in the report) were predicted to be about

2%-10% of the total. Considering this trend towards reduced total NOx emissions, the question was asked whether further reductions in LTO NOx would still have significant environmental value when products that meet mid-term goals are in service. During the Review, the Panel was informed that there were structural issues with this report but nevertheless the panel has received more information on the contribution of aircraft around airports that do support the need to ask the question whether reduced LTO NOx will still be significant in the long term and to address aviation NOx impact within the context of contributions from all sources.

9.3.4.2 It was noted that in the UK concentrations of NO2 are already in excess of prospective EU standard in some places around Heathrow, with smaller exceedence recorded at Gatwick. There are risks of exceedence at other UK airports. Similar situations were said to exist elsewhere in Europe, though Heathrow's problem may be more marked and has simply arisen first and thus attracted significant attention. However, it is symptomatic of a problem within Europe (P27) that is attributable to a number of emission sources including aircraft. Other regulated pollutants do not exceed limit values and are not predicted to do so, though there is increasing attention to PM, with an increasingly tough European stance, driven by the margin of compliance being eroded. In the U.S. ozone and PM are limiting factors for airports.

9.3.4.3 The IEs were informed that work by the DfT in the UK is ongoing to understand the relative contribution of the various sources to modelled NO_2 concentrations through inventory-based attribution studies at receptor points around airports. These studies show that the aircraft contribution is significant at locations close to the airport (within about a kilometre) but declines to a relatively small contribution beyond about 2-3 kilometres. The aircraft contribution can be a key influence in breach of NO_2 levels closer to the airport and further out the combined total of the residual contribution together with the contribution of other sources can still be sufficient to exceed limit values at some locations

9.3.4.4 Some more recent quantified information on areas around several US airports are shown in table 2, below. These non-attainment areas often include multiple counties in and around the metropolitan areas associated with these airports. For example, in Atlanta, the non-attainment area includes 13 counties – the sizes of the areas vary for each airport. This shows that in the cases presented the airport contribution to the area NOx inventory ranged up to 6% of the total NOx burden and up to 20% of the total non-road sources. These values bracket the ranges predicted in the EPA material presented during the review.

Table 2: US Airport Contribution to Area and Non-Road NOx Inventory

Airport	National Rank (enplanements)[19]	Ozone Attainment Area Status[20]	Airport Contribution to Area NO_x Inventory	Aircraft Contribution to Non-Road NO_x Inventory
Hartsfield Atlanta International (ATL)[21]	1	Marginal	2.8%	14.1%
Chicago Nonattainment Area (ORD, MDW)[22]	2 (ORD), 28 (MDW)	Moderate	0.8-2.0%	10.5%
South Coast California (BUR. LAX, LGB, ONT, SNA)[23]	3 (LAX), 44 (SNA), 51 (ONT), 61 (BUR), 93 (LGB)	Severe	1.5%	5.7%
Dallas/Fort Worth Air Quality Area (DFW, DAL, AFW)[24]	4 (DFW), 53 (DAL)	Moderate	6.1%	19.9%
Houston Bush Intercontinental (IAH)[25]	8	Moderate	0.7%	3.3%
New York (JFK, LGA, EWR)[26]	12 (EWR), 13 (JFK), 21 (LGA)	Moderate	4.0%	13.8%
Seattle-Tacoma International (SEA)[27]	15	Attainment	1.9%	6.7%
St. Louis Lambert	17	Moderate	1.4%	8.5%

[19] U.S. Department of Transportation, Federal Aviation Administration, *Enplanement Activity at Primary Airports*, http://www.faa.gov/arp/planning/stats/2002/CY02CommSerBoard.pdf , November 6, 2003.
[20] U.S. Environmental Protection Agency, *Classifications of Ozone Nonattainment Areas*, op.cit.
[21] U.S. Department of Transportation, Federal Aviation Administration, Federal Highway Administration (cooperating agency), *Final Environmental Impact Statement for 9,000-Foot Fifth Runway and Associated Projects: Hartsfield Atlanta International Airport*, August 2001.
[22] Illinois Environmental Protection Agency, *Illinois 1999 Periodic Emissions Inventory And Milestone Demonstration*, December, 2001. The higher value for in the area inventory data in the table is for a typical summer day, which is the ozone season and probably represents a worst case since it is the most active period for aviation activity. The non-road data also is based on typical summer day. The lower value, which is more representative for an annual value is from U.S. Department of Transportation, Federal Aviation Administration, *Final Environmental Assessment for the World Gateway Program and Other Capital Improvements: Chicago O'Hare International Airport, Chicago, Illinois*, June 21, 2002.
[23] South Coast Air Quality Management District, *Emissions by Category, 2001 Estimated Annual Average Emissions, South Coast Air Basin.* http://www.arb.ca.gov/app/emsinv/emssumcat_query.php?F_DIV=0&F_YR=2001&F_AREA=AB&F_AB=SC , 2001.
[24] Texas Natural Resource Conservation Commission, *Dallas/Fort Worth Ozone Nonattainment Area Emission Data*, http://www.tnrcc.state.tx.us/air/aqp/ei/rsumdfw.htm, 1996 inventory data. Data includes all airports in the nonattainment area including, DFW International Airport, Dallas Love Field, and Alliance Airport.
[25] U.S. Department of Transportation, Federal Aviation Administration, *Final Environmental Impact Statement Runway 8L-26R and Associated Near-Term Master Plan Projects; George Bush Intercontinental Airport/Houston*, July 2000.
[26] Compilation of data from the SIP inventories for New York and New Jersey provided by Mr. Raymond Forde, Region 2, U. S. Environmental Protection Agency, June 16, 2004. Additional data provided by Mr. Kevin McGarry, New York State Department of Conservation and Ms. Tonalee Key, New Jersey Department of Environmental Protection.
[27] Agyei, Kwame, Puget Sound Clean Air Agency, airport emissions calculated using EDMS 4.0; area non-road and total emissions from 1999 Air Emission Inventory Summary spreadsheet, February 11, 2003.

International (STL)[28]				
Boston Logan International (BOS)[29]	20	Moderate	0.7%	2.3%

Airports, including aircraft, ground support equipment, and all other vehicles operating around the airport, contribute only a small percentage of NO_x emissions to regional inventories even in cities with the greatest concentration of aviation activity. All of the cities shown include at least one of the 20 largest airports in the country and, except for Seattle-Tacoma, are nonattainment for NO_x under the new 8-hour ground-level ozone designation. [30]

9.3.4.5 The Panel noted that in the context of LAQ the possible health effects due to aircraft emissions were not reviewed though it certainly could be argued that such a study would fall under the requirement to report on the 'status of understanding of environmental impacts of aircraft engines emissions'. (See sections 1.4 and 3.1) This area could be considered for future reviews, though the IEs feel that this would require an expanded set of expertise from the review participants.

9.3.4.6 Despite the above qualifications, a clear overall conclusion was reached that LAQ driven pressure on aircraft NOx must be assumed to continue and especially given existing 'hot spots' and expected traffic/emissions growth. This conclusion should be reviewed by future Panels and particularly as low NOx technologies in the pipeline and under development continue to work through to the in-service fleet and given possible reductions in NOx from non-aircraft related sources.

9.3.5 GCC (See also Section 5.3)

9.3.5.1 As with LAQ, in the context of GCC, the clear advice received was that given today's level of scientific understanding, aircraft NOx is regarded as being a major component of the total aircraft impact. Though a complex question, if a ranking is needed then the Panel concluded that on the evidence presented the order of importance is likely to be CO_2, closely followed by NOx and with high levels of uncertainty noted with regard to contrails, cirrus cloud formation and role of PM in plume chemistry and cloud formation. Section 5.3 provides a discussion of these in greater depth.

9.3.5.2 In summary, today's commercial fleet cruises at altitudes of between 8km to 13 km (upper troposphere/ lower stratosphere) and with a tendency over time for higher average cruise altitudes. Primary aircraft emissions at these altitudes are CO_2, H_2O, NOx, SOx, Soot, and UHCs. A difficulty in comparing

---

[28] Nonattainment area non-road and total NO_x emissions, 68 FR 25431, May 12, 2003; Airport emissions escalated from 1995 estimate by URS Greiner, Inc. (1997) based on 2000 data provided by Tony Petruska, U.S. EPA.
[29] Massachusetts Department of Environmental Protection, *Massachusetts Periodic Emissions Inventories 1999*, April 2003, for nonattainment area off-road emissions and total emissions, which are based on summer day emissions. U.S. Department of Transportation, Federal Aviation Administration, *Final Environmental Impact Statement, Logan Airside Improvements Planning Projects: Boston Logan International Airport*, June 2002 for Logan Airport emissions, which are typical for an annual value.
[30] Federal Aviation Administration, Aviation Emissions: A Primer, 2004

the climate impacts is that these pollutants have very different residence or reaction times. For example, emitted CO_2 has a residence time of many decades (and therefore where the emission takes place is of no significance), whereas, NOx is relatively reactive and short-lived. Its altitude of emission is more relevant to its radiative forcing effect from the ozone formed given the sensitivity of the atmosphere at flight altitudes. It is for this reason that the impact of aircraft NOx emissions on GCC is considered to be potentially more significant than a simple proportion of all anthropogenic combustion sources would suggest. The IPCC study reports that in 1992 aircraft produced about 2% of anthropogenic CO2 but contributed about 3.5% to anthropogenic radiative forcing. This fact, coupled with expected increases in aircraft mass emissions, indicates that environmental pressures on aircraft emissions, including NOx, must be expected to increase.

9.3.5.3 To establish the relative GCC impact weightings of the various aircraft pollutants considerable time was spent establishing what integration period is most appropriate when considering the impact of the commercial aircraft fleet on GCC. There appeared to be several options, from instantaneous radiative forcing through to the very long term integrated global temperature response of 50-100 years or more. It was apparent that the choice of integration time had a great effect on the relative weightings of various pollutants and this has been discussed more fully in Section 5.5. Taking just the two pollutants NOx and CO_2 as examples, “instantaneous” forcing suggests the relative weightings are of the order 1:0.06, but a fifty year integration period for temperature response would suggest a weighting of nearer to parity. If an even longer timescale is used to reflect the full global temperature response (50+ years) if NOx is taken as the reference with a value of 1 then CO_2 appears to be weighted at probably 2 or 3, but perhaps 2 to 10. The Panel concluded that weightings related to instantaneous or very short integration times could be highly misleading and would weigh too heavily against NOx relative to CO_2. The Panel’s view is that for aircraft related studies a longer integration timeframe was required (of the order 50 years), and coincidentally such a time period would more closely match the long fleet response times described in Section 9.2 above and used in the IPCC 1999 study. However, some Panel members questioned 50 year fleet projections because of their high level of uncertainty and such future projections should examine a variety of scenarios to examine their possible futures.

9.3.5.4 Given both today’s level of scientific understanding and the environmental pressure to reduce aircraft emissions, then it appears reasonable to expect continued pressure to be exerted to reduce NOx in the medium (10 year) term, but great care should be exercised if this were to be at the expense of significantly increased CO_2 and PM production. Furthermore, it was noted that for fixed combustor conditions, reductions in fuel burn - and therefore of CO_2 emitted - also result in reduced mass of NOx, H_2O and other pollutants as well. In the longer (20 year) term the value of NOx reductions compared with the potential impact of growing CO_2 emissions might need to be considered. Continued dialogue with the scientific community will be necessary in order to benefit from developing understanding of GCC in general and aircraft impacts in particular.

9.4 Tradeoffs (See also Section 5.4)

9.4.1 When considering tradeoffs it must be remembered that at the heart of the engine designer's world is safety. Figure 11 taken from P&W's presentational material (P21) describes this world in illustrative form. The combustor is the heart of the turbofan engine and any moves to improve emissions (NOx) characteristics clearly cannot be allowed to compromise safety.

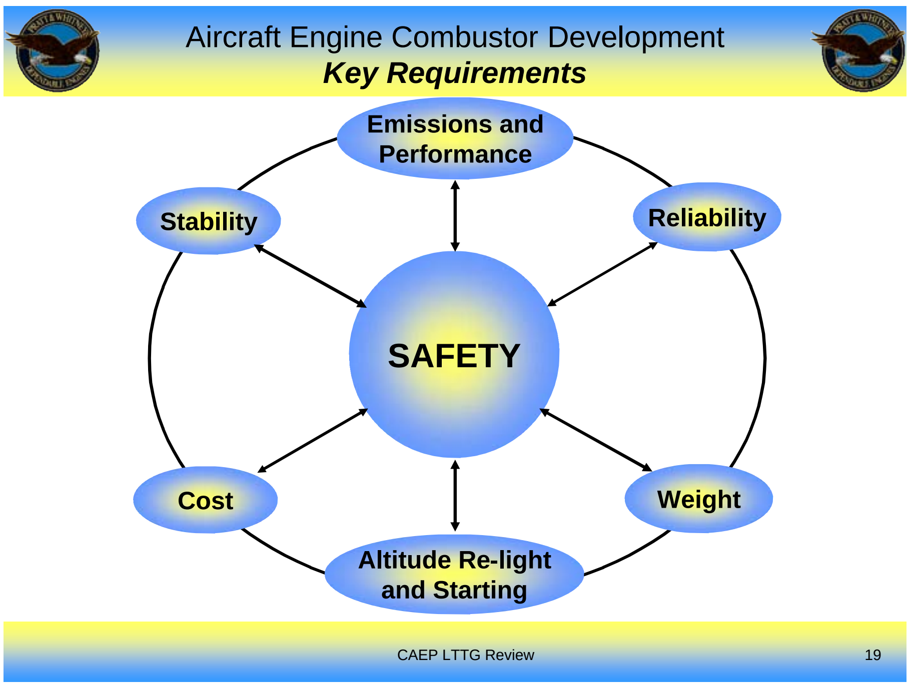


Figure 11: Aircraft Engine Combustor Development Key Requirements

9.4.2 In this context, the issue of altitude relight requirement is worthy of particular mention. Some of the future lean burn combustor technologies may have greater difficulty in meeting the commonly stipulated (by airline customers) relight capability of 9143 metres (30,000 ft). Some manufacturers are already questioning the need for this level of capability, and 7620 metres (25,000) ft is regarded by some as offering a satisfactory safety margin. If the safety issues can be resolved satisfactorily, then it would be helpful to debate whether such a change would be acceptable as NOx emissions performance benefits might result. The IEs understand that safety considerations are foremost and that better relight prediction capability is needed to inform such a debate. This is a greater challenge for lean burn concepts; RQL is projected to still meet the relight margins at lower NOx levels.

9.4.3 It seems clear that given current understanding of aircraft contributions to both LAQ and GCC there appears limited scope for trading one key emission against another. NOx clearly featured highly as a concern in both contexts and CO_2 (as well as NOx) is seen as a key pollutant in concerns over GCC. The direct link between CO_2 and H_2O reinforces this importance. The working assumption for the medium term 10 year goal must be that pressure towards reductions in both of these pollutants (CO_2 and NOx) must be expected to continue. CO and HC are generally well below certificated levels so theoretically there may be a possibility to consider trade with NOx, but this would be associated with worsening CO_2 so would be difficult to justify. Moreover, relatively high levels of uncertainty about PM and HAPs (a subset of HCs) impacts were reported, and therefore no realistic opportunity exists for significant tradeoff.

9.4.4 Evidence tabled by ICCAIA (P30, slide 9, shown at Fig. 12) indicated that a 22% reduction in NOx had resulted in a something like 2% increase in CO_2 – an 11:1 ratio. The Panel recognises that the strength of such relationships varies somewhat on a case-by-case basis and believes it is necessary to examine whether this ratio is likely to increases or decreases with new combustor technologies. Furthermore, as GCC modelling improves any benefits from such a tradeoff gearing might be explored, although any increase in CO_2 would have a direct effect on H_2O as well as an indirect effect on mass NOx. Large reductions in certificated NOx levels have resulted from combustor changes, and the mass of NOx emitted is reduced by overall fuel burn improvements through reducing EI values. It is also worth reflecting that in the context of the whole aircraft there is a wide range of opportunities to reduce CO_2 production through improvements in structural, aerodynamic and propulsive efficiencies all of which have a direct bearing on fuel burn, whereas with NOx, the primary focus is solely on combustion. Similar tradeoff studies related to PM, and potentially HAPs, should be pursued as scientific understanding permits.

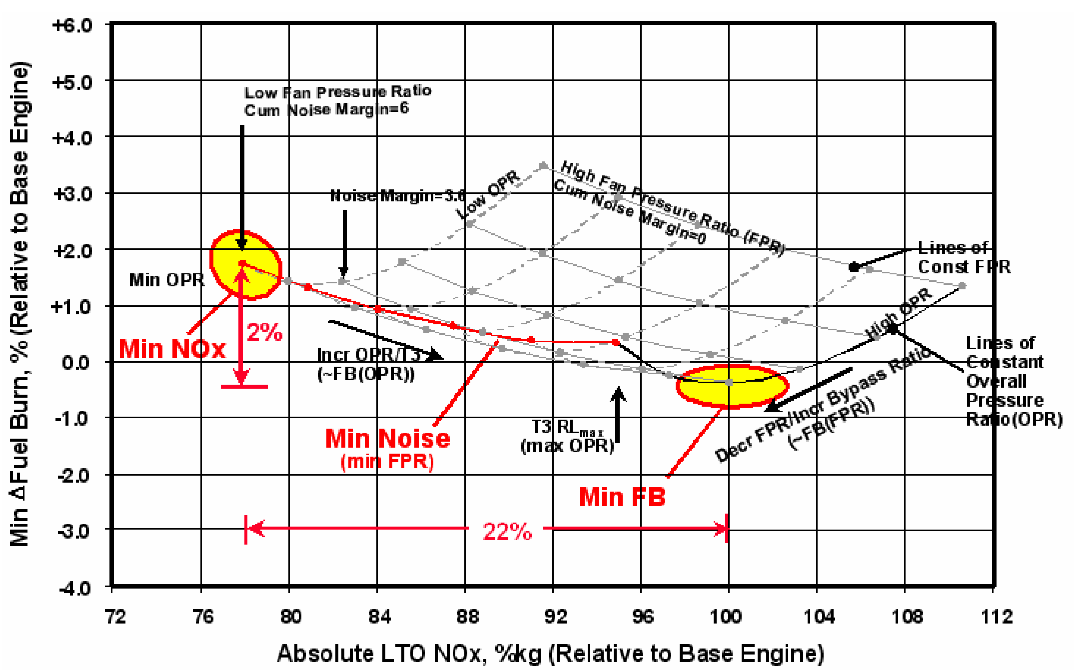


Figure 12: <u>Engine/Airframe Cycle Tradeoffs - Fuel Burn/NOx/Noise Carpet Plot Example</u>

9.4.5 At the engine level perhaps the most significant technology challenge has resulted from the drive for increased thermal efficiency through increased engine pressure ratio (PR) which, all other things being equal, has increased NOx production through higher compressor exit temperatures. Sections 6 and 7 deal in detail with such issues. A particularly strong relationship exists between increased temperature and NOx production. This link has been broken by step changes in combustor design. In the pursuit of fuel efficiency, historically, PR has risen at a rapid rate. The Panel questioned whether this rate has now slowed and therefore, at least in the 10 year time period, the level of conflict will have eased. Information passed to the Panel showed that over recent decades PR had risen by around 10 every 10 years (P10), but that the rate was now at half that level. This would tend to the view that in the near to medium term the climate for further NOx reduction is somewhat more favourable though there are concerns about this view on two counts. Firstly, that the full effects of recent (and probably sustained) rapid rises in fuel price will continue to drive engine core research programmes. And secondly, in the 20 year horizon an assumption of continued slow PR growth is much less certain, though significant strides in high temperature materials or cooling technologies will be needed. The possible use of geared turbofan technologies could also influence this trend.

9.4.6 Finally, significant technical tradeoff issues for future technologies were noted in the Review and for which there must be confidence about realistic solutions if LT technology goals are to lead to reductions in NOx emitted. Combining issues surrounding future Lean Burn, RQL and TAPS technologies the key challenges were reported as follows:

- Reduced combustor efficiency due to lower flame temperatures
- Reduced efficiency from increased pressure loss
- Increased instability and vibration
- Safety/operability issues e.g. cold ignition, reduced altitude re light, flameout margin, flame instability
- The conflict between cooling air requirements for turbine lifing as opposed to for NOx control
- Acoustic instabilities possibly leading to vibration damage to the combustor - not an external noise issue
- Fuel staging transition uncertainties
- Water and hail ingestion uncertainties
- Increased complexity of control and injector systems
- Weight and cost uncertainties

9.4.7 External noise/NOx tradeoff was not discussed by industry in large measure (See Section 6.7). Nonetheless, given the expected continued pressure on external noise, possibly compounded by pressures on fuel consumption, this topic should be addressed in future Reviews. All new technologies (e.g., lean burn, RQL and TAPS) will have tradeoff challenges that must be faced. The severity of these challenges will likely be different for different combustor design approaches and will need to be evaluated as part of the development process.

9.4.8 In summary, the product of any engineering exercise is the result of numerous compromises and therefore any design will accommodate a number of tradeoffs. There appears to be little clear opportunity, with the possible exception of CO, to trade one emission against another and even a CO needs to be weighed against any potential increase in CO_2. Moreover, careful cost–benefit analysis would need to be performed before reaching justifiable commercial and environmental decisions. In the 10 year horizon it is not thought likely that tradeoffs will provide significant easing of current pressures on the individual key pollutants and especially for NOx in both the GCC and LAQ contexts. In the 20 year period the results from improvements in GCC modelling may alter these conclusions, but an easing of LAQ NOx concerns is unlikely given the predicted level of air transport and emissions growth. Finally, the shock to the system of recent fuel price rises (which have reversed a long term decline in real price) must be expected to result in economic signals to increase the pressure on manufacturers to reduce CO_2 emissions. Given current understanding of environmental impacts, trade with increased NOx production may not be advisable.

9.5 MT (10 YEAR) AND LT (20 YEAR) TECHNOLOGY GOALS

For reasons explained previously, the underlying working conclusion was that there would be no lessening of pressure to reduce NOx at least for the period of the MT technology goal. Similarly this has been assumed for the LT technology goals though, clearly, updated advice will need to be considered at future reviews. As there was no possibility of establishing scientifically justified aircraft NOx mass targets, the less attractive pragmatic alternative approach was taken of reaching a consensus view among the IEs of realistic, but challenging, targets for leading edge NOx technologies in the two time periods.

Section 8 has already described several existing technology goals of varying provenance (ACARE, etc.). These external goals have been included in this report and discussion for completeness only, as this Panel took an independent view of technology goals based on the Review material. The proposed goals have been based on the technology presentations, the follow-up Q&A sessions, coupled with the Panel’s own in-depth knowledge of the specialist combustor area and of the wider air transport sector.

The MT and LT goals established in the following pages represent levels of potential achievement by an industry, not a company, and assume that efforts leading to these achievements are funded. Progress will require appropriate funding, this is fundamental to the business. The MT and LT goals are based on the best targets and achievements presented at the London Review, regardless of source or design approach. It is recognized that over the next 10 to 20 years, refinements as well as major design changes will occur, but all in an effort to reach these “best” targets. All presentations were considered. In the interest of both brevity and objectivity brief discussions of the concepts and sources were included (see Sect. 6) only for those that set the goals for both MT and LT. These are technology goals, not predictions of stringency levels.

9.5.1 Engine Goal Compliance Assumptions

For setting both the 10 and 20 year goals the Panel were asked to consider the levels of NOx performance likely to be reached by the due dates and refined up to Technology Readiness Level 8 (TRL 8) – ready for service - see Appendix 2, Ref P3, and P12. However, it was evident to the Panel that further interpretation was needed as it was not stipulated whether this level of readiness was to apply only to the very best or, for example, to the average of all manufacturers or the average of a family of engines etc. The criterion adopted by the Panel was that a goal will be met when one or more manufacturers achieve a performance within the goal band (see 9.5.3 below) judged against TRL 8. Thus the goal bands are predicting the leading edge capability.

The Panel is aware that this 'simple' approach will raise several issues of concern to industry and regulators. Chief amongst these are difficulties related to the relatively steep NOx emission characteristic slopes of families of engines (as compared even with the stringency slope) where thrust increase is achieved more through throttle push than re-scaling. Furthermore, there are crucial questions about the implications of perhaps only one manufacturer achieving the goal level, the position and degree of any kink in the certification line, and possible special needs related to small engines. After careful consideration, it was felt by the Panel that such questions were appropriate to the debate on regulatory stringency rather than to goal setting and this served to emphasise the differences between goal setting and standards stringency.

9.5.2 Technology Goals Different From Standard Stringency

Several of the Panel members have experience of the ICAO CAEP standard-setting process. Section 3.8 describes the TRL related continuum as between technology goals and standards stringency. Nonetheless, the Panel would stress there are fundamental differences between technology goals and CAEP standards. CAEP standards have historically been recommended at levels where capability has already been demonstrated across a wide variety of aircraft size classes and proven in service. Standards therefore lag rather than lead technology and in essence 'bank' improvements that have already been achieved. On the other hand, the philosophy of setting technology goals is very much a judgement about where leading edge technology capability is likely to have progressed by a given date, with one or more manufacturer having a technology to the TRL 8 "ready for service" level. Technology goals very much lead rather than lag proven capability and their achievement level and timescale is not guaranteed. This is a fundamental difference between CAEP Standards and Technology Goals.

9.5.3 Derived MT and LT Technology Goals

Figure 13 shows the two bands derived by the panel of impartial experts for the 10 year and 20 year technology goals. The two bands have been shown against the ICAO NOx certification standards lines (for identification purposes only – see 9.5.1) together with some other public domain external goals. The IEs considered the performance suggested by single engine results in their deliberations. Figure 14 is more cluttered as in addition other technology and engine specific certification data points have been added. The NOx performance points plotted (Fig. 14) were helpfully provided by an ICCAIA airframe representative.

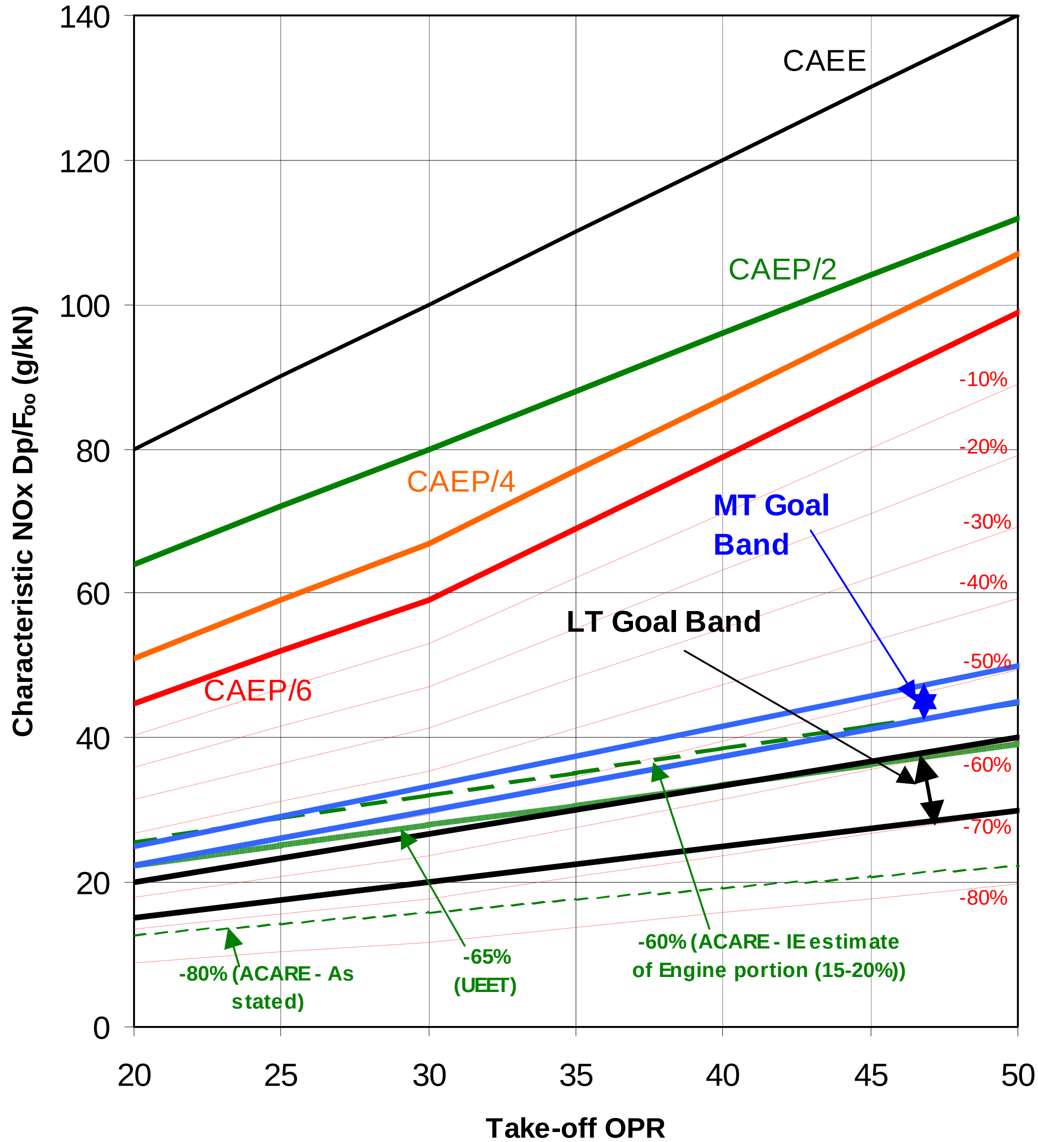


Figure 13: MT and LT Goal Bands

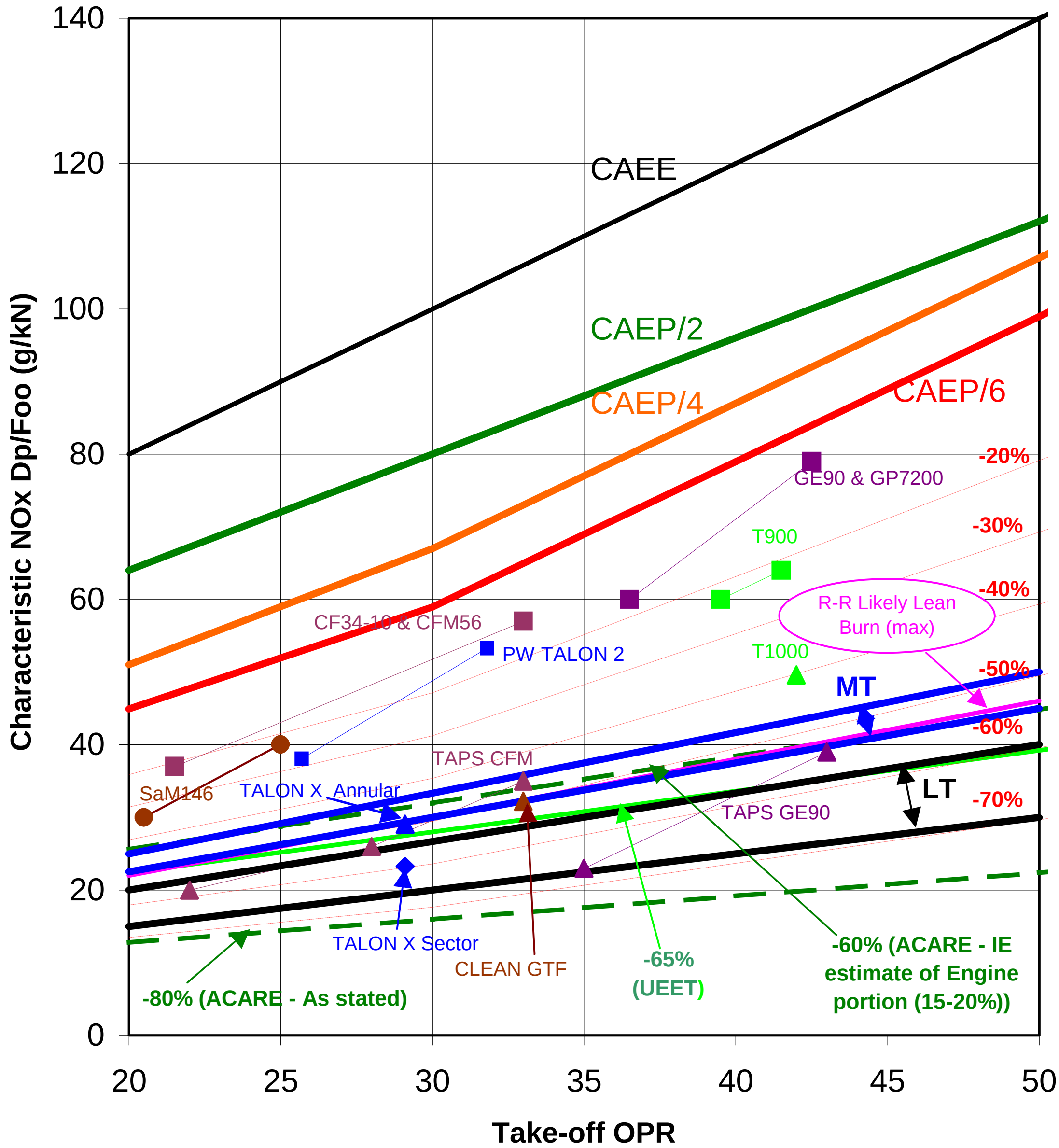


Figure 14: LTTG Goals and Industry NOx Performance Targets

The relatively shallow slopes of the two bands will be immediately apparent, as will the lack of any "kink" at OPR 30 (as introduced at CAEP 4 to restore the slope to that of the original regulation). The shallowness of the slopes is in contrast to the far steeper development slopes of families of engines e.g. GE90 and Trent 900. These features (the kink and steep development slopes) were not considered applicable to technology goal setting. The chosen technology bands were considered applicable to the initial engine type of a family than to possible later growth/development versions – see Sect. 9.5.1 on Compliance.

It should be noted that the IEs looked to the best or leading edge (in terms of NOx), only to set the goals. It is understood that, by this definition, all would not meet the goal at the same time (see section 9.5.1).

9.5.3.1 10 YEAR MT Technology Goal

The mid-term goal is described mathematically by 7.9 + 0.79*PR and is centred at about 45% below CAEP/6, at a reference OPR of 30[31]. The goal band width (+/-2.5% of the CAEP6 value) is defined mathematically by 8.3+0.83*PR (upper) and 7.5+0.75*PR (lower). This position results from the Panel's best judgement as to where the leading edge of combustor technologies and NOx reduction strategies could be progressed over the 10 years period to the TRL 8 level, i.e. ready for service. On the face of it there is a large gap between the latest ICAO CAEP/6 standard and this goal band, but as stated earlier in section 9.5.1 the two are completely different in nature and should not be directly compared.

The MT band is supported by the combination of TALON X (P&W P21), TAPS 2 (GE P20), and the lower portion of the RR likely lean burn projection (RR P18). Perspective is established by the RR T1000 target (787 application) for 2008 certification. This product to be certified nearly a decade before the timeframe of the MT band is only 10% above the MT band midpoint. The MT band is narrow (+/- 2.5%) because of the quantity of near term efforts targeted for product, giving confidence in its achievement.

It has been assumed that this level of achievement will be reached by the successful application of technologies from among the varied optimised rich burn approaches being pursued today e.g. RQL, and first generation lean burn e.g. TAPS. With this in mind, the upper line of the mid term (yr 2016) band has been placed at less than 10 percentage points below the expected level of achievement of B787/A350 class engines entering service around 2008/9. It is stressed again that this degree of achievement is by no means guaranteed and does represent a significant challenge. Uncertainty exists both as to the level of reduction that might be achieved as well as to the time taken for technologies to reach TRL8. It has also been recognised that no one TRL level adequately describes the current state of development of these technologies as various aspects will be at differing TRL levels. In reality this must mean that there is a chance that some critical elements may not progress sufficiently far in the timescale. Nonetheless, in this MT case the band width is relatively narrow indicating a reasonably good level of confidence. When considering likely EIS (entry into service) dates for MT technologies in a relatively short ten year horizon the relatively infrequent introduction of new types could result in EIS slippage by perhaps as much as 5 years.

[31] -53% +/- 2.5% below CAEP/4
-61% +/-2.5% below CAEP/2

As stated earlier, the chosen mid-term technology goal was not selected with direct reference to any previously published goals. Nonetheless, when making the inevitable comparisons it can be seen that the lower edge of this mid-term goal band lies above the UEET line and at or near the engine portion of the ACARE 2020 (year) NOx goal line.

9.5.3.2 20 YEAR Long-Term Technology Goal

The LT goal is described by 5.8 + 0.58*PR and is centred at about 60% below CAEP/6 at a reference OPR of 30[32]. The goal band width (+/-5% of the CAEP/6 value) is defined by 6.7+0.67*PR (upper) and 5.0+0.50*PR (lower). The greater bandwidth chosen for this goal as compared with the MT goal reflects the greater level of uncertainty of outcome, both level and timing. It is noteworthy that the upper band of the long-term goal lies relatively close to the lower band of the mid-term goal at just 5 percentage points apart.

The LT band is supported by TAPS 3, RR 2020 target, TAPS CFM and UEET. This band is considerably wider (+/-5%) due to the uncertainty caused by an additional 10 years, and the reduction in the number of supported efforts, estimates/targets, and committed funding for this time frame.

A significant contributory factor to the greater level of uncertainty over this longer time period is that, unlike the technologies required to meet the medium term goal, the technologies required to meet this LT goal are generally no further forward than the early phases of TRLs 1-3 e.g. GE TAPS3 is at TRL 2-3. It is thought likely that the technologies employed will be of lean burn types though Section 7.3 covers other possibilities as well. Technology down-selections have yet to be made from among the theoretical possibilities so at this stage it is not possible to have a high degree of certainty of either timing or level. The greater band width used in this case reflects this greater uncertainty. The Panel readily acknowledges that, in its efforts to fulfil the remit placed upon it, a high degree of judgement was exercised to arrive at this goal, but believes there is a 50% probability of achievement. As Section 6.6 described, the long term target for TAPS3 is 20 gm/kN, which puts it below our LT goal band. The RR 2020 target (20% of CAEP/2) is at the upper part of our LT goal band. Manufacturers presented RQL and lean burn concepts that could meet these goals at lower OPRs. Developments efforts are in the very early, high uncertainty, stage (pre TRL 3), but reflect goals consistent with the LTTG long-term goal view.

It is important to recognise that if the anticipated 20 year levels are achieved then combustor NOx performance will be getting close to the theoretical lower limit and at such a point continued successive reductions of the scale represented here cannot continue to be possible and indeed at such a point further NOx reductions would be likely to be approaching minimum practical levels. Long term environmental modelling will be needed to quantify the

[32] -65% +/- 2.5% below CAEP/4
-71% +/-2.5% below CAEP/2

consequences of this anticipated decline in the rate improvement of aircraft NOx and to inform future technology development pathways.

9.5.4 Uncertainty

The technology goals chosen do not come with a guarantee. The technologies required to meet these goals are not certain to be successfully developed within the two timeframes considered by the Review. Uncertainties exist both about achievement level and achievement date. Aspects of the required technologies are today at varying TRL levels, for example, TRL 5-6 for TALON X in the 10 yr timeframe and TRL 2-3 for TAPS3 in the next 20 years. Any one of a number of sub-scale technologies could fail to mature in time and therefore outcomes cannot be guaranteed, and during that time the environmental drivers might alter. The need to define the environmental context for goal-setting will be a continuing task. The uncertainties related to the 10 year mid-term technology goals are naturally of a lower order than for the longer time period, as the differences in TRL levels indicate and thus a narrower uncertainty band has been used. It is worth noting that, given the relatively rare introduction of new types, the entry into service (EIS) dates could slip by as much as 5 years outside the two timescales if a new generation of products has just been 'missed'. Sections 9.5.3.1 and 9.5.3.2 discuss some of the associated uncertainties.

The intention of the Panel was to avoid setting levels so severe they would be unlikely to be achieved nor so relaxed they would be likely to be easily exceeded. Thus the mid point of the chosen goal band of this first Review may be regarded as today's 50-percentile case, i.e. as likely to be achieved as not – challenging but not unrealistic. Future Reviews will need to consider whether the probability of successful achievement has increased or decreased depending on the rate of progress being made.

9.5.5 Use of Uncertainty Bands

In view of the uncertainties involved in setting the goals the Panel decided to make use of achievement bands rather than ICAO stringency-style lines. The width of the bands was used to illustrate the range of possible outcomes and thus the band width for the 20 year long-term goal is naturally wider than for the 10 year mid-term goal. The position of the 50 percentile (as likely to be achieved as not) may be taken to be at the middle of the band. The use of bands also emphasises the distinct differences between ICAO standards and technology goals.

The identification of this level of probability of achievement has been arrived at judgementally from Panel discussion of the variability of likely outcomes. No statistical analysis seemed sensibly possible to support this. The two band widths are +/- 2.5% of CAEP/6 (at OPR 30) for the MT Technology Goal (described at 9.5.3.1) and +/- 5% of CAEP/6 (at OPR 30) for the LT case (described at 9.5.2). The difference in the band widths illustrates the increased uncertainty over the longer timescale. The size of the widths themselves are conveniently rounded numbers though these are not totally arbitrary as the underlying process carried out to arrive at these was through a sharing amongst the Panel of views and judgements about the likely technology capability spread.

9.6 Metric

The Panel was asked to comment on the appropriateness of the current LTO-based metric for use in the scientific understanding of environmental impact. Currently the metric used in the setting of ICAO NOx standards is Dp/F_{oo}, defined as the mass of emissions per maximum certificated thrust, this parameter plotted against engine pressure ratio, for regulatory purposes with units of grams of NOx produced per kN of engine thrust. For the purposes of studying the impact of aircraft NOx on GCC the scientific community requires good estimation of the mass of NOx emitted and particularly in the cruise phase of flight. Currently, such information is provided by converting LTO-based certification data to an emissions index value (EI), whose units are simply grams NOx per kg fuel burned. This conversion is calculated using a number of methods, which have been shown to provide an accurate estimation of cruise mass NOx emitted. From the advice received, the Panel understands that for current combustor technologies these estimations are of sufficient accuracy for scientific model inputs. The Panel understands that these cruise emissions estimation methods are expected to remain sensibly viable for technologies expected to feature in the 10 year horizon. However, there is less certainty that this will remain the case for the different combustor technologies that might be introduced over the 20 year period and therefore the Panel recommends that this issue be kept under review.

9.7 In-Service Deterioration Rates

In answer to questions from the Panel current in service NOx performance deterioration rates were said to be between 3% and 6% before scheduled removals. When questioned whether these rates would be likely to change with the adoption of medium term technologies, a view presented suggested that the level of deterioration may rise significantly with a figure of up to 11% being mentioned for present engines, with no clarification as to whether this applied to would also apply to future products. This suggests there may be maintenance issues arising which will require consideration not least for the quantification of benefits from future combustor technologies and cruise EI values may need to reflect these greater in-service deterioration rates if thought to be significant, and the possible environmental benefits from less sensitive technologies might need to be re-examined when assessing emissions mitigation options.

9.8 Alternative Fuels

The question of alternative fuels is another area that the Panel believes will require an increased level of attention at future goal setting Reviews. This topic was included by the IEs to examine whether the use of alternative fuels might offer the prospect of significant reductions in NOx or other pollutants. This topic is discussed fully in Section 7.4. The Panel was advised that a semi-synthetic fuel, Sasol, which is a blend of petroleum derived and synthetic kerosene is in use today in South Africa. All engine manufacturers are pursuing efforts to qualify pure Sasol for operational use. Brazil demonstrated the use of biokerosene in aircraft in the 1980s and efforts are being reinvigorated. In fact, all of these fuels would be expected to have comparable NOx and CO_2 emissions. The Panel took the commonly held view that such fuels are unlikely to make a major impact in the medium term though their proportion would be expected to begin to rise, especially in the longer term. “Drop in” fuels that have similar properties to oil based kerosene were deemed most feasible; radical changes such as hydrogen and methane which could give significant NOx and CO_2 overall reductions (ie need to include production) were not viewed as practical even in 20 years. Economic factors also will need to be weighed against any potential benefits. However, ultimately, the use of alternative fuels in aviation may also be driven by energy security and independence considerations (since the Review we have learned that the U.S. Department of Defense has initiated a significant effort to advance the introduction of alternative fuels (i.e. synthetic fuels) for aviation use).

Alternative fuels may provide environmental benefits and could become an element of a total environmental strategy where the industry may be able to use alternative fuels to deal with some local air quality issues (e.g., PM), allowing manufacturers to focus engine design to reduce noise or other environmental issues such as NOx. Given expected traffic growth and growth in aviation fuel consumption, pressure on aircraft emissions cannot be assumed to diminish. The IEs felt that there is sufficient evidence to suggest that synthetic fuels could lead to reduced PM emissions. The overall environmental consequences of alternative aviation fuels will require study and advice from the scientific community. Environmental assessments should also consider the wider environmental questions relating to the production of alternative fuels (e.g., bio fuels or issues associated with carbon sequestration).

9.9 Affordability

There are two aspects to affordability that have been put to the Panel. First, whether the research monies will be available for the development of future NOx reduction technologies, and second, the affordability of these new technologies. In economic terms these questions are of course linked, to the extent the airline industry operates as most other markets where ultimately the customer pays.

With regards to research funding, evidence was presented which showed that successive combustor improvements over recent decades had their beginnings in publicly funded research projects. For the future the focus on combustor technologies is likely to continue in the area of the EU ‘Framework Research Programmes’. By contrast in the US NASA is ceasing its involvement on combustion technology development although it will continue its involvement with industry in R&T in the combustion area, though in this case there may be a shift towards focusing on improving predictive modelling tools. It was not clear how manufacturers would fill the research gap left by NASA.

Regarding airline affordability, it was put to the Panel that with the difficult economic circumstances faced by many airlines, it may be more difficult for the airline industry to afford (perhaps justify) new technologies. This assertion, at least in the context of NOx reduction technologies, was not put in detail to the Panel and remains an area of further investigation. In terms of any direct operating cost (DOC) delta the sums of money involved in combustion R&T were not considered to be significant when set against, for example, either the impact of recent fuel price hikes or simply the scale of passenger taxes now being levelled in several countries both of which amount to several $billion. This compares, for example, with the figure of $60m said to have been spent on R&D to develop TAPS technology since 1995. These findings ignore any possible impacts on fleet residual values or other economic factors. A detailed economic analysis of these arguments was outside the scope of this Review.

9.10 Small engines

Since CAEP 4 in 1998 a measure of "relief" has been given in the ICAO standards to 'small engines' between 26.9kN and 89kN of thrust (P19). The advice to the Panel was somewhat contradictory on this point, being told on the one hand that there were no specific additional factors that needed to be considered in relation to the adoption of new technologies in small engines in the medium term, but on the other hand also being told that some smaller engines may experience some difficulties with technology scaling. In the longer term this is likely to be something of an open question that will need to be carried forward to future reviews.

The Panel established goals on a pure "OPR basis". That is, the technologies, and projections thereof, were considered fundamental to OPR, and not limited by either the physical design space (small engines) or by inevitable, difficult growth paths within existing engine architectures (typically large engines). Relief from these influences was considered to be a stringency issue. This permits/encourages the design systems to seek these NOx goal levels and to "discover" the real limits, rather than limiting the original goal by anticipating "trouble". Again, we are setting goals, not stringencies. The panel believes that relief should come from stringency, not from goals.

9.11 Handling of Differences

The Panel was able to arrive at consensus views on all significant findings of this report. The Panel's views expressed in this report have benefited greatly from comments received from the industry-based Committee members (airlines and manufacturers) as well as from all other presenters and participants in the Review. The Panel is particularly grateful for the open and cooperative manner in which all industry representatives and other participants have approached this Review. The Panel is not aware of any remaining fundamental differences of view between the findings of the IE Panel and other participants though that is not to say that all suggested drafting changes were adopted. Where some more minor differences of view remain between the IE Panel and other participants, whether successful or not, the IE's intent was for the Report to fairly reflect in the text where a variety of views exists. In an effort to maintain openness of process, comment tracking documents were produced for both draft versions of the report and the IE's understanding is that both of these are to be made available on the CAEP website.

10. Conclusions

This section of the report is written as a series of short statements with discussion added only where it is required for clarity. The intention is to have already provided discussion of any particular conclusions primarily in Discussion Section 9 or in some cases elsewhere in the Report. These are the conclusions of the Independent Experts.

10.1 Process

1. The process developed to enable an evidence-based review to inform medium and long term technology goals appeared to the Panel to work well during this pilot Review. It was a significant challenge for the IEs to produce their report

in the time available. Only one follow-up face to face IE meeting was possible; a second later in the drafting process would have been very beneficial. For the benefit of all concerned future reviews should avoid later drafting stages during the summer holiday period. Secretariat support was provided and was essential. This facilitation provided by the LTTG Chair was helpful to the IEs and did not influence the setting of the goals. However, to totally demonstrate independence, it would be helpful in any future independent Review to provide a facilitator/secretariat from outside the LTTG and perhaps also CAEP.

2. It is accepted that this report is more extensive than some participants anticipated, however, it is the IEs view that the breadth was necessary for a first review of this kind and their expectation is that subsequent reviews will draw on this report to produce short update-style reports.

3. All contributors appeared to take a positive stance and provided a wealth of information for which the Panel is grateful. However, on this occasion it was not possible to consider all interdependencies.

4. Follow-up question and answer sessions were very valuable to the IEs. These sessions were closed in order to protect commercial sensitivities. There is a question remaining over whether these should be conducted in full open session, which was the industries' preferred method of discussion. Presentational material alone would not be expected to be sufficient for a successful review of this kind. The ability for the IEs to request later follow-up information was very useful and should form part of any future review.

5. Presentation material not being available ahead of time, and in some cases not even on the day, hampered the efficient working of the IEs and the formation of probing questions.

6. Consensus on the goals and on all major findings was reached among the IEs. Furthermore, the IE Panel is not aware there are remaining major areas of disagreement with other participants. Where more minor differences of view remain the report has sought fairly to indicate where these exist. Consultation at the draft stages was essential and participants remained engaged and cooperative throughout.

7. An early draft exchanged with industry representatives was a useful approach to ensure against inadvertent release of commercially sensitive information or judgements.

8. A pack of CAEP approved background information on industry trends and medium term and long term forecasts of aircraft mass emissions burdens would have been extremely helpful to the Review. Likewise a suite of analytical tools that could have been used to assess global trend curves and general interdependencies amongst emissions and between noise and emissions would have been a helpful aid to the efficient working of the Review and help answer "what if" questions.

9. Regional representation was limited, with representation limited to Europe and the US and the lack of participation from the fastest growing regions of the world was regretted and needs addressing for future reviews

10.2 Basis of goals setting:

10. "Environmental need" fell in to two parts, LAQ and GCC. In neither case was there evidence available to quantify the need for further aircraft NOx reductions, in terms of either ceiling mass levels not to be exceeded, or mass emission or concentration reductions needed to reduce environmental impact to an accepted (sustainable) level

11. Quantified environmental need notwithstanding, the Panel was convinced that in the context of both LAQ and GCC the scientific community considers aircraft NOx to rank highly against other aircraft pollutants as a contributor to adverse environmental effects and the Panel concluded that significant pressure for further reductions must be assumed for the future. Continuing research is needed to better establish the aircraft contribution and quantify the cost benefit of reductions.

12. In the area of LAQ the impending date for enactment of a European EC Directive, and the location of a significant number of U.S. airports in non-attainment areas for local air quality, must be assumed to keep the focus on aircraft NOx emissions around airports, as will 'hot spots' in other regions of the world. Forecast growth in aircraft emissions will add to this focus. However, trends associated with other key emission sources must be considered to provide a comprehensive context. Finally, significant uncertainties remain, particularly with PM and HAPs, that should be pursued with continuing research and included in future reviews.

13. With respect to GCC aircraft NOx emissions were thought to be close but second to CO_2 in terms of long term impact. The Panel noted that the choice of integration timeframe has a large effect on pollutant weightings, with 100+ years being appropriate for long term climate change pollutants. Policymakers may find it difficult to work with such long timeframes, however, the RFPs pointed out that 100 years is used for current trading policy for long-lived greenhouse gases. Further scientific understanding is required, particularly in regard to long term impacts of aircraft emissions, on GCC and relative to other sources. Significant uncertainties remain with PM, H_2O and cirrus that should be pursued with continuing research and included in future reviews.

14. Views within the Panel on the appropriate practical timeframe for studies of aviation mass emissions projections ranged from at least 20-30 years to 50 years or more. Helpfully, the longer time periods correspond with the longest term fleet scenario modelling experience, e.g. IPCC, though with increasing uncertainty with increasing time.

15. Given current knowledge no clear significant opportunities emerged for achieving lower NOx by trading off one pollutant against another, other than

possibly CO. With regard to CO_2 and NOx it was concluded that both needed to be minimised and it was recognised that reducing fuel burn also leads to a reduction in mass NOx emitted if achieved at the same overall pressure ratio.

16. Little noise tradeoff information was presented to the Independent Experts, which made fulfilling the terms of reference with respect to tradeoffs with noise difficult. Given that noise remains a major environmental driver, we believe that in the future it is important to consider all environmental impacts, including noise, when assessing technology goals and more information will be required at future review.

17. A watch would needs to be kept on progress in scientific understanding of the impact of aircraft emissions and in the long term the balance of advice on individual pollutants might change. Beyond the LT technology goal further NOx reductions may reach minimum practical levels.

18. Given the absence of quantified environmental need, but mindful of the assumed continuing pressure on aircraft NOx, the Panel resorted to considering goals judged against the expected leading edge of technology capability at the two given time periods.

19. The Panel was not asked to conduct a full economic assessment of the consequences of its chosen Technology goals. For the MT technology goal the Panel concluded that achieving the goal appeared affordable given that the required technologies were part of existing long term projects as long as research funding continued to be available. The relatively high uncertainty of the LT goals will make any economic assessment problematic.

10.3 MT Technology Goal (10 year):

20. As a result of past investments the engine industry is expected to deliver further reductions in NOx. Engines that are better than the 2008 CAEP/6 requirements have already been certificated.

21. There is considerable technology in the pipeline to support an expectation of substantial further NOx reduction, but the outcomes of the technology developments are uncertain. This uncertainty supports bands being used to describe the likely leading edge performance.

22. While there is considerable uncertainty about the impact of aircraft NOx and other pollutants the Panel accepts that currently the pressure to reduce NOx can not be assumed to diminish, but an environmental and practical balance would be prudent suggesting that NOx reductions should not be pursued at the expense of significantly worse fuel burn.

23. This Panel has positioned the MT technology goal at CAEP/6 minus 45% +/- 2.5% at a reference OPR of 30. The band width is relatively small indicating a reasonable degree of confidence of achievement. The surprisingly large difference between the most recent CAEP Standard (CAEP/6) and the MT

technology goal serves to emphasise the fundamental difference between a CAEP Standard which ‘banks’ in-service proven technologies across a wide variety of aircraft versus goals which seek to predict the position of leading edge technologies which do not exist today but would be expected to be ready for service at a given point in the future.

24. The relatively shallow slopes of the proposed goal bands were noted especially in comparison with historically much steeper development slopes. Also recognised was the absence of any kink at OPR 30. Small engines have issues with size and cost, and large engines with higher pressure and temperature conditions. However, the Panel concluded that its goals were achievable and that detailed discussion of these issues is a matter for the stringency debate rather than goal setting.

25. Alternative fuels are not expected to make a big impact in the MT goal time period, but given world energy pressures such developments should be monitored. Energy security and independence concerns may speed their adoption. These fuels are unlikely to impact NOx emissions, but could have a positive effect on PM emissions, which could open up the design space to address other environmental parameters, including NOx. They also pose challenges with regards to wider environmental consequences. Such considerations should lead the debate rather than lag.

10.4 LT Technology Goal (20 year):

26. Further significant reductions beyond the MT technology goal described above are potentially possible. Manufacturers have identified lean burn and RQL options that appear viable to reach long term goals but the Independent Experts judged these to require major changes in NOx control technologies. Manufacturers are at the early stages of identifying possible alternative technology routes, but these are not yet ready for down-selection.

27. The Panel has positioned the LT technology goal at CAEP/6 minus 60% +/- 5% at a reference OPR of 30. The greater band width as compared with the MT technology goal reflects the greater degree of uncertainty of outcome.

28. If achieved the NOx reductions represent a very large proportion of what is theoretically possible. Beyond this level further reductions may not be practical.

29. Long term scenarios of the fleet emissions burden highlight the slow fleet turnover and impact of new technologies. Despite individual perturbations traffic and fuel burn are expected to grow and environmental pressures are not expected to decline.

30. Possible alternative fuels are beginning to emerge (as MT technology goal above). In this longer time period, if viable, they would be expected to begin

making inroads. Any environmental benefits or otherwise, including related to their production, will be needed to inform any emissions trade off selections.

31. There is some concern in some quarters that changes to publicly funded research policies may result in less swift development of NOx control technologies than has been the experience of the last few decades. In broader economic terms, the scale of research and development funding required, when viewed as a proportion of total airline costs, is not thought to be significant in absolute terms.

11. Recommendations of the Panel of Independent Experts

The Independent Experts Panel recommends that:

1. The LTTG note that the Review process delivered MT and LT technology goals for NOx achieving a consensus amongst the independent experts.

2. The MT and LT technology goals contained in this report are commended to the LTTG as guidance for WG3 and CAEP. It should be noted that the predicted levels are not guaranteed and would benefit from periodic independent review. It is recommended this take place prior to the triennial CAEP meetings.

3. In the longer term the Environmental need for emissions reductions should be quantified. It is recommended that this be addressed at future Reviews.

4. LTTG note the Panel's conclusion that aircraft NOx emissions are ranked highly in importance against other aircraft pollutants in the contexts of both GCC and LAQ and that pressure for further reductions is not expected to diminish at least for the medium term.

5. That the quantification of tradeoffs be considered for future Reviews, though the Panel concluded that given the current level of scientific understanding little practical room for manoeuvre exists and one emission cannot presently practically be traded for another, with the possible exception of CO. Sufficient information was not made available to reach conclusions about trades with noise. This information should be considered in future reviews.

6. The LTTG takes particular note of the fundamentally different philosophies underlying technology goals and stringency of ICAO CAEP standards.

7. LTTG develops or gains access to consensus long term projections of emissions and noise burdens from the commercial fleet [of the kind described in Conclusion 14 so as] to better understand the impacts of reductions already in the pipeline and trends associated with technology and other changes within the industry with these projections made available to future Reviews.

8. LTTG continues study of the likely NOx/CO2 trade associated with future technologies and also of expected OPR trends particularly given expected impact of higher fuel prices.

9. A detailed economic appraisal be considered for future Reviews, working with FESG as appropriate.

10. LTTG consider analyses that might better inform the Review process and explore the availability of tools to support these analyses

11. LTTG raise with WG3, subject to ensuring any safety concerns are addressed, consideration of the possibility/desirability of reducing the altitude relight envelope from 9143m to 7620m (30,000 ft to 25,000 ft.)

12. LTTG monitor the accuracy of metrics and methods appropriate for estimating cruise mass NOx emissions from LTO data when applied to future combustor technologies

13. LTTG update information on the potential impact on NOx and other emissions of alternative carbon based and renewable fuels.

14. The present Committee structure comprising Independent Experts and industry representatives should be retained for future Reviews.

15. Consideration be given to redesigning the structure of the review such that all the presentations be made available to the IEs ahead of the review for them to meet and discuss the material and formulate probing questions. Following the presentations, there should be opportunities to reconvene with select presenters in an open forum if needed.

16. Participation at future Reviews of this kind should be expanded to include wider regional representation (e.g. Asia, southern hemisphere) also broader sectoral representation (e.g. airports).

17. Prior to future Reviews, consideration be given to the provision of agreed independent (of the LTTG process and possibly also CAEP) facilitation/secretariat support to aid preparation and conduct of the Review and production of Reports.

18. LTTG note that this report has sought to incorporate the views of all participants and that no fundamental differences of view are thought to remain. Where some differences remain, the intent was for these to be fairly indicated in the text. To maintain openness of process, two comprehensive tracking documents of received comments and their handling are to be made available on the CAEP website.

Appendix 1

List of Review Participants:

Name	**Affiliation**	**Representing**	**E-mail**	**Status**
Malcolm Ralph	Consultant	UK	malcolmralph@hotmail.com	Independent Expert
Lourdes Maurice	FAA	US	Lourdes.Maurice@faa.gov	Independent Expert
Ben T Zinn	Georgia Tech.	US	Ben.zinn@ae.gatech.edu	Independent Expert
John Tilston	Consultant (sole trader)	UK	jrandml@tiscali.co.uk	Independent Expert
Daniel E Webb	Consultant	US	nadbbew@aol.com	Independent Expert
Paul Kuentzmann	ONERA	France	paul.kuentzmann@onera.fr	Independent Expert
Dan Allyn	Boeing	ICCAIA	Daniel.m.allyn@boeing.com	Moderator / Observer
Peter Newton	DTI	UK	Peter.Newton@dti.gsi.gov.uk	Committee
Sebastien Remy	Airbus	ICCAIA	Sebastien.remy@airbus.com	Committee
Bengt-Olov Nas	SAS	IATA	Bengt-olov.nas@sas.se	Committee
Alain Joselzon	Airbus France	ICCAIA	Alain.joselzon@airbus.com	Moderator / Committee
Domingo Sepulveda	Pratt & Whitney	ICCAIA	Domingo.Sepulveda@pw.utc.com	Committee / Presenter
Matt Pfeifer	American Airlines	IATA	l.m.pfeifer@aa.com	Presenter
William Sowa	Pratt & Whitney	ICCAIA	William.sowa@pw.utc.com	Presenter / Observer
Betty L Hawkins	ATA	IATA	bhawkins@airlines.org	Observer
Peter Joyce	DTI	UK	Peter.joyce@dti.gsi.gov.uk	Facilitator
David H Lister	UK CAA	UK	Dave.lister@caa.srg.co.uk	WG3 Rapporteur
Willard Dodds	GE Aviation	ICCAIA	Willard.dodds@ae.ge.com	Presenter
Hukam Mongia	GE Aviation	ICCAIA	Hukam.mongia@ae.ge.com	Presenter
Claus Bruning	EU Commission DG Research	RFP	Claus.bruning@cec.eu.int	Presenter
Luis Acosta	Embraer	ICCAIA	Luis.Acosta@embraer.com.br	Observer
Martin Capstick	DfT	UK	Martin.Capstick@dft.gsi.gov.uk	Presenter

Gary Seng	ARL/NASA	US	Gary.seng@grc.nasa.gov	Presenter
Hans-Joerg Bauer	University Kahlsruhe	Germany	hans-joerg.bauer@its.uni-karlsruhe.de	Presenter
Valerie Jones	American Airlines	IATA	Valerie.jones@aa.com	Observer
Christophe Viguier	SNECMA	ICCAIA	Christophe.viguier@snecma.fr	Presenter
Rick Miake-Lye	Aerodyne Research	RFP	rick@aerodyne.com	Presenter
Olivier Penanhoat	SNECMA	EC, ICCAIA	Olivier.penanhoat@snecma.fr	Presenter
Paul Madden	Rolls Royce UK	ICCAIA	paul.madden@rolls-royce.com	Presenter
Steve Yates	Rolls Royce UK	ICCAIA	steve.yates@rolls-royce.com	Presenter
John Moran	Rolls Royce UK	ICCAIA	john.moran@rolls-royce.com	Presenter
Ralph von der Bank	Rolls Royce Germany	EC	Ralf.von_der_bank@rolls-royce.com	Presenter
Curtis Holsclaw	FAA	US	Curtis.Holsclaw@faa.gov	WG3 Deputy Rapporteur/ Presenter
Roger Gardner	Dept. for Transport	UK	Roger.gardner@dft.gsi.gov.uk	Presenter
Malcolm K Ko	NASA	RFP	Malcolm.k.ko@nasa.gov	Presenter
Randal McKinney	P&W	ICCAIA	Randal.mckinney@pw.utc.com	Presenter
Valerie Jones	AA	IATA	Valerie.Jones@aa.com	Observer
Ralf von der Bank	R-R Germany	EC	Ralf.von_der_Bank@Rolls-Royce.com	Presenter
Tim Johnson	AEF	ICSA	tim@aef.org.uk	Presenter
Stephen D'Gava	DTI	UK	Stephen.d'gava@dti.gsi.gov.uk	Facilitator
David Lee	MMU	UK	D.S.Lee@mmu.ac.uk	Presenter

Appendix 1a

CAEP/WG3/LTTG (Rio, Nov 2005)

Terms of Reference for the Independent Panel Members for the Technology Review

a. General:

The WG3 Long Term Technology Review Panel will comprise a Review Committee of nominated independent experts and designated members of airlines, airframe manufacturers, NGOs, regulators/air worthiness experts, and the scientific community represented by the RFPs. The review committee will be assisted by additional members drawn from representative trade associations and research establishments, two session moderators, provided by ICCAIA,

Industry presenters who will present the technical information for the review.

an airline specialist nominated by IATA, and CAEP RFPs and/or nominated representatives.

Major elements of the review will include:

a. Scientific understanding of climate effects
b. Understanding of aircraft engine emissions effects on local and regional air quality
c. Focus and progress in development of revolutionary technologies for the long term future (>20 years), and
d. Application of new technologies to future products in the middle term (the next 10 years).

b. Objectivity

Material relevant to middle term goals will be presented by expert technologists having detailed understanding of the principles and status of development of technologies that are hoped to be ready for commercialization within the next 10 years. The major manufacturing companies expect 3 to 4 people from each company to be present at the review who are either involved in the CAEP process or involved in the development of the technologies under review. In order to give a full description of the status of these technologies, it might be necessary to reveal proprietary information. In addition, material will be presented by representatives of research organisations and industry on the progress with longer-term research activities on emissions reductions.

c. **Function of the Review Team**

To provide CAEP with a consensus view of realistic medium term (10 year) and long term (20 year) NOx reduction goals.

d. **Format of the Review**:

Subject to Review Committee requirements, the format of the review will probably cover a science overview, a technology update and programme review, and a research programme review. The technology session will be open to all members of the review panel when technology developments of a non-proprietary nature are reviewed. Subsequent sessions, if necessary, will cover more detailed information and will be open only to expert reviewers cleared to review manufacturer proprietary data. All presentations will be summarised in a written statement for the Review report to ensure accuracy of reporting.

e. **Reviewers Expertise Required:**
The expert review team needs to be made up of independent technical experts with expertise in the following areas:

- Product Development
- Airworthiness
- Customer Requirements
- Technology Development and Transition
- Broad technical expert with experience several industries, including aviation

Candidates for the expert reviewers would be nominated and sponsored by stakeholders including CAEP, WG3, and LTTG members, subject to challenge by individual research establishments and manufacturers. Such sponsorship might necessitate short term funding for expert consultants.

f. **Independent Panel Documentation Requirements:**

a. to report on the status of technology developments for NO_x emissions reduction and control that will be brought to market within 10 years from the date of review, and the 20 year prospects for NO_x reductions suggested by research progress.

b. to assess the possibility of success, based on experience from past research and development programmes

c. to comment on the environmental tradeoffs resulting from such NOx reduction developments – both for emissions and noise

d. to comment on the appropriateness of LTO emissions of NOx as the primary technology focus, based on current scientific understanding of environmental impact of aircraft engine emissions.

e. to provide a balanced view of the state of emissions reduction technologies, and in a manner suitable for broad understanding

f. to report on the status of understanding of environmental impacts of aircraft engine emissions and identify areas where further research is needed to help focus ongoing and future technology development efforts

g. to draft a report on the review proceedings to WG3 regarding their assessments for NOx emissions reductions for the future, stated as improvements against the current regulatory limits (relative to CAEP/2, with reference to CAEP/4 and CAEP/6) for the medium term and in a metric appropriate for the long term as agreed by the review panel.

Appendix 1b

LTTG Terms of Reference

CAEP/WG3 LTTG has been addressing the remit from CAEP/6, recorded in the Appendix A to the CAEP/6 report on Agenda Item 4, para E.4.2, as follows:

- for the purposes of establishing long term technology goals for aircraft emissions reductions:

    a) implement a CAEP-approved process to set, periodically review and update technology goals and identify environmental benefits, taking into account progress in ongoing R&D efforts towards reducing aircraft emissions, environmental interdependencies and trade-offs, and scientific understanding of the effects of aircraft engine emissions;

    b) support and monitor development of methods for understanding the interrelationship of technology goals targeting individual emissions performance improvements: and

    c) develop the inputs appropriate for use of air quality and climate impact models to be used by CAEP to quantify the value of emissions reduction and to estimate the benefit from long term goals.

-- End --

Appendix 2

NASA TRL Scale

The following Figure has been taken from the presentation "Relationship Between the CAEP Goal-setting setting and Standard-setting Processes, Curtis Holsclaw, WG3 Deputy Rapporteur, WG3, March 20, 2006, offered to the LTTG Technology Review in London between 20-24 March 2006. The figure explains the TRL steps for technology status characterization.

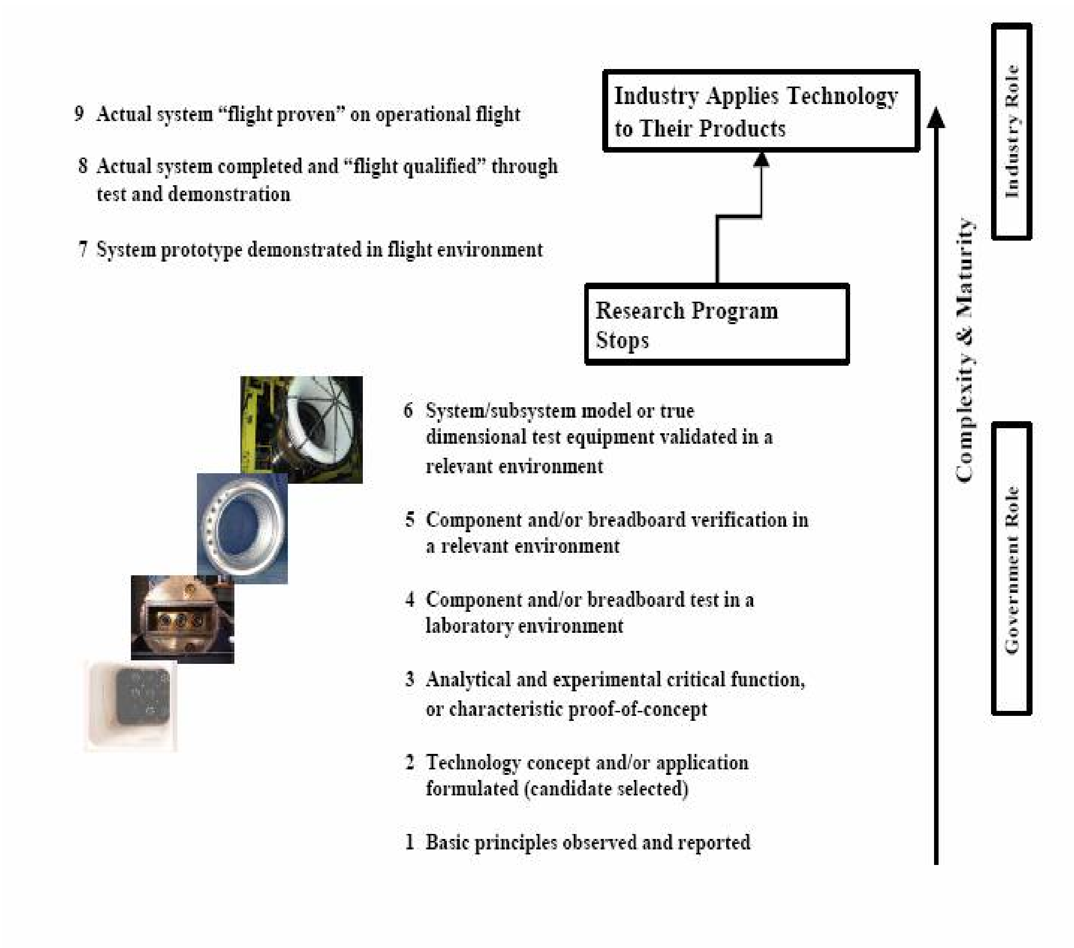


Figure 1. Technology readiness levels

Appendix 3
Notes from the LTTG Review 20-24 March, 2006

Monday – Wednesday 20-22 March

Introduction

The LTTG Review meeting was hosted by DTI in London during the week of 20 March, 2006. The attendees - listed in Appendix 1 - represented ICCAIA, IATA, NASA, FAA NGOs and the UK government, amongst others.

Beginning with the aims and objectives of the Review, this being to assess the prospects for NOx emissions reductions and to recommend NOx goals for CAEP, the meeting was also reminded of the CAEP remits for its activities. The remit required the Review to:

"for the purposes of establishing long term technology goals for aircraft emissions reductions:

i. implement a CAEP-approved process to set, periodically review and update technology goals and identify environmental benefits, taking into account progress in ongoing R&D efforts towards reducing aircraft emissions, environmental interdependencies and trade-offs, and scientific understanding of the effects of aircraft engine emissions;
ii. support and monitor development of methods for understanding the interrelationship of technology goals targeting individual emissions performance improvements: and
iii. develop the inputs appropriate for use of air quality and climate impact models to be used by CAEP to quantify the value of emissions reduction and to estimate the benefit from long term goals."

Additional advice from CAEP SG required an initial focus on the prospects for technological developments to reduce NOx emissions from aircraft. Goals were to characterize those technological developments in the form of mid- and long-term goals, 10 and 20-year timeframes respectively. It was also noted that there would be limits to the extent the remit could be discharged at this first Review and an appropriate metric would be required for the long term technology goal.

Information was presented to a committee comprising impartial experts (IEs), four representatives from industry trade associations, and the LTTG leader. The IE role was to provide an independent view on the extent to which technology and research programmes might developments might reduce NOx emissions in the future, and offer a consensus view on goal recommendation. It was agreed that Malcolm Ralph would take the chair on behalf of the impartial experts.

These Notes contain a summary of each presentation and related discussion at the LTTG Review meeting, prepared by the respective presenter. All presentations referred to in the following will be available from the CAEP web site, and will be issued to Review attendees on a CD.

Discussion during the introductory session ICCAIA raised a concern that the group might need to consider the "environmental need" for technology goals. The meeting was reminded about the specifics of the CAEP remit – these did not explicitly cover the "need" issue, although there was general recognition that this should be considered for any future goal-setting work, to the extent possible at the time. It was accepted that this first goal-setting exercise for CAEP would offer lessons for any future goal setting, and the "need" requirement should be considered in this regard. Claus Bruning from the EC suggested to the meeting that setting of goals is important in light of aviation's growth trend irrespective of an alternative "need" definition.

Scene-setting Presentations

Policy overview

Presented by Martin Capstick of the UK department for transport, the presentation informed the meeting about the pressures to which policymakers had to respond in providing an appropriate climate in which civil aviation can develop. The need to recognize and respond to the environmental problems that this important industry could create was at the forefront of policy development. The political necessity of providing a balance to permit the legitimate and proper growth of the industry while safeguarding the environment could be addressed through a range of measures. The need for a strategic vision for the future of air transport was vital, and the UK has developed a 30-year strategic view that is described in the DfT White Paper on Aviation in 2002. The strategy seeks to strike the right balance between aviation growth and environmental impact (noise and emissions) to reduce the negative effects from the industry's anticipated growth, but also needs to be flexible. However, the policy horizon of 30 years goes beyond the research goals that are underpinning technology developments within Europe and elsewhere. The international context means that the health of the industry must not be damaged or compromised. And one of the policy aims must be to create predictability for the aviation sector, as this will be in the best interests for all.

Technological developments had a significant role to play in the sustainability of the industry. Strategically based research is needed, and it needs to be funded appropriately, not least to maintain the momentum on the developments that will bring environmental improvements for this important industry for the future. Having a robust and clear view of the possibilities that technology might offer, especially over the long term, was enormously valuable to the policymaker and it was hoped that the outcome of this Review would provide that robust long-term view for CAEP and it member states. In conclusion, technology gains are essential for aviation growth and to meet CAEP objectives. The more technology delivers, the less pressure there will be on other market instruments that might need to be considered to address aviation's environmental problems.

The technology goals were welcomed as a means to inform the extent to which future technology developments might assist with environmental mitigation, and it was recognized that goals would need to be managed and would be non binding. Environmental standards would still be required for aviation in order to bank the gains that technology might offer and goals would need to be flexible and would need to be re-evaluated in the event it was found they were not able to respond to what may be a changing environmental need. However, caution on goal setting might result in caution in their application as inputs to environmental models. In this event, model results might suggest a greater need for other environmental mitigation options.

Environmental overview

Presented by Tim Johnson of ICSA, he reminded the meeting and that the role of the NGO was to highlight environmental issues, both local and global, and to encourage appropriate solutions. He informed the Review committee that the growth of the aviation industry represented a challenge to society. He noted that the goal review process will encourage innovation and examination of trade-offs, which is valuable since, without continued technological progress, either the environment or industry would suffer. However, less aviation is not the correct solution, and neither would “flying smarter” address all concerns, but it is important that this challenge is met. The environmental problem of local air quality is already posing difficulties regarding the means to achieve a third runway at London Heathrow, and this is yet another technology challenge, and a policy challenge within which technology developments in aviation must play a role. Tim commented that although difficult to be precise, an industry study suggested that emissions improvements such as CAEP4 -40% might be sufficient to permit a third runway. Aviation must exist as part of a sustainable society, and this means that the environmental externalities of the industry must be addressed. Many measures will be available for this, and the use of the precautionary principle should be adopted if policy-makers believe this represents a reasonable response. In addition the use of environmental regulations were considered appropriate by the NGOs, as well as market based options, the technology has an important role to play although technological developments must extend beyond control of NOx emissions. It was hoped that the setting of goals would provide important guidance for the CAEP process for the future.

During discussions industry noted that the ozone implications for aviation had a regional effect, the regulatory issue may well address local air quality concerns and were unlikely to be relaxed. The relative contribution of aviation emissions to the environmental problems of airports was still uncertain, but the challenge is recognized by the industry. The relative importance of NOx compared with CO2 was questioned in the context of climate change emissions: the industry commented that fuel cost was an adequate driver for CO2 reductions.

Goal relevance to stringency

Curtis Holsclaw of the FAA gave a brief presentation on the relationship between goal setting and the CAEP regulatory regime. During the discussions of the LTTG on the means to address and assess technology goals it had been recognized that goals might be confused with future emissions standards. In order to avoid any confusion in this regard it had been agreed that the NASA TRL scale should be used as the primary mechanism for judging the state of development of technologies that are considered as appropriate for setting technology goals and judging their achievement. The TRL scale would also be used to inform the transition from long-term to mid term goals. TRL1-7 was useful for long-term and mid term goals and TRL 8-9 for standard setting. He suggested that the forthcoming presentations might define at what level technologies are on the TRL scales. There was a comment regarding the issue of quantifying the "economic reasonableness" of long-term goals: Peter Newton noted that the demonstration of technologies is predicated on long term funding, but the assessment of both economic reasonableness and environmental benefit might need to be pursued once goals had been established.

Science overview

A Scientific Review of the latest understanding of the effects of aircraft emissions on the atmosphere for both local air quality and global climate change was presented by Malcolm Ko, Rick Miake-Lye, Claus Brüning, and David Lee. The presentations described the chemical effects of emissions on the atmosphere, and reviewed the results from the latest research activities into the environmental impact of aircraft emissions.

The report identified the impact on human health as the primary environmental drivers for controlling local air equality emissions. The impacts related to those emissions affecting global climate change were less easy to quantify and less certain to define (temperature, sea-level rise, resources, economics) but it was noted that these effects were becoming increasingly recognized as important over the past decade. The report also highlighted a number of uncertainties regarding the effects of aircraft emissions and noted that some of these were still poorly understood such as the impact of aviation on cirrus clouds. However, the need to ensure that both the technological and environmental tradeoffs were addressed correctly for the long-term development of the industry was paramount.

Malcolm Ko noted the emissions that were of concern in the environmental context of aviation, and reminded the meeting of the tradeoff relationships that existed between them. He explained the difficulties in devising an appropriate environmental metric that captured both the immediate effect of the emissions, and their timescale. He also suggested that in formulating any aviation environmental policy it would be necessary to ensure that aviation emissions were put in context with the emissions from other industrial sources.

David Lee described the work within Europe to quantify the radiative forcing effects of aviation's emissions, in the context of climate change. Recent studies had revised the values that were reported in the IPCC report. In terms of the atmospheric effects of aviation emissions he concluded that the amount of NOx produced is an important parameter: globally, more NOx resulted in more ozone and therefore forcing. Again, aviation NOx needs to be put in context with NOx created from other sources. He reported that the estimates of NOx created by lighting, a major natural source, had been reduced from the results of the EU TROCCINOX study and that NOx impacts from aviation could be of the same order of magnitude.

Rick Miake-Lye reported on the local air quality effects of aviation emissions. His presentation noted the difficulty in measuring volatile particulates, as these developed downstream within the exhaust plume and were undetectable at the high temperatures of the engine exit plane. Since volatile particles are formed as the exhaust mixes with ambient air in the plume, a compounding difficulty is that different regions, having different climates, may result in different volatile particle emissions from aircraft. This may cause difficulty in devising a standard means to assess the effects of aircraft particle emissions on local air quality. A comment from industry questioned the significance of the local air quality primary concern within the U.S. being ozone, and in the European Union being nitrogen dioxide.

Claus Brüning described the science research activities within the European Union and the priorities being given within the different framework programs. Some of the work under FP7 would focus on the atmospheric compositional change including NOx emissions and on the impact on climate from cirrus and contrails resulting from aircraft activity.

Note: Roger Gardner, UK DfT, presented additional information on the environmental pressures from aviation's perceived effect on Local Air Quality later in the meeting.

Aviation industry perspective

Matt Pfeifer of American Airlines gave a presentation on behalf of IATA concerning airline fleet planning practices. It is important for the Committee to understand these practices because they form the economic context within which new low-emissions technology is incorporated into the in-service fleet, thereby improving overall environmental performance of that fleet.

Fleet planning principles proceed from the fact that aircraft (here defined to include both airframe and engine) are costly assets with a long useful life of 30 to 45+ years. Aircraft must be financed, and financing entities require that assets retain their value throughout their useful life. Specifically, airlines look for aircraft that have operating costs competitive with substitutable aircraft, do not require large mid-life investments and will retain their marketability worldwide.

Airline fleet planning practices are designed to minimize costs in a highly competitive environment where near-100 percent operational reliability is essential. Airlines want technology to be proven and robust before introducing it into service, and therefore are wary of newly-developed technologies. They avoid technology that will not be as long-lived as the aircraft and/or has a high initial price. They simplify their fleets as much as possible, seeking commonality of aircraft types and interchangeability of components, to minimize costs associated with varied fleets.

The life-cycle economics of a fleet involves a balance of three major cost categories. Fuel efficiency has long been the primary cost factor. This is now particularly true given current and predicted high fuel prices. Price increases raised airlines' fuel costs from US$ 61 billion in 2004 to US$ 92 billion in 2005.

Airlines favour technology that produces lower fuel burn, balancing fuel efficiency with an acceptable initial price and predictable, low maintenance costs.

Choices of aircraft type are a fleet planner's most significant and risky decisions, and in practice airlines make very few such decisions. Since equipment is long-lived, airlines have few opportunities in their long-term fleet turnover schedules to introduce newly developed aircraft types.

Environmental considerations play a part in fleet planning decisions. Airlines prefer to acquire aircraft types that provide a comfortable margin to current ICAO emission standards relating to local air quality (e.g., NOx). Although aircraft that do not meet current standards may still be operated, such aircraft have limited marketability and do not retain value. Airlines also look for a comfortable margin to current CAEP noise standards, in some cases with attention to requirements in their key markets. Airlines are concerned, however, that these few local restrictions may drive design standards away from the world's consensus view of the balance between local air quality, noise and CO2 emissions. For example, adapting the A380 to meet Heathrow QC2 requirements cost at least 0.5 percent in fuel efficiency, which means that a world-wide fleet of A380s would burn 15 million gallons more per year. CO2 emissions, which correspond directly to fuel burn, are not an independent concern, since airlines already select aircraft for fuel efficiency and have strong economic motivation to minimize fuel consumption. Technology that reduces both NOx and CO2, e.g., weight reduction, is viewed favourably. As demonstrated in the goal review, NOx reduction technology has developed significantly, and airlines would prefer to see further improvement in fuel efficiency while retaining these NOx improvements.

The effect of current or proposed market-based measures must be viewed with reference to the economics of fleet planning. The local air quality charges imposed by some States on NOx emissions have not affected fleet planning decisions of the airlines serving those locations or their decisions concerning aircraft to serve those markets (<u>See</u> IATA Survey on airline response to Local Air Quality emissions charges at Stockholm Arlanda and Zürich airports, FESG, Montreal 21 February 2006). Airlines factor such local charges into their economic assessments of the market in question; on economically marginal routes, charges can affect airlines' decisions to reduce or withdraw service from the market in question. Potential measures addressing greenhouse gases remain under ICAO review, and have not been implemented. Airlines already have intense economic motivation to conserve fuel, and use fuel efficiency as the primary factor in future fleet planning decisions. To the extent that airlines bear costs of GHG charges and/or carbon credits under an emissions trading system, their ability to invest in newer, more fuel-efficient technology may be constrained. It will usually be impractical for airlines to seek to avoid such charges by simply accelerating substitution of more fuel-efficient new aircraft types, given the limited opportunity to introduce new types and the expense of such investments.

Airlines see value in a regular CAEP goal review process, separate from the standard setting process. Goal review can provide a "feedback loop" for exchange of technical information among manufacturers and research institutions, which will enhance the consideration of environmental factors in technology development. Goal review will also constructively inform standard setting by enabling CAEP to decide when to begin consideration of future stringency measures based on the demonstrated status of developing technology. The airlines hope that goal review will facilitate the development of consistent, long-term guidance on the relative priority between local air quality, climate issues and noise, thus providing the predictable conditions that airlines need to manage their long-lived assets. The current lack of consistency adds uncertainty to airline fleet decision making.

Academic view on emissions reduction technologies

Hans-Joerg Bauer offered an independent view on the theoretical limits to emissions reductions for a range of different current and future combustion systems. His presentation can be summarized as follows:

Combustors need to comply with many requirements besides the demand for low emissions and within emissions NOx is not the only species which needs to be considered. But in order to assess potential technologies to achieve mid term and long-term NOx reduction targets other requirements need to be taken into account in appropriate manner. Other requirements comprise safe operability as ensured by compliance with all certification parameters for an aircraft engine.

For the future, trends towards higher bypass ratio engines for increased propulsive efficiency and lower noise can be expected and would imply richer cycles and hence higher turbine inlet temperatures. The increase of combustor pressure and turbine inlet temperatures generally leads to higher NO formation rates. In order to reduce NO formation stoichiometric conditions have to be avoided and/or residence times to be reduced.

In addressing the requirements for Midterm goals he described the advantages and limitations of the Rich Burn, Quick Quench, Lean Burn principle and Lean Direct Ignition. NOx reduction potential of between 30% and 40% CAEP2 should be feasible from these technologies. Water injection - used in the past to increase engine thrust – could also be used for NOx reduction purposes and this technology was described.

For the Long term goals lean premixed pre-vapourised concepts [LPP] were described and the prospect for very low NOx emissions reductions could result should the technology be developed successfully. This has been successfully demonstrated on a laboratory scale for operational conditions for responding to present mid- size and large size turbofan engines. However, there are many technological problems to solve with these concepts, although if successful and emissions reduction potential in NOx to greater than 20% of CAEP2 is estimated. However, CO and HC emissions are likely to be higher than present values. FLOX and catalytic combustion concepts were also covered, as were alternative fuels. Finally, the potential of the inter-cooled recuperative cycles were described, and their complexities for the aero gas turbine.

Research Presentations – Long Term Technologies

NASA

Gary Seng presented a report on NASA's past R&T in combustors/engines and emissions reduction. It gave an insight into NASA aeronautics' current efforts to re-shape itself and provide a pre-decisional view of the content that would be relevant to LTTG. In summary, the report presented the results of NASA's research programmes since the 1970s - ECCP, EEE, HSR, AST and UEET – and their success in developing low NOx combustors that, as derivative combustion systems, successfully entered service.

More recently, in 2000, NASA initiated its fourth major engine technology development effort, the Ultra-Efficient Engine Program. In this Program, NASA continued working with industry to develop technology and reduce risk for fuel-efficient engines and low emission combustors aimed at large and regional engines. The goals were:

- Propulsion technologies to enable increases in system efficiency and, therefore, fuel burn reductions of up to 15 % (equivalent reductions in CO2)
- Combustor technologies (configuration and materials) which will enable reductions in Landing/Takeoff NOx of 70% relative to 1996 ICAO standards.
- Emission levels of aerosols and particulates coming from low emission combustors will be assessed and reduced if possible.
- Improve and validate the combustor design codes to reduce the design and development cycle time by 50 percent for low emission combustors.

UEET as a formal program was ended in 2005, prior to the completion of all the planned work. A few final technology development efforts are still being completed, for example NASA continues to work with Pratt and Whitney to complete the technology development for the TALON X full annular combustor through engine testing (TRL 6), to further establish the operability and viability. This is a rich quick-quench lean burning (RQL) combustor concept for both low emissions, stable combustion with good operability. General Electric Aircraft Engines' Twin Annular Premixing Swirler (TAPS) combustion concept, a lean premixed (LPP) combustor, has successfully completed sector testing (TRL 4) and will be brought into commercial engine service when the GENX engine is introduced on Boeing's 787 aircraft. Rolls-Royce North America developed through successful sector testing (TRL 4), a lean burning combustion concept that may be introduced in their AE 3007 regional engine family.

Based on the progress in work sponsored by UEET, NASA is continuing campaigns to assess and understand emission levels of particles and particle precursors emitted from engines in commercial service, as well as low emission combustors. Particle/precursor projects were initiated in 2004 with the Aircraft Particle Emissions eXperiment (APEX) series. The focus of all of these experiments/studies is to understand particle evolution with the data collected being:

- Particle number, size, mass, composition
- Probe location – at engine exit plane, engine exit to downstream
- Fuel properties – sulphur, aromatic
- Engine - type, performance, ambient conditions
- Sampling system – probe, line

NASA is now a re-shaping its Aeronautics Programs to assess long-term research needs and goals and establish technical roadmaps to accomplish these goals. For WG3-LTTG, the relevant research areas are Subsonics Fixed Wing (SFW) and Supersonics in the Fundamental Aeronautics Program (the remaining thrusts are Subsonics Rotary Wing and Hypersonics). In responding to WG3-LTTG for priorities within the relevant SFW and Supersonics thrusts, the following list of research areas are pre-decisional, since the proposal process is not complete. Key technologies/tools that will aid in the advancement of low emissions combustion technology are listed below:

- Increase the predictive accuracy, relative to current SOA combustion CFD with "no tuning", of the emissions indices and combustor performance metrics

- Develop fundamental databases on emissions production using advanced diagnostics to provide accurate, non-intrusive measurement at realistic operating conditions

- Conduct particulates research in sampling methodology development and validation, emissions database development and particle transport and transformation model development and validation. Perform experiments that elucidate soot inception and growth as functions of combustor design/operation and fuel type

- Investigate low cost, MEMS-based fuel-air injectors with high speed, micro-actuators embedded in the assembly

- Develop quantitative high accuracy chemical kinetic mechanisms for alternative and current hydrocarbon fuels

In responding to WG3-LTTG request for targets, the assessment is less clear yet, and the following are described as "notional":

- Progress in the projects will be measured through a well-structured set of milestones beginning at level 1 and integrating sets to achieve successive levels, culminating in level 4 multi-disciplinary analysis and optimization milestones.

- Notional targets will be for example, improving the prediction accuracy of a model predicting emission species by xx%, or the ability to predict species to +/- YY%. Included in the prediction will be: CO, NOx, unburned HC, SO_2, as well as particle and precursor growth and size distribution.

- Diagnostic instrumentation will be improved to more accurately temporally and spatially measure species, velocity, temperature, pressure, particle sizes and distribution.

European Research Programmes – ELECT

Ralf von der Bank (R-R) described the ELECT research programme being pursued in Europe. He explained that European partners are pooling their resources to develop commercially viable environmentally friendly combustion systems and ELECT-AE is bringing together engine manufacturers, research establishments and Europe's leading universities in the field. There is a clear vision and forecast of environmental needs. The ambitious ACARE targets, especially the demand for 80% reduction of NOx emissions from aviation, require very well focused and balanced pre-competitive research and development initiatives for the future. This will prepare technology for the successful implementation of the ACARE goals.

ELECT-AE's first Workshop was targeting the identification of medium and long-term research requirements to pro-actively support the ACARE target of 80% reduction of NOx emissions. This workshop was carried out on 8 and 9 March 2006 near Paris (Bois du Lys). The fields of Combustion Technology, CFD Methods & Design Methodology, Diagnostics & Test Rigs, Design Life Prediction and Fuels were addressed. Results will be reported to ACARE and ICAO's task group on long-term technology goals.

The workshop agreed that lean-burn technology is essential to achieve the low NOx targets and that it has to be driven towards higher technology readiness levels and application in aero-engine gas turbines. One main result of the workshop was that the development of lean combustion systems, featuring lean injection systems and single-annular combustor architecture, has to be intensified. Optimization of rich-burn style combustion equipment is regarded as being competitive and therefore related to product development.

Design methodologies and rules for lean combustion systems (single annular combustors) and lean injection systems focusing on operability and emission performance are urgently required. Advanced models for the prediction of fuel atomization, cooling technologies and thermo-acoustics have to be developed. Design tools, which integrate the various design aspects, have to comprise so-called multi-physics incorporating heat–transfer and coupling with thermo-acoustics. This research and development has to be supported by enabling new theoretical and experimental methods. The fundamental knowledge base and the understanding of processes concerning fuel-air mixture preparation (fuel film / droplet break-up), particulate matter formation (soot) and pressure oscillations driven by combustion instability have to be improved. Design life prediction methods have to be integrated with tools that predict the combusting fluid flows.

The existing diagnostics and test rigs have to enhance test capability at realistic engine operation conditions. Optical access is a main issue for large scale testing of combustion devices and the application of advanced LASER techniques. Simultaneous multi-parameter measurements and the development of new techniques to explore optically dense regions of sprays must have high priority.

Fuels could play an important part in reducing emissions but needs co-ordination with the global industries. In this field safety of supply and production costs are regarded as the decisive drivers. Here, so-called Fischer-Tropsch synthetic kerosene, which can be produced from natural gas, coal and biomass, and blends thereof with conventional Jet-A1 kerosene are in the focus of interest. Assessment of their combustion and emission performance should be initiated.

SNECMA – European Research Activities

Long term - European activities - ACARE / CLEAN / VITAL: Olivier Penanhoat presented the results of the European research activities on emissions reduction technologies. The European long term research & technology developments respond to "**ACARE** Goals" for CO2, NOx and Noise emissions. ACARE is the Advisory Council for Aeronautics Research in Europe and was created after the report "European Aeronautics: a Vision for 2020" was issued in January 2001. This document proposed, among others, the following ambitious Environmental Challenge for air transport: a reduction of perceived noise to one half of current average levels; a 50% cut in CO2 emissions per passenger kilometre (which means a 50% cut in fuel consumption in new aircraft in service in 2020); an 80% cut in nitrogen oxides emissions. ACARE's first Strategic Research Agenda "SRA1" was issued in October 2002, and "SRA2" was issued in October 2004. SRA1 provided clarification and more details on the previous goals. In particular, the three previous goals on Noise, CO2 and NOx, concern the technology of Aircrafts and Engines as well as ATM and refer to the 2020 entry into service (EIS) level compared to that of 2000.

Focusing on NOx, Vision 2020 80% cut is to be considered in term of total mass emitted either during LTO cycle (for Air Quality) or during the whole mission (for Climate Change). Combined with the fuel consumption reduction goal, it is estimated at the engine level, that the average cruise emission index should be reduced by 50% and that the LTO NOx D_P/F00 parameter should be reduced by 60% to 80% depending on the aircraft take-off weight reduction from the 50% fuel burn reduction.

The **CLEAN** project illustrates one important European programme contributing to low NOx combustor technology development, in order to meet ACARE goals. This project was initiated in 2000 and completed in 2005. It involved main European partners in aeronautics. A double annular combustor with Lean Premixed Prevaporized (LPP) injection system on the main dome was the solution explored. Following full annular combustor and core tests, the results demonstrated a 45% NOx margin to CAEP2 at TRL5 and around 62% margin to CAEP2 at TRL3.

The **VITAL** project, initiated in 2005, is a major European on-going engine program not directly concerned by combustor technology, but more dedicated to delivering low pressure technology (with assessment of new engine architectures) in order to reduce noise (by 6dB) and CO_2 (or fuel burn) by 7%. This fuel burn improvement would contribute also to total NOx reduction. Therefore, VITAL will be a step towards ACARE CO_2 and NOx goals.

Manufacturer's Reflection on Research and on goal metrics

Some initial comments from ICCAIA representatives advised that should goals be determined they must offer tangible environmental benefits to justify government and industry investment in technology development. The goals would only be achieved in the event there was stable and appropriate funding, and goals must be "meaningful", i.e. they must reflect need and achievability. The "need" element should also reflect the proportionality of the problem: data from a U.S. EPA study of ten large airports in the U.S. indicates that

Commercial aircraft were responsible for less than 1% of regional NOx in 1990, and are forecast to be about 2% in 2010. Can aircraft emissions reductions significantly reduce this problem?

Total regional NOx was forecast to decrease about 50% between 1990 and 2010. If emissions continue to decrease, will there still be a local air quality problem in 25 years when the long-term technologies go into service?

Data from an ICAO Forecasting and Economic Support Group study of costs and benefits of CAEP/6 NOx stringency options also indicated that aircraft NOx reductions are expensive (at least $20,000/tonne) compared to costs to reduce NOx from other sources. However, during the discussion, it was pointed out that the study did not take credit for reduced NOx at altitude, so a somewhat higher cost might be justified.

On goal metric there was some discussion given to the appropriate metric for long-term technology goals. The general view from industry proposed that Dp/Foo addressed not only the local impacts of aviation emissions, but also provided a reasonable proxy for emissions performance during cruise. However, others felt this relationship may not apply to future technologies, and given the long-term nature of goal-setting this might be important. But simplicity would be key, and in the absence of other metrics Dp/Foo should be acceptable. Some participants noted that the use of EI, or mass of NOx, might address not only NOx emissions but also fuel burn [CO2] and a metric with this component would capture the tradeoff between these emissions, as Dp/Foo does not. It was noted that certification was unlikely to apply to total emissions mass and there was general agreement that there is not yet any sufficiently mature alternative to using Dp/Foo for the long-term goal metric.

Manufacturer's Presentations

Combustion Technology Fundamentals

Randall McKinney, P&W, gave a presentation on the basics of combustion system design and performance. Gas Turbine Combustors must satisfy a wide range of requirements imposed upon them by the engine system, such as stability, durability, exit temperature quality, altitude relight and starting, emissions, and flight safety. The relationship of these requirements is complex, leading to an iterative design and development process to optimize a design that satisfies the customer. This presentation described the configuration of modern combustors, fundamentals of emissions formation processes, the relationship between different emissions, and the interrelationship of emissions formation with the other requirements the combustor must meet. This presentation also described the operation of staged combustor configurations, discussed some of the challenges faced by future designs, and introduced the increasing capability of manufacturers to analytically model combustor performance.

Tradeoffs - ICCAIA presentation

Environmental trade-offs in engine and aircraft design are one of many trade-offs that the engineer needs to consider when designing new products, and were described by Paul Madden. All the trade-offs can change depending on aircraft and engine size and mission requirement, and we should always remember that the engine hangs off the airframe wing in case there are multiplier affects (e.g. engine weight increase also increases pylon and wing weight). The focus of this Long Term Technology Review is NO_x emissions, and the environmental trade-offs for NOx are mainly driven by the engine cycle and the combustor design.

The best-known engine cycle design trade-off is between NOx and CO_2 driven by the engineers' choice of engine pressure ratio. Higher engine pressure ratios drive higher combustion temperatures and pressures, increasing the amount of NOx emissions produced as NOx is formed at high temperature conditions. These same higher temperatures reduce CO2 as the engine cycle becomes more efficient. The growth in engine pressure ratio has now slowed down due to material limitations so the trade-off may not be as great in the future.

Engine bypass ratio (BPR) also has a complicated effect on noise, NOx and CO2. Higher bypass ratio helps CO2 and noise until the physical size of the engine drags too much at cruise forward speed conditions. Higher BPR engines may require higher engine pressure ratio such that the core has sufficient energy to drive the big fan so there maybe an increase in NOx. It is possible to produce carpet plots of NOx, noise and CO2 with controlling parameters of fan pressure ratio (closely related to BPR) and engine pressure ratio. Such plots are useful to consider cycle trade-offs and are now part of the Environmental Design Space development sponsored by the FAA.

The other important environmental trade-offs are driven by the choice of combustion design. Rich burn combustors typically trade NOx with smoke and have low CO and HC. Lean burn combustors typically trade NOx with CO and to a lesser extent HC but have low smoke. Another important trade in combustion design is combustor volume trades CO/HC with NOx but the sizing is mainly dictated by altitude starting requirements. Any staged combustion system is likely to weigh more than an un-staged system so there will be some trade with CO2. The cooling air budget of the combustor is important and if cooling air can be saved emissions can be reduced as the air becomes available for mixing.

In summary research establishments and manufacturers are pursuing technologies with acceptable environmental trade-offs.

Low Emission Combustor Technology Transition

The ICCAIA presentation from Will Dodds on Low Emission Combustor Technology Transition described the current technology development and product transition process (using staged low emission combustors as an example). This started with a discussion of the multiple and sometimes conflicting requirements the combustor must meet to provide reliable, stable operation of the combustor with acceptable durability at the extreme operating conditions of modern engines. At the same time, the combustor must also be able to restart the engine should it be necessary at high altitude, and be designed for low emissions. Next, potential barriers to technology transition were discussed, including high development and certification costs and long development cycles for aircraft components, uncertain environmental benefits and tradeoffs, and effects of low production volume were discussed.

A case study covering the development of the staged low emissions combustor was described to illustrate these points. It took more than 20 years and four major research and development programs sponsored by government research agencies, military and industry to go from initial definition of the combustor concept to entry into commercial service. Although the research establishments sponsored programs taking the technology to engine test (TRL6) in two engines, it was estimated that the research establishment expenditure was less than 15% of the total investment in the specific combustor concept being considered.

The initial research goal was also compared to the actual results. The initial goal was to reduce NOx by 80% over a period of approximately 6 years. What was actually achieved was a reduction of about 40% over 20 years.

Lessons learned from this example are that:

- The technology transition process, is complex and expensive, and may not progress in a predictable fashion
- Commitment of a new technology to product requires a solid technology foundation (complete TRL 6 demonstration), understanding of environmental benefits and tradeoffs, a clear customer need, and enabling technologies (e.g. digital control and fuel nozzle protection technologies)
- Initial research goals tend to overestimate benefits because the environmental benefit relative to evolving current technologies tends to decrease with time and the time required to complete product transition tends to exceed initial estimates
- Technology transition is not complete at certification (TRL8). Product upgrades continue to cover more engine models and improve combustor performance after TRL8.

Recent Low Emissions Combustor Introductions

Summary of Recent Certification: Dan Allyn - Moderator

A summary of recent engines certification data, from General Electric, Pratt & Whitney, and Rolls-Royce, for that have been certified with new, advanced combustors shows several key items.

- All engine companies' recent combustor technologies result in similar NOx certification levels.
- All recently certified engines meet CAEP/6 NOx standard, well ahead of the CAEP/6 effectivity date of 1 January 2008.
- CAEP/6 NOx standard is working to encourage continued NOx reductions.

Pratt & Whitney – Dom Sepulveda

Engine manufacturers, cognizant of aviation's growing impact on the environment, continue to develop and introduce into service cleaner and more fuel-efficient engines. It must be understood that technology development and introduction of products into revenue service is heavily influenced by customer pull. To address this environmental concern, Pratt & Whitney has continued aggressive development of the TALON family of combustors that employ advances in RQL technology.

Since 2000 P&W has introduced the TALON II combustors into the PW4158 engine on the Airbus A300/A310, the PW4168 engine on the A330 and the PW6000 engine on the A318. These combustors offer NOx margins of 15 to 28% relative to CAEP/6 while maintaining low levels of CO, HC and smoke.

Rolls-Royce -

Rolls-Royce has certificated their best-practice rich burn combustion system over all the in-production engines including smaller engines such as the BR700 and AE3007. The latest Rolls-Royce engine the Trent 900 incorporates all the best-practice rich burn combustion features such as optimised tiled cooling air, chutes on the mixing holes, and optimised combustion volume. The emissions have certificated at around 40% below the CAEP/2 NOx limit. Rolls-Royce reports externally on emissions and has a target of 50% below the CAEP/2 NOx limit for 2010. Both the Trent 500 and Trent 900 combustor NOx emissions came close to the predictions made when the RR external environment report was first produced.

GE

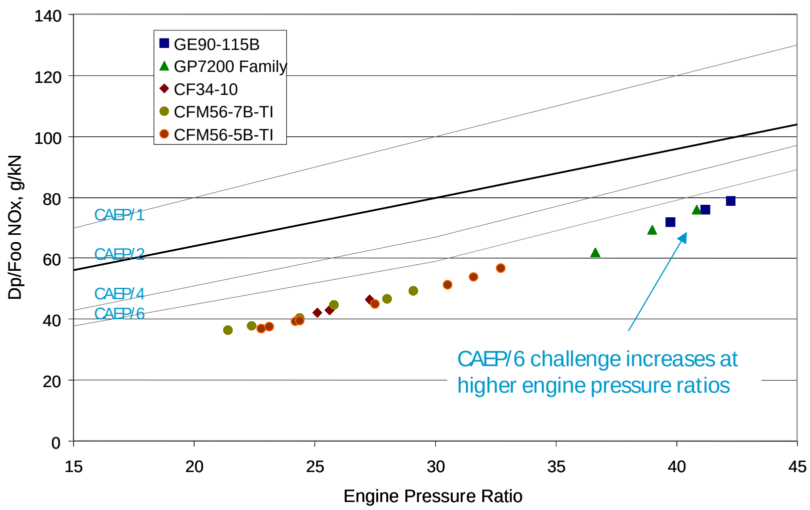
For existing production engines, GE periodically updates engines to maintain state of the art durability, performance and emissions. These updates focus on customer needs for continuous reductions in operating cost and maintaining environmental compliance. To simplify the process, combustor changes are typically introduced as "block" changes that incorporate multiple technologies. When possible, new components are made to be interchangeable with the components they replace in order to minimize spares. For new products mature and cost effective technologies are selected to provide margin to current and estimated near term standards.

Results reported here are based on single certification tests of recent engines produced by General Electric Aviation, CFM International and the Engine Alliance having combustors designed by GE. All results were expressed a single engine characteristic levels, although final results submitted to the ICAO data bank might include additional test results in come cases. Six engine families were discussed, including the CF34-10 (Embraer 190 series aircraft), CFM56-7B/P Technology Insertion (Boeing 737 family), CFM56-5B/P Technology Insertion (Airbus A320 family), CFM56-5C/P (Airbus A340-200/300), GP7200 (Airbus

A380) and GE90-115B (Boeing 777) engine families. Of these engine families, the CF34-10, GP7200 and GE90-115B are new engines or significant derivatives. All of the CFM engines are performance upgrades of current engines. These engines span the thrust range from 75 to 514 kN and engine pressure ratios from 21 to 42. It is expected that all final certification results will be submitted to the ICAO Emissions Data Bank by the time of the CAEP/7 meeting.

Except for the CFM56-5C/P, all of the engine families described apply optimized RQL combustor NOx reduction technology. This is a basic rich-dome configuration with combustor volume selected to balance NOx emissions and starting capability, advanced cooling features to preserve air for emissions control, advanced fuel air mixing features enables richer mixtures with low smoke and combustor dilution location selected to minimize NOx formation time at high temperature.

A summary of results is shown in the figure below. In all cases using optimized RQL combustor technology, NOx emissions were reduced 10 to 20 % relative to previous similar engines, and met the CAEP/6 requirement. For the CFM56-7B, CO and smoke increased, but the increase was in the range of measurement uncertainty. This plot shows that the CAEP/6 limit is a reasonable control over a wide range of engine types, and that the challenge in meeting the standard increases for higher pressure-ratio engines.



Mid term Technology Developments

Introduction – Alain Joselzon - Moderator

The boundaries between near-term and mid-term technologies and between mid-term and long-term, are sometimes fuzzy and the three categories present common problematics. The timeline of technology development is not a simple line: unexpected difficulties lead to reorientations, reassessments, and backward moves sometimes. As a result, realistic goals should encompass the range of real situations, and based on limited scientific background, NOx-related goal(s) should not impair the capability to address the environmental issues related to carbon dioxide.

There are common characteristics and lessons learned emerging from the various engine manufacturers' presentations on mid-term and near-term technologies, also similar to those relative to long-term: intensive and widely spread activities; large spectrum of factors and requirements involved, in addition to environmental ones: operability, weight, performance, reliability, durability, maintainability, reparability, affordability, costs, with overarching safety; unavoidable necessary adjustments reducing the initial potential gains along the technology and product development path; environmental and other trade-offs playing a big role in all domains and at all levels.

The high degree of consistency between engine manufacturers' approaches results from the natural convergence in the way to address similar issues. The aircraft manufacturers' perspective converges to the engine manufacturers' one because all problematic issues are strongly intertwined (similar technology transition aspects; NOx emissions not independent from aircraft characteristics and operation). Aircraft Manufacturers are interested in the review process and prepared to shed additional light based on their specific expertise. They are willing to participate, on a minimum interference basis.

Goals harmonized at international level may help framing and monitoring progress, homogenising the situation worldwide, encouraging a fair sharing of efforts, facilitating scenario analyses, making environmental impact mitigation more efficient overall, in a globally optimised systems approach.

What should be the Goal? By experience, the way a product is operated and the air traffic conditions can be at least as influential as, if not more than, the design characteristics and the level of technologies involved, so that there are gaps between product capability, product performance in operation, fleet performance and overall environmental impact. This should be considered when setting goals and monitoring progress, to ensure valid analysis, balanced treatment, and maximum efficiency. In that context, should environmental goals be extended beyond new product capability (e.g. engines NOx emissions level) to encompass other elements of the emissions systems approach (e.g. ATM).

Relating technologies and goals is a challenge, as potential gains are subject to transition uncertainties and product-dependent. This challenge is further increased for long-term goals. Relating design, technologies and goals adds another degree of complexity in assessing environmental effects, because of the high degree of interactions and trades among and between design and technologies during product development. Again, the challenge increases with long-term goals.

The NOx technology and goal setting process, although focused on combustor technologies, is already a very challenging exercise, involving considerable efforts from all actors, including Industry, Science, Research, Academia, Policy-makers. Projecting a similar process for noise or carbon dioxide (CO_2) related goals, would widen the scope, increase considerably the number of factors, criteria and requirements, and the challenges would increase by several orders of magnitude. Corresponding expectations therefore need to remain within a realistic frame.

Mid-term Technology Presentations

Rolls-Royce **– Paul Madden**
The Trent 1000 engine is only at TRL7 so this was presented in this section of the meeting even though it is a further evolution of the RR phase5 combustor technology. The predicted emissions results for this phase5 combustor are around the 50% CAEP/2 Rolls-Royce NOx target with entry into service date of 2008. RR chose to stay with the phase 5 combustor for this product because of the excellent emissions capability and because the TRL of the lean burn combustor was not sufficient for RR to specify it for this engine. Rolls-Royce are still pursuing lean burn combustion technology for the future as they see that as the way towards lower NOx emissions and later to work towards the ACARE target.

The presentation discussed current performance of RR lean burn combustion technology and explained some project targets such as the intent to have altitude relight to 25Kft (rather than 30Kft). All the attributes except water ingestion were at the level of TRL5/6 and a water ingestion test will be carried out this year on the next engine demonstrator test. The last engine demonstrator test gave NOx emissions to the project target of 40% CAEP/2 but there are a number of areas where some of this excellent NOX may be traded to improve other attributes. In addition the final lean burn combustion system will depend on the engine application and what the next aircraft is. Rolls-Royce presented that a NOx goal close to their 2010 company goal of 50% CAEP/2 was suitable for the mid-term CAEP goal for 2015.

GE – Hukam Mongia

Propulsion engine low-emission combustion technology evolution of the last 30 years is described with a special emphasis on the most recent development, namely Twin Annular Premixing Swirler, TAPS. TAPS mixer technology has been developed for potential application in Single and Dual Annular Combustors, SAC and DAC. Both SAC and DAC TAPS technology development efforts have gone through full-scale annular combustor demonstration for emissions, pressure and airflow distribution, combustor exit temperature quality, structure temperature levels and gradients, lean blowout and ignition characteristics. The SAC TAPS technology demonstration effort involved full-scale engine testing including sea-level emissions, performance, cyclic durability, operability in regard to ignition, acceleration and snap deceleration (throttle burst-chop transient) and operation under inclement weather conditions. TAPS Technology Readiness Level (TRL) and its demonstration in single annular combustions systems are at 6 whereas that of the DAC TAPS is 5.

A brief overview was offered on the combustion system tradeoffs, the evolution of the rich-quench-lean (RQL) of Single and Dual Annular (SAC, DAC) and the lean DAC Combustors leading to discussion on the medium terms goals and development of a first generation Twin Annular Premixing Swirler (TAPS1) for both SAC and DAC applications. Extensive rig testing was done to demonstrate TRL5 capability of SAC and DAC TAPS1. TAPS1 mixers have been tested to cover extreme operating conditions. Even though neither SAC nor DAC TAPS1 have been tested in a flight test bed, very thorough flame ignition, propagation and flameout investigations were undertaken in the sector and full annular combustor rigs under simulated conditions along the relight envelope. The CFM SAC TAPS1 combustion system comprising the combustor, fuel nozzles, valves, and the fuel injection control system was installed in a development CFM56-7B engine. Two engine tests were conducted accumulating a total of 909 hours of testing including more than 200 hours run time at the maximum rated thrust. The engine successfully completed approximately 4,000 LCF cycles and 2,000 fuel nozzle purge cycles to validate critical technologies. The SAC TAPS is judged to be at TRL6; we conservatively call the restart capability demonstration being at TRL5 because we have not flown this system on a flying test bed. The CFM TAPS has demonstrated single engine NOx characteristics value of 44% CAEP2 standard with CO being at 62% for the CFM56-7B27 engine model. Even though DAC TAPS1 technology development on the test rigs has been done over a broad range of operating conditions, and it uses the same SAC TAPS1 mixer technology, we judge it conservatively at TRL5, because the DAC TAPS has not been subject to engine testing. It is predicted to have single engine characteristic LTO NOx values of 44% and 30% CAEP2, respectively for the GE90-115B and GE90-76B. DAC TAPS is expected to meet all other design requirements.

Pratt & Whitney – Bill Sowa

Pratt & Whitney (P&W) is committed to develop low NOx products. Talon X is the current development technology. It is a Rich-Quench-Lean system that is targeted for engine application in 2010 to 2015 time frame. P&W follows a Technology Readiness Level process. At P&W, TRL-6 balances timely & affordable readiness and acceptable risk. Technical feasibility of NOx reduction levels are not validated until TRL-8 after all system level trades are made in the product. P&W chose RQL based on several factors: estimated capability of technologies, carryover of subcomponent technology, ability to maintain low complexity, and ability to address customer concerns of maintainability, life cycle cost and general performance parameters.

Talon X is a step change in performance from the P&W Talon family (Talon I and Talon II). It incorporates many features of Talon I and II but has improved aerodynamic features to significantly lower NOx levels. Many rig development runs have been completed resulting in single engine characteristic NOx levels ranging from 23 – 29 g/kN LTO NOx DP/FOO. This corresponds to a single engine characteristic ranging from 30% to 36% of CAEP/2 standards from TRL-4 and TRL5 rigs. TRL-8 product projections from these results require additional "adders" which consider uncertainties in cycle and engine component development and are product specific. Hence, these "adders" are not provided in this review. Engine demonstration of the technology and further annular rig development is expected in 2006. Ultimate NOx potential for RQL technology is expected to approach lean premixed, prevapourised combustion technology based on idealized TRL-3 RQL rig testing in the 1980's and 1990's. In the long run, the engineering challenge will be to translate ideal system characteristics and performance to practical systems that can be used in aeroengines. Talon X will result in a reliable system achieving revolutionary emissions while extending the known benefits of RQL.

Snecma - Near-Term / Mid Term product review – SaM146 engine – Olivier Penanhoat

Snecma develops the SaM 146engine in collaboration with NPO-Saturn. AVIO is associated to Snecma on the combustor technology. This engine will be applied on the Sukhoi Russian Regional Jet (RRJ) with a thrust range between 14000 lb and 17500 lb. Certification completion is planned beginning of 2008. The combustor technology is an optimised conventional design (comparable to that of recent entry into service engines) in order to minimise NOx emissions, keeping a margin to CAEP2 standard for other pollutants (CO, UHC, soot) and satisfying in the same time high altitude relight capability and all other operational constraints. This technology is derived from Dem21 demonstrator with core tests and altitude cell results available. A 40% margin from CAEP2 NOx standard is estimated at TRL6 level.

Thursday 23 March

Feedback Sessions

The foregoing represented the end of the formal presentations and these were followed by a series of informal discussions with the main presenters at which the independent experts questioned more closely the information they had received in open forum. Discussions with engine companies were held *in camera* with the IEs and these discussions were facilitated by a common set of questions devised by the IEs. The content of these discussions is not recorded here.

RFPs

On global warming -

The uncertainties associated with cirrus cloud and contrails are so large that the RFPs do not feel it appropriate to comment on the trade-off involving those impacts. Thus, the discussion was restricted to trade-off between NOx and CO_2. Questions have been raised whether regional impacts from NOx and CO_2 are sufficiently different that globally averaged forcing or temperature response could be used to compare their impacts. Again, we do not have enough information to answer this question. In the discussion, we focus on what are the issues in comparing globally averaged forcing or temperature response from NOx and CO_2. Because CO_2 has a long-lifetime, a portion of the emitted remains in the atmosphere for at least a century and continue to provide the radiative forcing. In contrast, the effects from NOx emissions are more transient. Using instantaneous global averaged forcing from the annual fleet emission as the metric, the effect from NOx is about 20 times larger than that from CO_2. The RFPs agree that it is unlikely that instantaneous forcing will be accepted as the metric for trade-off between the climatic impacts from NOx and CO_2 emissions. The alternative is to use time-integrated forcing or time-integrated globally averaged temperature response. Given that the response time of the climate system to forcing is of order several decades, the integration time could be 50 years or longer, though the exact duration to be used requires more scientific study. Results from a linear parameterized climate model suggest that the temperature responses from an annual pulse NOx and CO_2 emissions integrated over 50 years are about the same. Other methods suggest that using similar metric on forcing with integration time less than 100 years, the impact from NOx emission on a typical fleet will not be much smaller than 1/10 of the CO_2 effects.

On local air quality

The environmental effects of aircraft emissions on local and regional air quality are immediate, and short-lived. The relative rankings discussed below are based on current understanding of the expected effects. This ranking may change as better scientific understanding is gained of the potential environmental and human health impacts, and if future long-term regional climate changes result in changes in the balance of regional air quality. While understanding of NO_x impacts are fairly mature, increases in understanding of PM impacts and those of specific HAPs may shift our interpretation of their relative importance in the coming years.

NO_x emissions continue to be a major environmental issue for local and regional air quality, due to its contributions to ozone production, additions to PM mass, and direct health impacts from the NO_2 component of NO_x. While aviation contributions to NO_x and NO_2 inventories in areas surrounding airports will need to be quantified for the foreseeable future, growing concerns for PM emissions from all anthropogenic sources may raise the issue of trade-offs between NO_x and PM emissions from aircraft in particular. As improved understanding allows such trade-offs to be evaluated, it is conceivable that PM may overtake NO_x as the emission of primary concern at some point in the future.

Emissions of unburned hydrocarbons (UHCs) and carbon monoxide (CO) from aviation, given the current levels of these various emissions, continue to rank as lower impacts relative to NO_x and PM. However, as regulatory interest focuses on specific hydrocarbon species, due to either specific toxicity or carcinogenic concerns, the relative ranking of such individual species may also be raised. For example, formaldehyde, as one of the most abundant UHCs, is a hazardous air pollutant (HAP) of note, and there is continued uncertainty regarding levels of acrolein, a notable carcinogen, in aircraft exhaust. HAPs such as these may gain increased attention as regulatory agencies interpret the results of environmental health studies.

Local Air Quality – UK Airport Experience

Roger Gardner presented some information on the Heathrow air quality problems, by way of an example of the AQ situation affecting major airports around the world that is attributable to a number of emission sources including aircraft. Concentrations of NO2 are already well in excess of prospective 2010 EU standards and UK objectives in some places around Heathrow, smaller exceedence is recorded at Gatwick and there are risks of exceedence at some other UK airports. Exceedence of applicable air quality regulations exist elsewhere in Europe though Heathrow's problem may be more marked and has just arisen first and thus attracted significant attention. Other regulated pollutants do not exceed limit values and are not predicted to do so though increasing attention to PM, with an increasingly tough European stance, is needed as the margin of compliance may be eroded from above.

He noted that future NOx technology assumptions would be used to assess the status of Heathrow non-attainment of air quality legislation, although there was some concern that technology goals might be used for future fleet forecasting at airports. Demonstration that in the future local air quality limits would not be breached was a prerequisite for expansion of Heathrow's runway capacity. It was noted that the air quality issue at Heathrow was merely offered as an example to illustrate the importance of directing technology developments for the future towards addressing this important environmental problem. However, any suggestion that the use of technology goals might suggest a guaranteed attainment by industry was not acceptable.

Work by the DfT has sought to understand the relative contribution of the various sources to modelled NO2 concentrations through inventory-based attribution studies at receptor points around the airport. These studies show that the aircraft contribution is significant at locations close to the airport (within about a kilometre) and can be a key influence in breaches of NO2 levels closer to the airport. This declines to a relative small contribution beyond about 2-3 kilometres range, but the residual contribution can still be sufficient to tip the balance into exceedence of limit values at some locations.

This situation demonstrates the clear need to bring cleaner aircraft technologies on stream as quickly as possible, and to maintain pressure on certification standards. The forecast growth of aviation and the trend towards aircraft size growth at major airports such suggest an increase in the absolute aircraft mass emissions and the relative aircraft contribution. Predicted improvements in vehicular emissions and relative saturation of the roads network (in the vicinity of Heathrow) only sharpen the need for improved aviation technology. As the roads' contribution declines, the aircraft contribution is expected to increase both proportionately and in real terms. Net emissions from all sources have still to reduce in absolute levels to achieve the 2010 NO2 requirement, let alone allow for growth.

A practical issue for environmental policy-making to know what predictions of future NOx performance should be used when constructing growth scenarios for future years (out to 2030). Information from the LTTG process carries significant authority and it has to be taken into account in the assessment work that will underpin the UK government's decision-making process on the future development of its airports.

Further points of discussion

There was some discussion on the use of goals and the information brought forth in the goal review process. It was noted that the CAEP8 meeting would examine the case for more stringent limits for both noise and emissions. Emissions and noise interdependencies would be an issue at this time. Setting technology goals would provide information that might be of value to the stringency debate.

The meeting was reminded that the LTTG technology goal review was viewed as a pilot process which, if successful, might be broadened to address other parameters in the interdependency analyses. The reporting timescale was discussed, and it was agreed that the final report on LTTG goals should be available for the CAEP SG in October. There was a clear recognition that Mid-term goals and stringency were not linked, and a further point noted during discussion was the need to reflect, when setting goals, on the ability of airlines to purchase new technologies.

Friday 24 March

IE Reporting Meeting

Review summary
This final day of the review was devoted to the independent experts, assisted by industry members of the committee, in assessing the information they had received during the previous days. The consensus was that the technology review process had worked well, and that the ability to question industry representatives on a one to one basis had been particularly useful and should be considered as a feature of any subsequent goal-setting exercises.

There was also consensus that local air quality issues presented a need for technology goals, but there was also a need to perform a more thorough analysis to inform future goals. At the climate level it was noted that both CO2 and NOx emissions needed to be addressed, and the more detailed scientific advice had been helpful in this regard. The use of Dp/Foo as a metric for both mid- and long-term goals was accepted for this Review, but this metric might not be the most appropriate for the future.

Reporting process
It was agreed that a draft report should be prepared by the independent experts, and this should be sent to first of the manufacturers for the comment. Following consideration of these comments, the report should go to all stakeholders present at the review, after which further comments might be noted before the report was forwarded to WG3 prior to presentation to the CAEP SG. A report preparation schedule was agreed, as follows:

Schedule

- Summary of meeting for reporting to WG-3 - target 4 weeks, including IE comments (few pages) - Peter Newton

- Reporting to Steering Group would be WG-3 report + comments + working group comments; Peter Newton would only report progress on Review Report

Review Report

- April 14 – Share Bullet comments on specific points of interest and for consideration in the report to IEs by 1 April

- May 12 – Zero Draft (IEs only) - draft contributions on Chapters to Lourdes by 5 May for collation to First Order Draft;

- FOD to Peter for final editing by end of June

- June 9 – FO Draft to Engine Industry for comment

- July 12-14 – IEs final Report drafting meeting Atlanta [engine company comments required by 23rd June]

- August 4 – Delivery of Final Draft to all LTTG Review attendees

- Final report due 15 September 2006 for presentation to WG3

Report format:
Executive Summary

Introduction (scene-setting, background to LTTG, CAEP remit) [Peter]

Scope of review (what it will and won't do) [Peter]

Policy overview (Peter to draft 1-1.5 pages) [Peter]
    Goal relevance to stringency
    Options for use of goals
    Limitations, health warnings for first review

Science Overview (RFP Appendix – summary included here) [Lourdes]
    Major environmental concerns
    Latest understandings
    Environmental priorities, impact relevance
        GC
        LAQ

Academic review [John]

Research Review:
    NASA, EU, other [Paul, Lourdes]
        Priorities
        Targets
        Programmes
        Achievements
        Future work planned

Technology review [Ben, Dan]
        Historical perspective re NOx including Trade-offs
        Priorities
        Targets
        Programmes
        Achievements
        NOx Goals – measure/metric (assumed Dp/F_{00})

Fleet average – how to measure?
New production
Engine Thrust, PR?
Tradeoff implications, quantified, qualified
Monitoring

Conclusions of LTTG Review [Malcolm]
Recommended NOx Goals
Trade–offs in respect of other pollutants
Contribution to aviation environmental trend
Monitoring of goals
Review Committee consensus

Review Panel Recommendations [Malcolm]

Process improvements

Appendices - There will need to be a number of Appendices for the industry and other presentational material.

-- End --

Appendix 4
LTTG NOx Technology Review
List of Presentations

Presentation Reference	Presentation
P1	LTTG Technology Review London, March 2006 Peter Newton DTI
P2	Why Technology Goals matter - a Government Policy Perspective Martin Capstick Aviation Environmental Division, UK Department for Transport
P3	Relationship Between the CAEP Goal setting and Standard setting Processes. Curtis Holsclaw Deputy Rapporteur, WG3
P4	An Environmental Overview: NGO Perspectives Tim Johnson International Coalition for Sustainable Aviation (ICSA)
P5	Science Overview Summary Report on Consensus Views Malcolm Ko (NASA Langley Research Center, USA)
P6	Emerging science on global climate David S. Lee and the Quantify Core Science Community MMU
P7	Relevant Emerging Science: Local Air Quality R.C. Miake-Lye Aerodyne Research, Inc.
P8	Aviation NOx Reduction and Climate Change Impact EU Research Activities and Prospects Claus Brüning Environment and Climate System Unit Environment Directorate Research DG Brussels
P9	Airline Fleet Planning - IATA L.M. Pfeifer Managing Director, Tech Ops Strategic Planning American Airlines
P10	LTTG Technology Review –Academic Input - Long Term & Mid Term Emission Goals Combustion Technology for Future Turbofan Engines Hans-JörgBauer

	Universität Karlsruhe (TH)
P11	ELECT European Research and Technology Strategy on Low Emissions Combustion in Aeroengines for the 21st Century R v.d. Bank RRD
P12	Research Review of NASA's Aeronautics Program Dr. Gary T. Seng Presentation to: ICAO WG #3 - LTTG
P13	Gas Turbine Combustors - Description & Operation Randy McKinney Fellow – Combustor Technology & Modelling Engineering Pratt & Whitney East Hartford, Connecticut
P14	An Overview of The Tradeoffs Relevant to NOx Goals Paul Madden (ICCAIA)
P15	Technology Transition Case Study: Low NOx Combustor Technology Transition to Product ICCAIA (P&W)
P16	Recent Emissions Certification Test Results with GE Aviation Combustor Designs Will Dodds GE Aviation Cincinnati, Ohio, USA
P17	Recent Pratt & Whitney Low Emissions Combustors (TALON II) Introduced Into Revenue Service Dom Sepulveda Pratt & Whitney
P18	Developments of the Rolls-Royce Engines and the Phase 5 Combustor Background History to Recent Products and Near Term Developments – Setting the Scene for Future Revolutionary Changes London WG3 LTTG Meeting – 21st March 2006 By Paul Madden
P19	Near term : Technology of SaM146, an environmentaly friendly engine C. VIGUIER (SaM146 Combustor Module Manager)
P20	GE Aviation Low Emissions Combustion Technology Evolution Hukam C. Mongia, Manager Adv. Comb. Eng., GE Aviation, Cincinnati, Ohio, U.S.A.

P21	Dependable Combustor Technologies For Environmentally Responsible Aircraft Engines Dr. William Sowa Advanced Technology Combustor, Augmentor and Nozzle Pratt & Whitney East Hartford, Connecticut
P22	Mid Term Technology Wrap-up 22 March, 14:15 Will Dodds ICCAIA
P23	LTTG Mid-Term Technology Presentation Trent 1000 Phase 5 Combustor Background to Rolls-Royce Emissions Research and Status of RR Lean Burn Combustion System Rolls-Royce plc Presentation
P24	Aircraft Emissions in the Heathrow Context Roger Gardner Aviation Environmental Division, UK Department for Transport
P25	Reflection on Environmental (LAQ) Justification for LTO Mid-Term Goals? 21 March, 13:00 R. Miake-Lye Aerodyne Research
P26	U.S and European National Ambient air quality Standards RFP?
P27	Airparif Actualite Paris Airport Air Quality Information ???
P28	Lean Burn Combustor Status – Emissions (single page presentation) ICCAIA
P29	Long Term ACARE Environmental Goals (CLEAN and VITAL) Olivier Penanhoat SNECMA/SAFRAN Group Villaroche, France
P30	ICCAIA Tradeoff Presentation Paul Madden R-R

ICAO PUBLICATIONS AND RELATED PRODUCTS IN THE AIR TRANSPORT FIELD

The following summarizes the various publications and related products in the air transport field issued by the International Civil Aviation Organization:

- *International Standards and Recommended Practices (SARPs)* adopted by the Council in accordance with Articles 37, 54 and 90 of the Convention on International Civil Aviation and designated, for convenience, as Annexes to the Convention. Annex 9 — *Facilitation* — contains SARPs dealing with customs, quarantine, immigration and health matters concerned with international air navigation. Annex 17 — *Security* — is composed of SARPs on all matters related to safeguarding civil aviation against acts of unlawful interference. Any differences between the national regulations and practices of a State and what is prescribed by an International Standard must be notified to the Council in accordance with Article 38 of the Convention. The Council has also invited Contracting States to notify differences from the provisions of the Recommended Practices.

- *ICAO's policies* on the regulation of international air transport, charges for airports and air navigation services, and taxation in the field of international air transport.

- *Technical specifications* on machine readable travel documents (MRTDs).

- *Tariffs* for airports and air navigation services, including charges applied towards users in more than 180 States.

- *Manuals* providing information or guidance to Contracting States on such issues as regulation of international air transport, financial management of airports and air navigation services, air traffic forecasting methods, and compliance with Annex 17 provisions.

- *Circulars* providing specialized information of interest to Contracting States. They include studies on medium- and long-term trends in the air transport industry at a global and regional level and specialized studies of a worldwide nature covering issues such as the economic and financial aspects of CNS/ATM systems implementation, regional differences in airline operating economics, economic contribution of civil aviation, privatization of airports and air navigation services, and regulatory implications of slot allocation.

- *Aviation Security Training Packages (ASTPs) and courses* on a range of subjects designed to assist security professionals, managers and staff in developing a more comprehensive understanding of SARPs, as well as to offer specialized practical expertise in the implementation and monitoring of measures and provisions in accordance with local programmes. For further information, please contact avsec@icao.int or visit the training page on the ICAO AVSEC website at www.icao.int/avsec.

- *Publications in electronic form,* in database and interactive forms, such as the world's air services agreements and the ICAO template air services agreements. *Civil aviation statistics* can be accessed by purchasing an annual subscription to one or more of the data series distributed by ICAO through its commercial website at www.icaodata.com. Questions regarding ICAO statistics or special orders for statistical data should be sent to sta@icao.int.

- *Reports of meetings in the air transport field,* including reports on the Facilitation and Statistics divisional-type meetings and those related to conferences on aviation security, regulation of international air transport, and economics of airports and air navigation services.

5/08, E/P1/585

Order No. 9887
Printed in ICAO

ISBN 978-92-9231-088-2