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

REPORT

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Term Technology Goals for NO_x**

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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, 5 th 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 CO ₂ , NO _x (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
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 .
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. PM ₁₀ and PM _{2.5} 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
SO _x	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 NO_x Review and the Establishment of Medium and Long Term Technology Goals for NO_x

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 (NO_x) culminating in the IEs recommendations for medium (10 year) and long term (20 year) goals for NO_x 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 (NO_x) 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 CO₂ 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 years¹ – 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 NO_x 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 NO_x 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 NO_x 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, D_p/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 NO_x 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 NO_x control technologies has led to NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x emissions and given projected growth in demand for aviation services mitigation pressure is expected to grow. NO_x cannot be ignored from either a local air quality or global climate impact perspective.
- 1.7.1.2 From a global climate perspective SO_x 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., CO₂).
- 1.7.1.3 From a local air quality perspective, NO_x/NO₂ 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 NO_x 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 CO₂ emission is 8 times that from NO_x. Figure 3 in the Report shows the relative surface temperature response to an annual pulse of NO_x and CO₂ emissions from a fleet. Data presented indicated that over a 50 year timeframe NO_x and CO₂ were approximately of equal importance for integrated global mean surface temperature response although this was based on an *indicative* calculation. Over longer timeframes, CO₂ 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x emissions from a fleet of aircraft was similar to that of CO₂ in terms of long term (~ 50 years) Global Climate Change (GCC), although as noted above there is a slight bias toward CO₂ 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 CO₂, 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, H₂O and cirrus. From a global climate perspective both NO_x and CO₂ are of approximately equal importance over an impact assessment 50 year timescale, but CO₂ tends to increase in importance over longer timescales. Technology goals for NO_x 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 NO_x. With regard to CO₂ and NO_x, given current understanding, it was concluded that both need to be minimised: reducing fuel burn also leads to a reduction in mass NO_x emitted if the emissions index is unaltered. NO_x emissions are a concern of both LAQ and GCC environmental issues and CO₂ is also a key GCC pollutant. Any medium term goal must recognise that pressure to reduce both these pollutants (CO₂ and NO_x) will

continue. Since CO and HC are generally well below certificated levels, then, in principle, they may be traded with NO_x, but an associated worsening of fuel burn (CO₂) 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/NO_x linkage is relatively weak for the NO_x 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 NO_x 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 NO_x emissions. Alternative fuels with lower calorific values could reduce flame temperatures and NO_x but would require a higher fuel load or would reduce range. Higher calorific value fuels, such as liquid hydrogen, would offer both reduced NO_x and CO₂ (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 NO_x 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 NO_x Review and the Establishment of Medium and Long Term Technology Goals for NO_x

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 (NO_x) and using this to establish medium term (10 year) and long term (20 year) technology goals for NO_x 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 NO_x 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.

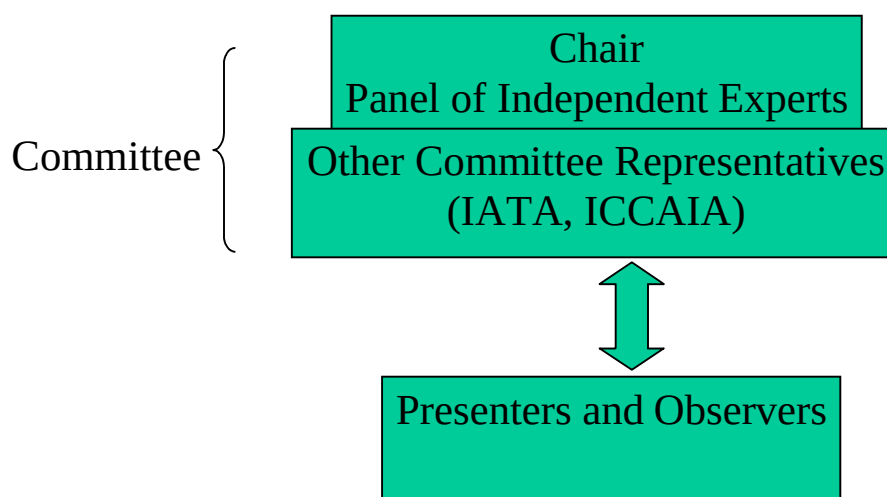


Figure 1: Review Structure

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, NO_x) 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 NO_x 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 NO_x 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/F₀₀.

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 NO_x 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. CO₂ 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 CO₂, 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 NO_x 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 CO₂, a little less than 30 percent H₂O, 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

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

Emissions from Combustion Processes

CO₂ – 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 CO₂.

H₂O – Water vapour is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produce H₂O.

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.

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 NO_x as well as other pollutants to provide at least a qualitative need for long term NO_x goals for aircraft.

5.2.2 NO_x (NO and NO₂) 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 NO₂, and as a precursor for ozone, and a minor precursor for PM_{2.5}. The relative contribution from aviation NO_x 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 SO₂. What is less understood is how sulphates and SO₂ 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 NO_x 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 NO_x 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 NO_x, but if fuel efficiency and CO₂ 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. CO₂), and indirectly to changes in concentrations of other species through photochemical interactions (changes in concentration of O₃ and CH₄ as a result of NO_x 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 NO_x. 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 NO_x emitted at the ground is transported to the upper troposphere, NO_x 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 GWP⁶ for NO_x/O₃ 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, CO₂ emitted by aircraft at cruise altitudes has the same effect as CO₂ 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 H₂O 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 CO₂ 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 (CO₂), 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 CO₂.

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. Additional 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 (O₃)** under the influence of sunlight. As a consequence of complex tropospheric chemistry, NO_x will also reduce the ambient atmospheric concentration of **methane (CH₄)**. 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 O₃ and CH₄ 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/m²] due to aviation emissions from historical operation of the subsonic fleet in the year 1992 as reported in by IPCC (1999).

Emission/concentration	RF [mW/m ²] Range*	Comment
CO ₂ /CO ₂	18.0 13 to 23	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.
NO _x /O ₃	23.0 13 to 45	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 .
NO _x /CH ₄	-14.0 -44 to -4	
H ₂ O/ H ₂ O	1.5 1.5 to 3	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.
SO _x ,PM/Sulphate	-3.0 -5.0 to 0	

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 ₂ O, 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.

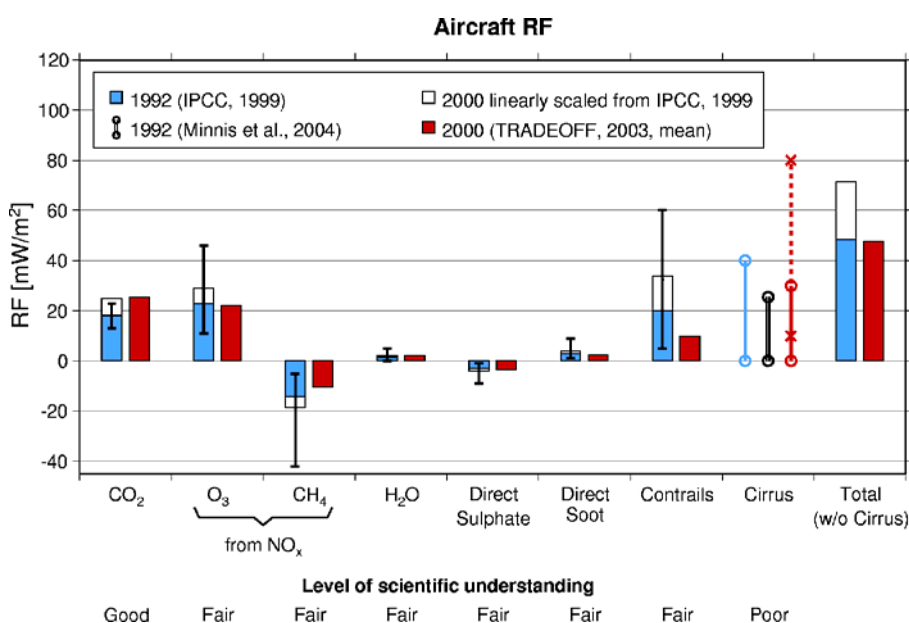


Figure 2: Bar charts of radiative forcing (using various integrating times) from aviation effects in 1992 (subsonic fleet) and subsequent modifications.⁸

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 NO_x 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 CO₂, NO_x, H₂O and PM emissions at cruise, the outstanding science question is whether RF (instantaneous or cumulative) from short-lived emissions (NO_x, H₂O, 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 (CO₂). 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 tradeoffs⁹, 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 NO_x reductions? Yes/No
- 2) If yes, is the need greater or less than previously?
- 3) What is the relative impact of aircraft NO_x 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: CO₂, NO_x, CO, UHC, SO₂, 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 NO_x reductions and this need is expected to grow given projected growth in demand for aviation services. NO_x 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 NO_x emissions. It is advisable to limit SO_x and PM, but from a global climate perspective CO and HC are not a concern. For local air quality NO_x/NO₂ are the main concern, with PM next in importance (and its relative importance may exceed NO_x/NO₂ 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, NO_x 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 CO₂ emission is 1/15th that of NO_x. At the other extreme, using forcing integrated over 100 year as the tradeoff metric, the effect from annual CO₂ 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 NO_x and CO₂ for the global fleet (i.e. NO_x and CO₂ in proportion to emissions). This clearly shows the importance of time frame considerations. This figure indicates that over a 50 year timeframe NO_x and CO₂ were approximately of equal importance for integrated global mean surface temperature response although this is an *indicative* calculation. Over longer timeframes, CO₂ will be of greater importance.

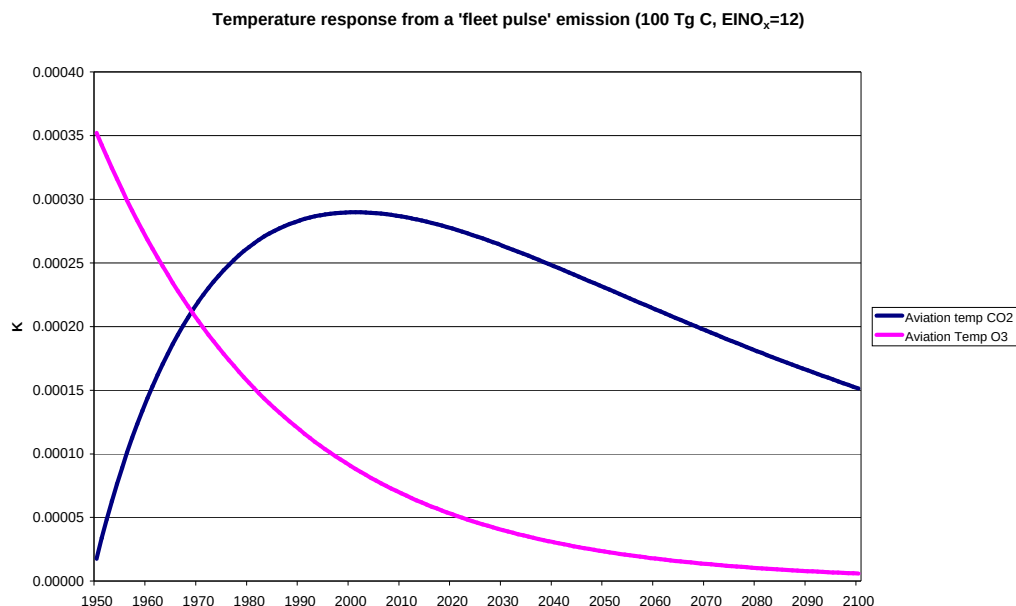


Figure 3: Relative pulse temperature response (K) for global fleet of NO_x and CO₂

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 NO_x and CO₂ and trading one for the other now is not advisable, although there is a slight bias toward reducing CO₂. The general conclusion from the scientific discussion is that the need for technology goals (for NO_x) 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 NO_x began with the ICAO CAEP limits of 1986 (year of certification compliance P3). Figure 4 below shows the current and historical CAEP certification standards for NO_x. Using a takeoff OPR of 30, for convenience, to examine subsequent increases in the stringency of the NO_x 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 NO_x 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 NO_x 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 D_p/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, D_p , normalised against the maximum engine thrust, F_{00} .

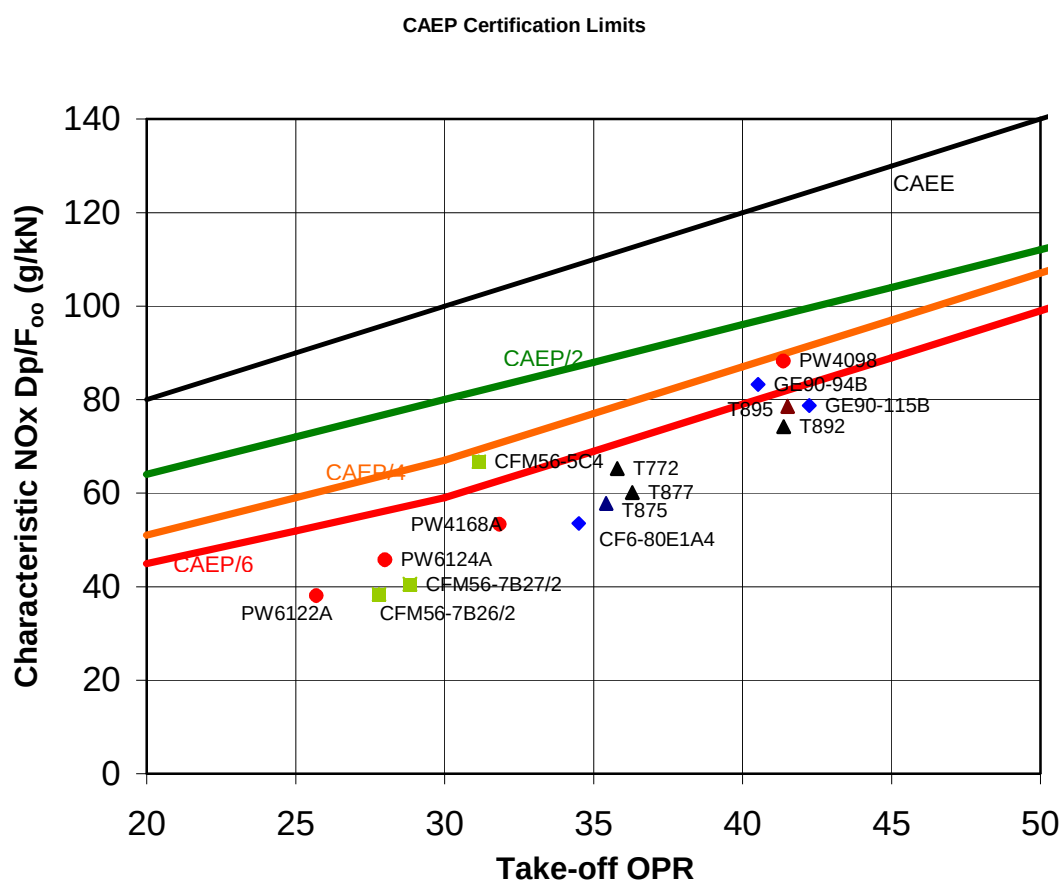


Figure 4: CAEP Stringencies

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 NO_x 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. NO_x 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 NO_x.

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 CO₂ and H₂O emissions (fuel burned). NO_x, 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 bypass 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 CO₂ 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 NO_x 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 CO₂, 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 NO_x 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 NO_x 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

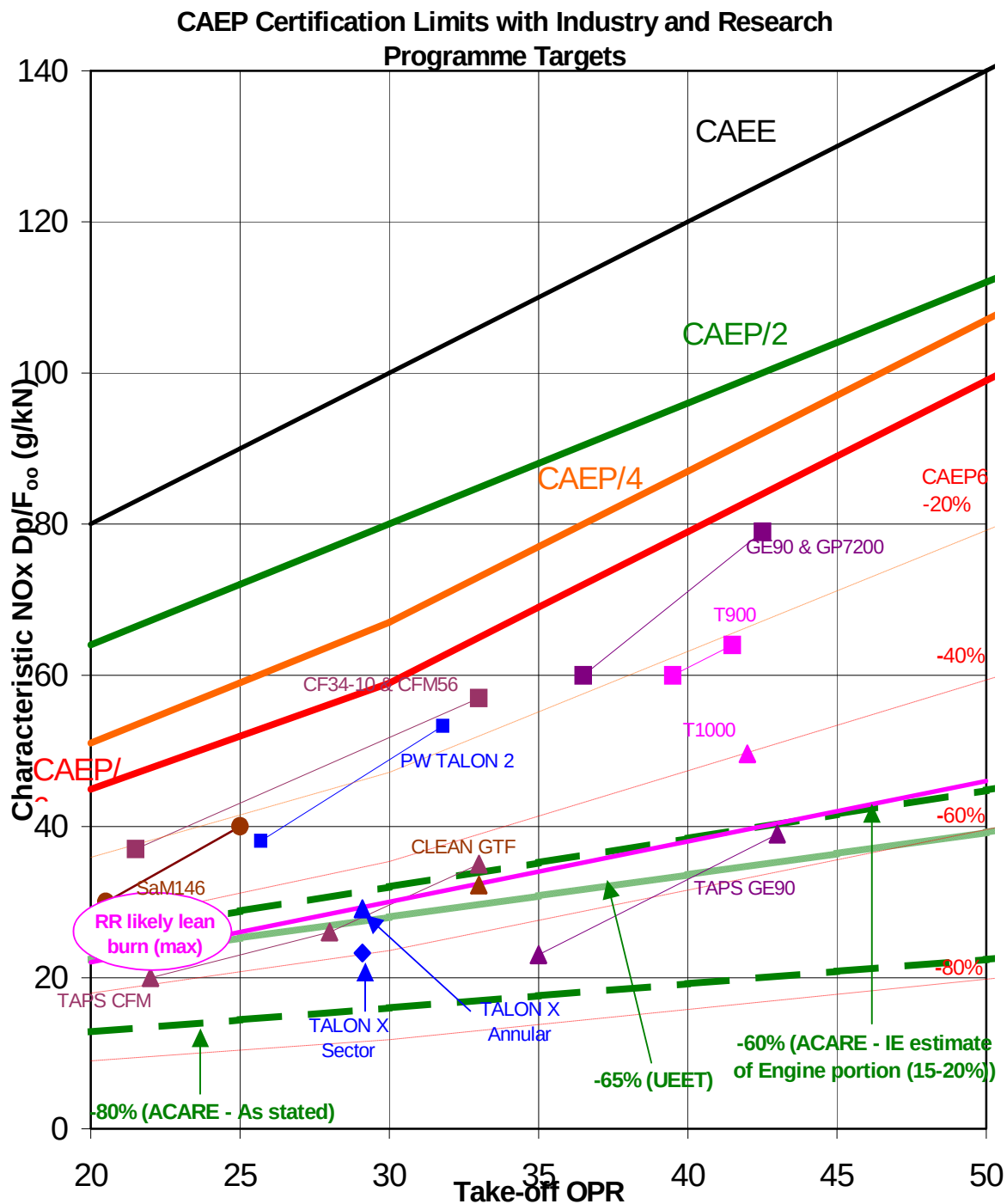


Figure 5: CAEP Certification Limits with Industry and Research Programme Targets

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 CO₂ 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