

INTERNATIONAL CIVIL
AVIATION ORGANIZATION



REPORT OF THE INDEPENDENT
EXPERTS TO CAEP/8 ON THE SECOND
NO_x REVIEW AND THE ESTABLISHMENT
OF MEDIUM AND LONG TERM
TECHNOLOGY GOALS FOR NO_x

REPORT

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ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION

**Report of the Independent Experts to CAEP/ 8 on the Second
NOx Review and the Establishment of Medium and Long Term
Technology Goals for NOx**

Authors

P. Kuentzmann (France)

L. Maurice (US)

M. Ralph (UK), Chair

J. Tilston (UK)

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1. Executive Summary

1.1 Following the 2006 first Review of aircraft NO_x control technologies and the setting of 10 year Mid Term (MT) and 20 year Long Term (LT) Goals, this second 2009 Review by Independent Experts (IEs) was requested by CAEP7 to review progress towards meeting the goals and update, where necessary, the previous work. The Review was held in London during March 2009 and a report prepared for presentation to the Eighth Meeting of CAEP (CAEP/8) in Montreal, Canada on 1-12 February 2010. The IE Panel consisted of four members: one from France, two from the UK, and one from the US, as compared with six members in 2006.

1.2 Presentations were made by the CAEP Research Focal Points (RFPs) on the latest consensus scientific understanding of the impact of aircraft NO_x on both Surface Air Quality (SAQ) and Global Climate Change (GCC). On the basis of these presentations and follow-up questioning, the IEs concluded that the scientific evidence supports continued efforts to reduce NO_x emissions from aircraft and that the impact of aircraft NO_x on both SAQ and GCC is, if anything, more compelling than during the first review. Nonetheless, given the still considerable uncertainty about the quantification of these impacts, the IEs recommended continued research on NO_x emissions and other emerging concerns such as particulate matter (PM) and the role of NO_x in PM formation.

1.3 Presentations were made of further significant reductions in NO_x emitted by aircraft engines fitted with the latest combustors and of predicted reductions resulting from combustors still in development. At the time of the review no engines had as yet met the Goals set at the first review as defined by having reached Technology Readiness Level 8 (TRL8)¹. However, considerable data was presented for advanced conventional Rich burn, quick Quench, Lean burn (RQL) combustors indicating that, as expected from the first Review, evolutionary developments continue to appear likely to meet the MT Goal though with a considerable challenge remaining. Data was also presented for new and more revolutionary staged Direct Lean Injection (DLI) combustors which showed dramatic reductions in NO_x production, again in line with the expectations of the 2006 Review. The lead engine family to be fitted with a DLI combustor, the GE GENX, was shown as being developed over a remarkably wide range of Overall Pressure Ratio (OPR). The lowest OPR development of this engine showed promise of meeting even the LT Goal, whereas, at the highest OPR it would have difficulty meeting even the MT Goal. This wide spread of NO_x performance raised questions about how such families of engines might be handled within a Goals setting. Despite the considerable progress made since the first Review, the IEs decided not to recommend a change either to the Goals or the definition of their achievement. The key reasoning for retaining the present Goals was to avoid hasty, and possibly ill-conceived, changes to what were intended to be mid and long term targets, and in this regard to give time for the in-service performance of the new staged DLI combustors to clarify and for their applicability to smaller engines to be investigated. It was also concluded that DLI- style combustors are likely to be essential for meeting the LT Goal especially for large, high OPR engines. Furthermore, if it transpires that for small low OPR engines the trade-offs associated with fitting advanced RQL and DLI combustors in fact precludes their use in such engines then the characteristic slope of the Goals may well require significant change. For current RQL combustors nothing in this Review was found to disturb the currently accepted relationship between the amount of NO_x produced during the prescribed certification Landing and Take-Off Cycle (LTO) as compared with that produced at the Cruise condition. However, concern was again expressed about uncertainties for this relationship as a result of both the significantly different behaviour of staged DLI combustors as well as of potential new engine architectures such as open rotor engines.

¹ TRLs can be found in Appendix A

1.4 In all some thirty-seven Conclusions and ten Recommendations were recorded with some referring to further work that it would be useful to be pursued in the interim period before a future Review, should one take place. The IE's expressed a view that a period of about three years would be an appropriate elapsed time for sufficient progress to be made before a further Review.

2. Introduction

2.1 In support of the work of the International Civil Aviation Organization (ICAO), Committee on Aviation Environmental Protection (CAEP), Long Term Technology Task Group (LTTG) of Working Group 3 (WG3), the first LTTG oxides of nitrogen (NO_x) Technology Review was held in London in March 2006. For this Review a group of Independent Experts (IEs) was tasked with leading the review of technologies for the control of NO_x culminating in the IEs recommendations for medium term [MT] (10 year) and long term [LT] (20 year) goals for NO_x control. The IEs recommended (and CAEP 7 subsequently accepted) MT (2016) and LT (2026) Technology goals. The IEs used the Landing-and-Takeoff (LTO) NO_x certification metric to define the goals. The 2006 IE Report is available on the FAA website: http://www.faa.gov/about/office_org/headquarters_offices/aep/research/science_integrated_modeling/media/Independent%20Experts%20Report.pdf

2.2 In the 2006 Review the IEs positioned the MT technology goal at CAEP/6 minus 45% ± 2.5% at a reference Operating Pressure Ratio (OPR) of 30. The bandwidth is relatively small indicating a reasonable degree of confidence in the ability to achieve the Goal. The IEs positioned the LT technology goal at CAEP/6 minus 60% ± 5% at the same reference OPR of 30. The greater bandwidth as compared with the MT technology goal reflected the greater degree of uncertainty of meeting the Goal. The criterion adopted by the IEs was that a goal would be considered met when one or more manufacturers achieve a performance at or below the upper line of the goal band judged against achieving a Technology Readiness Level (TRL) 8² (Appendix A). The 2006 Review report stressed the difference between CAEP standards which follow technology capability and the NO_x Goals which attempt to predict where the leading edge capability may lie at ten and twenty years in to the future.

2.3 This Report of the second NO_x Review was commissioned by CAEP7 for reporting to CAEP8. Key participants and organizations within the LTTG process have been given the opportunity to comment on draft versions of this Report. A mature draft version was presented to the September 2009 meeting of WG3 and this final version is for presentation to the CAEP/8 meeting scheduled for February 2010 in Montreal, Canada.

² TRL 8 designates actual system completed and “flight qualified” through test and demonstration

3. **2009 Second LTTG NO_x Review, London UK, March 2009**

3.1 The 2009 Review was held on March 30 & 31 and again took place in London, UK. This status Review, following three years after the first, was expected not to be as extensive as the original 2006 review, and would focus primarily on what had changed during this intervening period. Nonetheless, the IEs were again charged with reviewing the scientific basis for the control of NO_x, progress in NO_x control technologies, as well as the validity of the 2006 MT and LT Goals. The full terms of reference for the IEs for the 2009 Review can be found at Appendix B.

3.2 A subset of the original IEs (P. Kuentzmann, L. Maurice, M. Ralph, and J. Tilston) conducted the 2009 Review of the goals. The IEs elected Malcolm Ralph (Chair of the 2006 Review) to Chair the 2009 Review. The IEs were asked to provide a brief preliminary report to the meeting of WG3 also held in London, UK on 1 to 3 April 2009. Given that the WG3 meeting immediately followed the Review itself, necessarily, only very preliminary comments were possible at that time. A later report, heavily based on the WG3 Report, was submitted to the June Steering Group of CAEP, which met in Salvador, Brazil. The IE Report to the June 2009 Steering Group meeting can be found at Appendix C. A list of presentations can be seen at Appendix D and a list of the attendees at Appendix E. The full presentations can be accessed on the FAA website: http://www.faa.gov/about/office_org/headquarters_offices/aep/research/science_integrated_modeling/media/CAEP%20Impacts%20Report.pdf

3.3 For this Report of the 2009 Review and Goals the IEs have reached a consensus on all matters of substance, including the stated Conclusions and Recommendations.

4. Science Overview

4.1 Introduction

4.1.1 In their 2006 report, the NO_x IEs noted that 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 aircraft engine emissions. During the 2009 review of the status of achieving the NO_x goals, the Independent Experts received an update on the state of the science. The Science and Research Focal Points (SFPs and RFPs) of CAEP focused on assessing the extent to which knowledge and scientific consensus had evolved.³ The SFPs and RFPs were asked to address the same questions that had been posed to them at the 2006 review:

- 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 emissions compared with other engine exhaust species in respect of:*
 - 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?*

4.1.2 The NO_x IEs posed some additional questions to the SFPs and RFPs in 2009, focused on addressing progress. Since the 2006 NO_x Technology Review, the intergovernmental Panel on Climate Change (IPCC) also released its fourth assessment report⁴, providing a source for further updates on the state of scientific knowledge.

4.1.3 In addition, during the 7th Meeting of CAEP in Montreal (February 2007), it was agreed that a scientific workshop would be organized, to advise CAEP, on how the existing state of scientific knowledge and practical approaches on noise, air quality and climate impacts of aviation may be used to inform policy decisions. The Workshop on “Assessing Current Scientific Knowledge, Uncertainties and Gaps Quantifying Climate Change, Noise and Air Quality Aviation Impacts” was held in Montreal, October 29-31, 2007. The Final Report of the Workshop was presented to CAEP in CAEP-SG/20082-WP-10 (<http://web.mit.edu/aeroastro/partner/reports/caepimpactreport.pdf>). The IEs also referred to this report as they assessed the status of scientific knowledge and evolving consensus.

4.1.4 It is important to note that the pace of science is such, that it is unrealistic to expect major developments in such a relatively short period. That said, there appears to have been some important developments that informed the NO_x IEs review of the status of achieving the goals and the need to continue to support and possibly to adjust those goals.

³ Rick Miake-Lye (climate and air quality), Claus Bruning (climate and air quality), Malcolm Ko (climate and air quality), David Lee (climate),

⁴ Intergovernmental Panel on Climate Change Fourth Assessment Report, “Working Group 1: The Physical Science Basis,” 2007.

4.2 Environmental Need

4.2.1 The IEs believe that environmental need for NO_x reductions appears even more compelling than during the 2006 NO_x Technology Review. The climate impact drivers appear more urgent, with actions (e.g., cap and trade schemes, CO₂ standards) to mitigate the impact being introduced or shortly expected throughout the world. Although NO_x is not a greenhouse gas *per se*, it is an indirect greenhouse gas; some theoretical progress has been made relating its impact to that of CO₂ via Global Warming Potential metrics, which are further discussed below.

4.2.2 Surface air quality constraints are also more compelling. For example, the EU has set a 2010 target of an annual average of no more than 40 microgrammes per cubic metre for Nitrogen Dioxide. As with most other major European economies, the United Kingdom does not yet fully comply with this limit and this has become a decisive constraining issue for the agreement to build a third runway at Heathrow. The UK Government has made a commitment to meet EU directives around the Heathrow area by 2015.

4.2.3 In the United States, the Environmental Protection Agency (EPA) is expected to tighten ozone standards, and this action will increase the number of U.S. airports in non-attainment areas for ambient air quality.

4.2.4 Recent scientific understanding of human health impacts of aircraft emissions appears to indicate that health impacts from particulate matter (PM) may be higher than those from ozone due to NO_x. However, NO_x does contribute to secondary PM formation, making its overall health impact more significant.

4.2.5 Though the Review did not include any quantitative data to evaluate environmental need, the IEs felt there was sufficient evidence to conclude that the environmental need for NO_x reduction continues to grow. The RFPs and SFPs noted that NO_x from any combustion sources will always be considered an important pollutant to mitigate for both air quality and climate change. If aviation continues to grow, the environmental impacts from aircraft NO_x will increase unless steps are taken to mitigate them. So, further NO_x reductions need to be considered. These considerations will take on more nuanced choices as trade-offs among different aircraft emissions are balanced, but the IEs believe the answer to the question of environmental need to reduce NO_x will continue to be “Yes”.

4.3 Level of Scientific Understanding

4.3.1 Original questions

Question 1) *Is there still a need to consider further aircraft NO_x reductions? Yes/No*

Yes.

The need was significant in 2006 and still is. This is from both surface and altitude emissions perspectives. There is increased understanding in 2009 relative to 2006 of NO_x contributions to PM in air quality. Uncertainties are being reduced in NO_x effects on ozone for climate change. The RFPs/SFPs and the IEs agree that we are “more sure” in 2009 that the need for NO_x reduction is still very important.

Question 2) *If yes, is the need greater or less than in 2006?*

Appears to be greater (both for surface and altitude emissions)

Question 3) *What is the relative impact of aircraft NO_x compared with other aircraft pollutants?*

Any relative assessment of impacts from different pollutants requires a metric for their comparison. Definitive metrics to compare disparate effects are the subject of ongoing active research and substantial debate. While the choice of metric should be based on scientific knowledge, ultimately policy decision(s) must be made to encourage a desired outcome(s). This is particularly true in comparing impacts for air quality and climate.

a) SAQ

The role of NO_x in ozone formation has been the impact on which mitigation efforts have historically focused. However, based on new findings, the role of NO_x in contributing to PM information is taking on increased importance. Including the formation of ozone and PM, NO_x makes contributions to two of the largest air quality concerns. Therefore, by most criteria, NO_x is a very important aircraft pollutant.

The relative impact of aircraft NO_x compared with other aircraft pollutants depends on the relative health impacts from ozone and PM, and the contribution of NO_x to PM formation relative to other sources of PM emissions. The RFPs/SFPs noted that they do not have expertise in these areas. However the IEs are aware of information available since the 2006 review that suggests that the impact of PM on health may be even more significant than had been thought previously. Since NO_x contributes to secondary PM formation, this finding makes the need to reduce NO_x emissions more compelling. Also, recent studies show that SO_x may be the primary contributor to PM (ref CAEP Impacts Workshop). This would imply that significant reductions of PM may be possible via reducing jet fuel sulfur content. Although this is not the subject of the review, the IEs have asked the industry for an opinion of whether using fuel specification changes to reduce PM emissions might offer combustor design opportunities to reduce NO_x.

b) Global warming

CO₂, NO_x and PM emissions have impacts on climate. They are listed in the previous sentence in order of increasing uncertainty associated with current ability to predict the climate impact. CO₂ is a greenhouse gas. NO_x alters ozone and CH₄ in the atmosphere, and ozone and CH₄ are greenhouse gases. PM emissions may be related to the formation of contrails, contrail induced cirrus, alteration of sulfate aerosols, and may affect cloud formation. Global averaged radiative forcing is one measure of the expected climate response. Most literature follows the example of the IPCC report and lists the instantaneous forcing from steady state changes in ozone, CH₄, and clouds generated from the PM emissions produced by the aircraft fleet. In contrast, the forcing from CO₂ is calculated from the cumulative change in atmospheric CO₂ concentration due to aircraft operations. Thus, those numbers cannot be used to compare the forcing. In addition, the actual climate impact depends on the persistence of the forcing after the emission because the lifetimes of the various forcing components are very different. A metric is needed before one can compare the climate impacts from CO₂ and other emissions.

In further refining Question 3,

Question 3-1) If the question is “*What is the current impact of aircraft NO_x compared with other aircraft pollutants?*”:

Radiative forcing is the most appropriate metric and the recent radiative forcing assessment of Lee et al. (2009)⁵ may provide a useful starting point (see figure below) for the year 2005.

Question 3-2) If the question is “What will be the future impact of aircraft NO_x at some future point in time?”:

A scenario needs to be constructed that accounts for growth, fleet, and technology changes (again an illustrative starting point is the assessment of potential RFs in 2050 according to two SRES-based scenarios, with technology variants from Lee et al (2009) reference 1.

Question 3-3) If the question is “what is the impact of a kg of NO_x compared with a kg of another pollutant?”:

Then a relative metric like a Global Warming Potential or Global Temperature Change Potential is needed. GWPs for aircraft NO_x are feasible but require further refinement, again see reference 5 GTPs for aircraft NO_x are ‘downstream’ metrics of GWPs and thus any requirement for improvement in a GWP is handed on to a GTP. GTPs introduce other parameters that have inherent uncertainties but represent a policy-useful metric for comparing emission impacts on a one-to-one basis.

Aviation Radiative Forcing Components in 2005

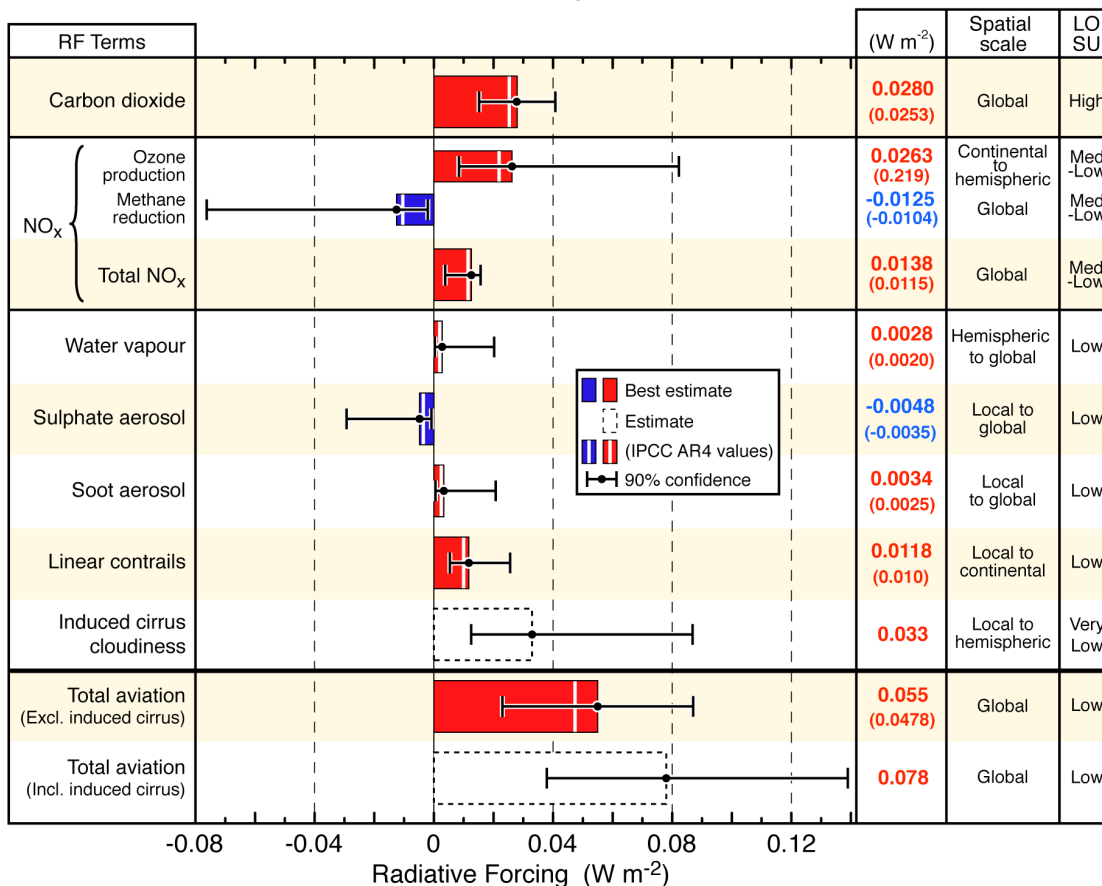


Figure 1. Radiative forcing components from global aviation as evaluated from preindustrial times until 2005.

⁵ Lee, D. S., D. W. Fahey, P. M. Foster, P. J. Newton, R C. N. Wit, L. L. Lim, B. Owen and R. Sausen, “Aviation and global climate change in the 21st century,” Atmos. Environ, 43 (2009): 3520-3537.

The bars represent updated best estimates or an estimate in the case of aircraft-induced cirrus cloudiness (AIC). IPCC AR4 values are indicated by the white lines in the bars as reported by Forster *et al.* (2007a)⁶. The induced cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the right for both IPCC AR4 (in parentheses) and updated values. Error bars represent the 90% likelihood range for each estimate. The median value of total radiative forcing from aviation is shown with and without AIC. The median values and uncertainties for the total NO_x RF and the two total aviation RFs are calculated using a Monte Carlo simulation (see text). The Total NO_x RF is the combination of the CH₄ and O₃ RF terms, which are also shown here. The AR4 value noted for the Total NO_x term is the sum of the AR4 CH₄ and O₃ best estimates. Note that the confidence interval for ‘Total NO_x’ is due to the assumption that the RFs from O₃ and CH₄ are 100% correlated; however, in reality, the correlation is likely to be less than 100% but to an unknown degree (see text). The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right.

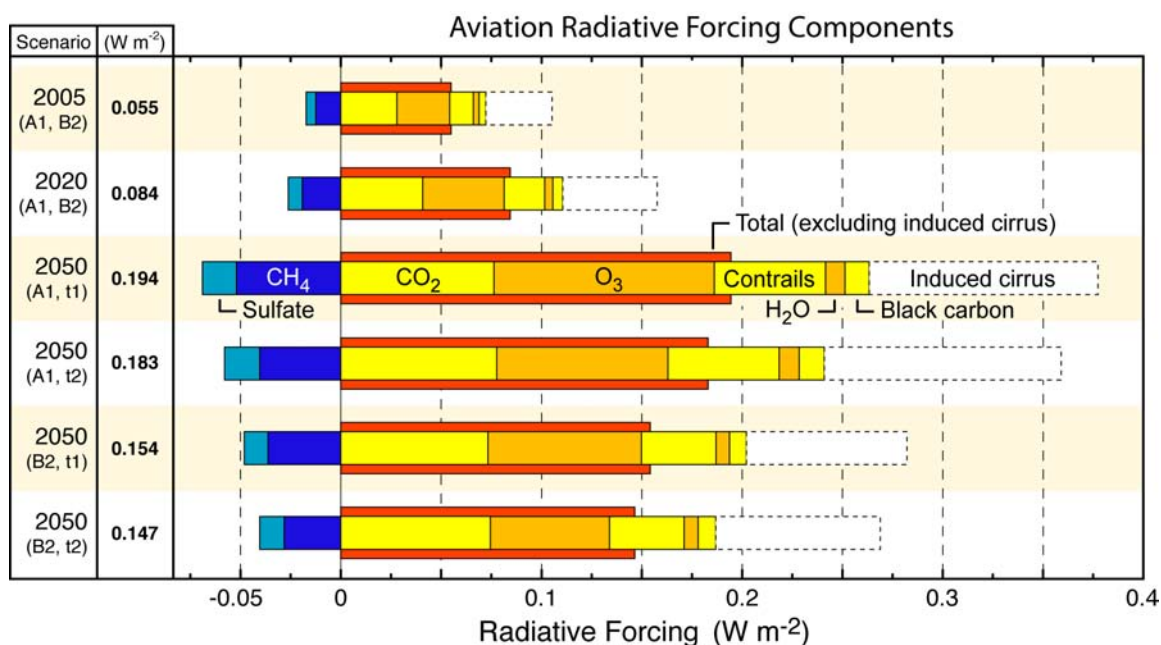


Figure 2. Aviation RF components for 2005, 2020 forecast and 2050 scenarios A1(t1), A1(t2), B1(t1), and B1(t2) as described by Lee et al. (2009). The total aviation RFs as shown by the red bars and numerically on the left do not include estimated induced-cirrus (AIC) RFs.

Given the information considered, the IEs ultimately noted that NO_x can be as important as CO₂. Either one of these can present the greater threat depending on the time horizon. Though the relationship has not been quantified, it appears that this may be possible in the near future. It is clearly important to reduce both NO_x and CO₂. The role of cirrus/contrails/PM on global climate

⁶ Foster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

effects continues to be uncertain as shown in the figures above and therefore difficult to relate to the effects of NO_x emissions. It continues to be important to limit SO_x and PM, but from a global climate perspective CO and HC are not a significant concern.

Question 4) *To what extent are these consensus views?*

The RFPs/SFPs noted that their assessments are a community consensus based on all the reports, publications, and workshops of which they have knowledge. The IEs agreed that for the most part, scientific information shared was based on consensus (IPCC 1999 report on aviation, the IPCC's Fourth Assessment Report, and CAEP's Impacts Workshop). However, some of the information presented, on the possibility to use Global Warming Potential (GWP) to relate CO₂ and NO_x, was based on very preliminary data.

Ultimately, on air quality issues, the importance of NO_x and particles as hazards to human health has been studied for many years and there is strong consensus that these are pollutants that should be minimized. On climate issues, there is strong consensus that aviation NO_x remains a significant contributor to current and potential future radiative forcing.

Question 5) *How would you rank the relative importance of: CO₂, NO_x, CO, UHC, SO₂, Soot, PM, other (without quantification) in the next 20 and 50 years?*

In the next 20 years and 50 years, the uncertainties associated with the forcing and estimated climate responses will decrease. Independent of how the science progresses, an appropriate metric will still be devised to rank the relative importance of these individual emissions.

a) **Surface Air Quality:** NO_x, PM, and UHC emissions are going to continue to be very important for the near future. The RFPs/SFPs believe that aspects of PM may take on increased importance, as these emissions become better understood. However the IEs noted that the CAEP Impacts workshop gave a much stronger endorsement to the relative importance of PM because of its contribution to mortality versus morbidity by ozone. This may however be negated by the contribution of NO_x to PM formation. Ultimately, NO_x, UHCs, and PM are linked via condensation and atmospheric processing, so relative rankings are marginally meaningful or useful. Distinctions between "soot" and "PM" will not become clear until much better understanding is obtained, so PM as listed included soot.

b) **Climate Change:** CO₂ and NO_x are both first order contributors to radiative forcing, although their lifetimes (via ozone and methane lifetimes for NO_x impacts) are different. PM has potentially important impacts but with very large uncertainties. As those uncertainties get reduced, the role of PM will become clearer. The question implies a particular type of assessment, i.e. marginal effects of an extra unit mass. The precise rankings and timings of the importance of aviation emissions and effects depends upon the time horizon utilized, the metric (GWP or GTP) and several key uncertainties in the input parameters to these metrics need to be reduced before giving a definitive ranking. What is certain, however, is that the longer the time-horizon, the greater is the tendency to weight CO₂ as the most important emission. The question could also imply the 'now' nature of radiative forcing: if this is the case, it is adequate to compare the relative rankings of the RFs. However, which question is being posed and for what purpose requires careful consideration.

Based on the information provided, the IEs agree that NO_x and CO₂ appear commensurately important when it comes to climate, dependant on the time horizon. NO_x is very important for

surface air quality – however PM and SO_x appear to be gaining in importance and may even overtake NO_x; CO, and UHC continue to be secondary effects.

4.3.2 New questions for the RFPs and SFPs

Question 6) *What is better understood since last time?*

The role of NO_x in adding to PM is taking on increased importance and is being actively studied.

Uncertainties in NO_x impacts in climate change are being reduced. Research is continuing on the impact of PM on radiative forcing via cirrus and contrail effects, but the uncertainties remain quite large. We know more than last time about aircraft-induced cirrus, although significant uncertainties remain. What is far more uncertain is the indirect effects of aviation particles on cirrus, i.e. the propensity to trigger additional cirrus from the emitted particles and the sign and magnitude of the resultant forcing.

Tools are being developed to assess relative impacts of various emissions, including analysis of costs and comparisons of disparate impacts. These tools and the metrics used in developing them are areas of much research activity. However, the clarification of the input data to such tools is still of primary importance, and these inputs are science-based.

The IEs concluded that three years is not much time when it comes to improving understanding of climate effects. There does appear to be greater certainty that the net impact of NO_x emissions is positive (contributes to warming). It also appears that after some further refinements GWP could be used as a metric to relate NO_x and CO₂ impacts. The effects of contrails/cirrus, however, continue to be as uncertain as before.

Question 7) *Would reduced fuel burn (with NO_x remaining constant) be good for reducing climate impacts beyond that of the CO₂ effect? Can you clarify changes in climate impacts from non-CO₂ emissions as they relate to fuel burn? What are the nonlinearities and the relative sign (+/-) of the impact?*

The RFPs/SFPs noted that in considering the total impact on climate from the global fleet, reducing CO₂ emissions with a constant fleet EINO_x will be beneficial from the reduction in CO₂ and the resultant reduced emission of NO_x. Nuances beyond this simple situation require scenario definition and analysis.

The IEs also probed where reducing water vapor as a target would be beneficial. From responses received it does appear that there are few gains to be made from reducing water vapor. The climatic impact of contrail formation is driven largely by the number of aircraft movements versus the total mass of water emitted. Even small amounts of water vapor can lead to cirrus cloud formation; hence a large number of smaller aircraft flying in a region of the atmosphere favorable to contrail formation could conceivably have more impact than a few large aircraft.

On the climate impacts of non-CO₂ pollutants, non-linearities arise from atmospheric chemistry, changing background atmosphere in terms of composition and physical parameters (i.e. from climate change) and changes in technology. Generalizations are difficult, if not impossible, beyond this in the absence of scenario definition.

Question 8) *Are there ways of reducing some pollutants (e.g., SO₂ from low sulfur alternative fuels) that enable additional reductions in NO_x (perhaps by giving more flexibility in the design space.)*

This question can be interpreted in several ways: as a technology question (which the RFP/SFPs felt they are not best to answer) or as question on impacts trade-offs. On the question of impacts trade-offs, quantitative evaluation of the trade-off would require a metric as previously discussed.

In qualitative terms, NO_x, SO_x, and PM are interrelated through PM formation processes, so that, as long as PM mass alone is the PM metric, there can be trade-offs between these species in regard to their PM contributions. However, only using PM mass as a metric is not likely to remain unchanged in the future, and pressure to reduce individual PM components may be judged individually on their own impacts. NO_x will have its ozone (AQ) impact and climate change impacts via ozone and methane changes. However changes in other pollutants do not have first order impacts on those effects, so the RFPs/SFPs flexibility in NO_x probably cannot be “bought” by reducing other emissions.

The RFPs/SFPs did not comment on alternative fuels. The IEs do note that it is possible to reduce or remove SO_x by removing sulfur from conventional jet fuels (or by means of alternative fuels, that are naturally low sulfur). The same technology that is currently used to remove sulfur from gasoline and diesel fuels could be used to de-sulfurise conventional jet fuel although capacity would clearly need to be increased. However on a life cycle, greenhouse gas, basis, this will entail some additional energy cost (CO₂ production) during processing. For alternative bio based fuels, there are no such additional penalties because the feedstocks and the processes used to produce jet fuel, naturally lead to a low sulfur product. However the production of aviation fuel from a bio-source generally has a somewhat higher energy cost than the production of fuel from a hydrocarbon source. The IEs expect to get feedback from industry on the implications to combustor design. This may contribute to progress in NO_x reductions by future reviews

Question 9) *How robust (quantitatively) is the view that aircraft contribute to cirrus?*

The view is robust – has been proven by observation. What is difficult is quantifying the effects as shown in the figures 1 & 2 above.

4.4 Summary

Based on input from the RFPs/SFPs as well as review of available literature, evidence strongly points toward the need to continue to pursue NO_x reductions, both from an air quality as well as a global climate perspective. NO_x and CO₂ appear commensurately important when it comes to climate impacts although, crucially, this depends on the selected time horizon. Therefore care should be taken when trading one against the other in the pursuit of technology gains. NO_x is very important for air quality. PM and SO_x appear to be gaining in importance and may even overtake direct NO_x emissions. However, NO_x does contribute to PM formation, so targeting its reduction also leads to gains from reducing the health impacts of PM. CO and UHC continue to be secondary effects.

5. Technology Review

5.1 2009 Review Data

5.1.1 At the 2009 Review IEs were provided data from the various manufacturers on recent certifications (2006-2009) as well as progress on technology developments. A summary of the data was compiled by the IEs and is presented in Table 1 on page 19.

5.1.2 Figure 3 was supplied by ICCAIA and shows the data presented for recent certifications at the 2006 review.

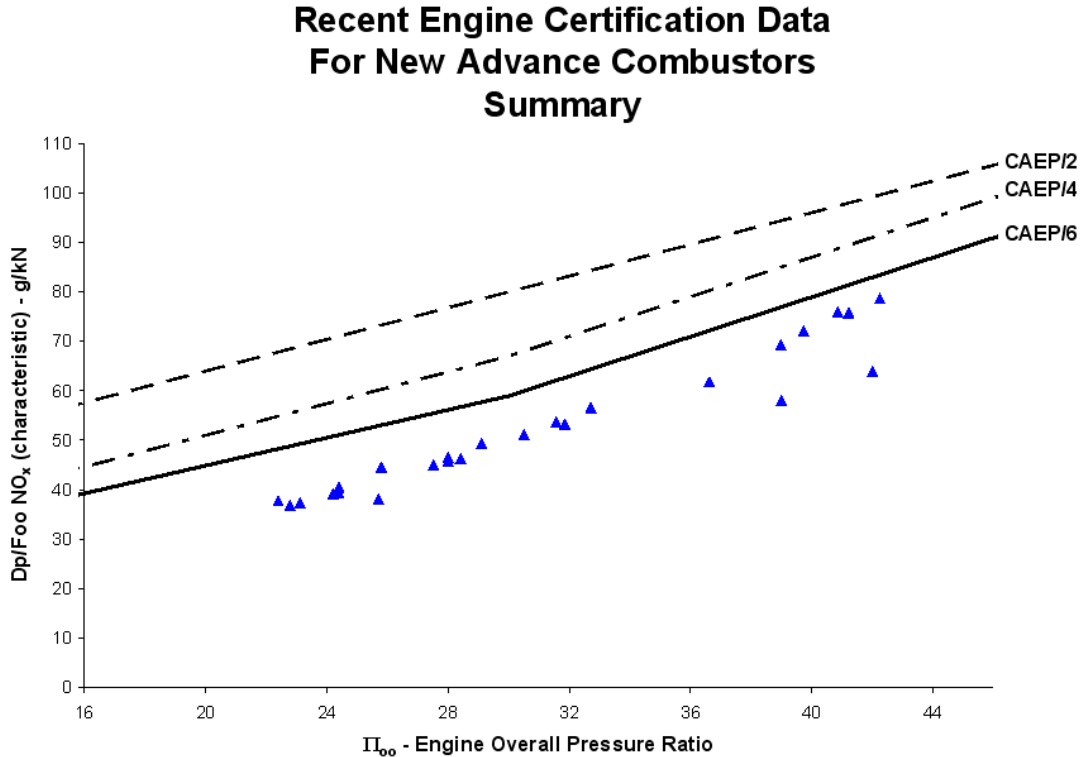


Figure 3. ICCAIA Data for Recent Certifications and Progressive CAEP Standards Presented to the 2006 Review.

5.1.3 Figure 4 is an updated version of Figure 3 provided for the 2009 Review. This figure depicts several layers of information: engines certified prior to 2006, certifications for the period between the 2006 and 2009 Reviews, data points for anticipated engine certifications and data for high TRL rig tests and demonstrations. The figure also shows the CAEP stringency lines and the 2006 Review MT and LT goal bands. Immediately apparent are the considerable number of engines certificated in the 3 years since the last Review and having comfortable margins below CAEP/6 (green points). Also very striking are the data for very recent uncertified engines and high TRL demonstrations (orange points).

	Engine	Thrust		OPR	NO _x (% CAEP6)	Combustor Technology	Certification
		kN	kLb				
L	GEnx-1B	255-322	57.3-72.4	34.9-42.7	36-48	DLI (TAPS)	Proj. 2010
L	GE 90-94B PEC	354-431	80-97	35.5-40.8	86-94	RQL (Optim)	2008
L	GP 7200	332.4-376.4	74.7-84.6	36.6-40.9	85-94	RQL (Optim)	2008
L	Trent 1000	277-332	62.3-74.6	37.7-44.1	64-67	RQL	Proj early 2010
L	Trent XWB	390	87.7	45.5	62	RQL	Proj 2011
L	RR DLI	Tbc	Tbc	39	38	DLI	TRL < 7
L	PW 4000 Adv. 70	287-311	64.5-70	31.3-33.8	85-87	RQL (TALON2B)	2008
M	PW1523G	104.6	23.5	35	50 (Proj)	RQL	TRL 6 October 2008
M	V2500 Select One	98-150	22-33	25.7-33.7	77-82	RQL	2009
M	CFM 56-5 B/TI	94.7-142.4	21.3-32.0	22.6-32.8	67-80	RQL (Optim)	Tbc
M	CFM 56 TAPS	121.4	27.3	28.8	44	DLI (TAPS)	Demonstrator
M	CFM 56-7 B/TI	86.7-121.4	19.5-27.3	21.4-29.0	72-79	RQL (Optim)	Tbc
M	PW1217G	73.9	16.6	30	54 (Proj)	RQL	TRL 6 October 2008
M	CFM 56-7B DAC	91.6-121.4	20.6-27.3	22.6-28.8	66-70	DAC	1997
M	CFM 56-5B DAC	102.2-142.4	23.0-32.1	24.3-32.9	58-76	DAC	1995
S	BR725	71.6	16.1	25.2	77	RQL (Optim)	2009
S	CF34-10A	75.4-83.7	17.0-18.8	25.0-27.2	79.81	RQL (Optim)	2009
S	Sam 146	68.9-77.8	15.5-17.5	20-23	65-70 (Proj)	RQL (Optim)	Proj. October 2009
S	PW 810	Tbc	Tbc	n/a	n/a	RQL	Proj. June 2009
S	HTF 7000-1	30.6	6.9	22	75* (Proj).	RQL (SABER)	Proj. mid 2010

S = Small, M=Medium, L=Large. Tbc=To be confirmed. Optim = optimized. n/a = not available. Proj = Projected, *HTF7000-1 with thrust alleviation

Table 1. Summary of Key Combustor Technology Data (LTO NO_x emission) for Engines and Demonstrators Presented to the Review and Compiled by the IEs.

Recent/Near Term Engine and In-Production Certification Data Summary for CAEP/8

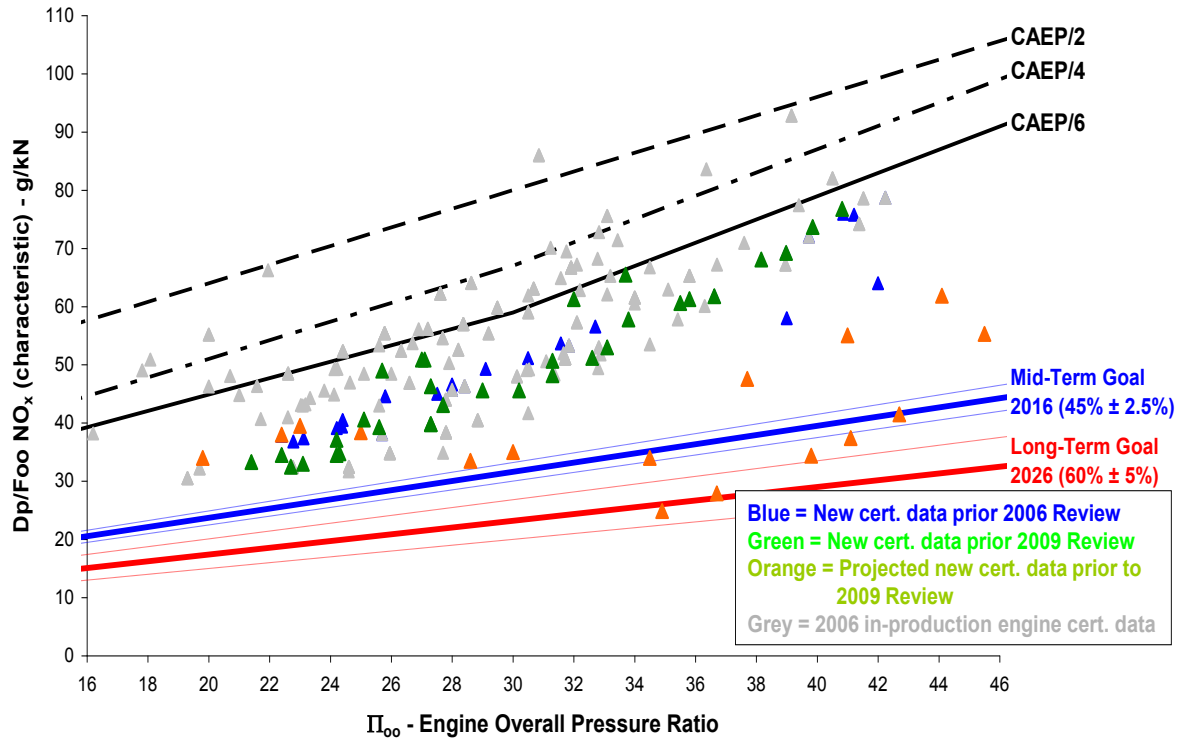


Figure 4. Data presented to the 2009 review including uncertified and high TRL Demonstration Results.

5.1.4 Figure 5 below has been produced by the IEs based upon data provided to the Review by ICCAIA. It develops the data included in Figure 4 identifying engine types both certificated and uncertified, and has been extended to include the high TRL demonstrators and predictions. Where available, this Figure also identifies data for engine families over the design OPR range.

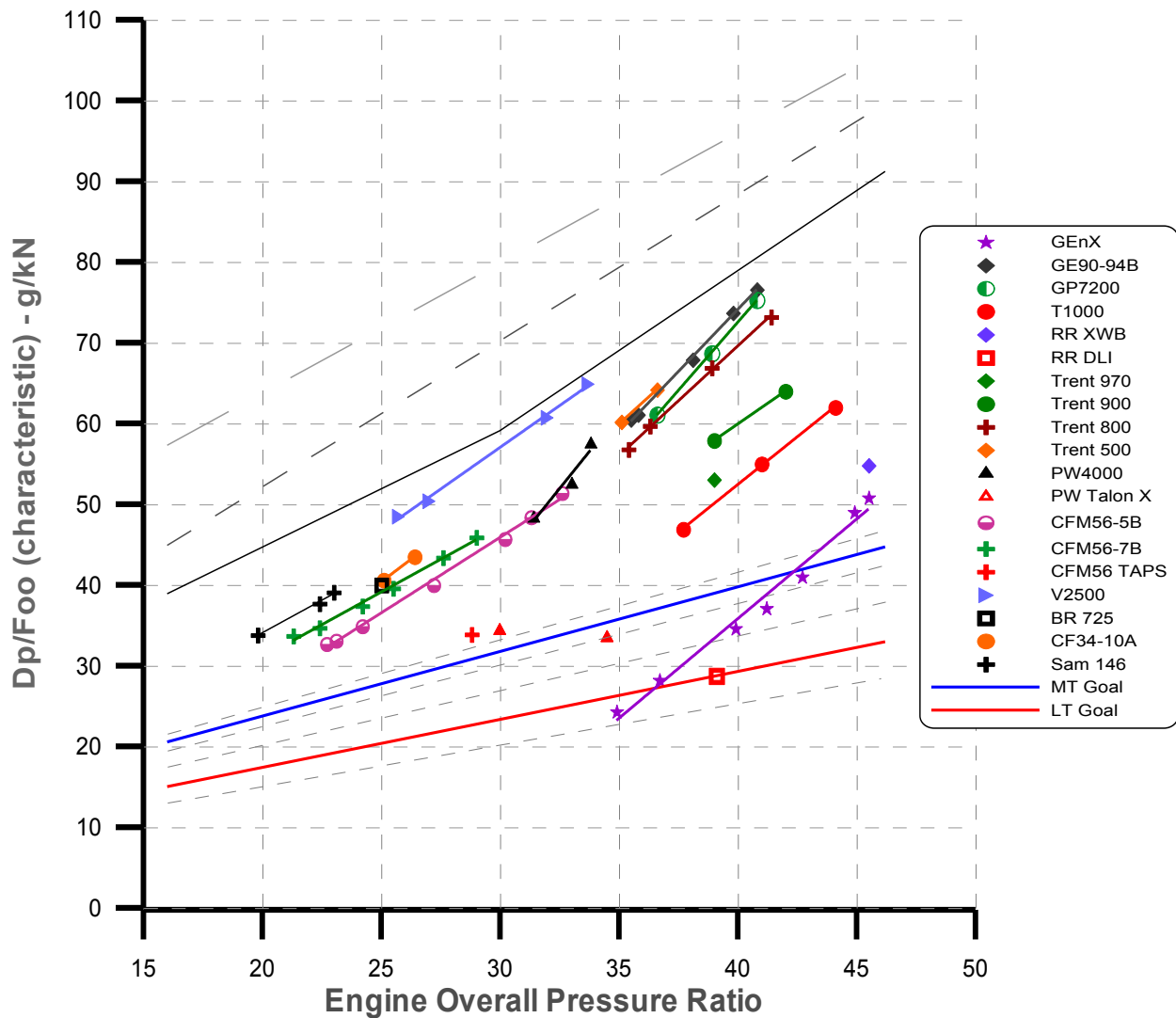


Figure 5. Historical Engine Data Points, Recent Certifications, Uncertified Engines and High TRL Tests and Demonstrations – figure compiled by the IEs.

5.1.5 All recent engine certifications use RQL technology. Since the 2006 review, all products fall below the CAEP/6 line (with a few exceptions for which industry representatives indicated there would be only limited production.) Performance projections presented for engines using RQL technologies would indicate that, though a challenge, these products will achieve the MT goal by 2016. Manufacturers have plans in place to continue efforts to achieve TRL8. These projections for RQL, coupled with the achievements of the GEnx-1B using staged direct lean injection (DLI) combustion, would indicate that there is a good chance that the MT goal will be met.

5.1.6 There is a consensus amongst the IEs that RQL technology appears to be well poised to meet the MT goals though a considerable challenge remains; however, from data presented by two large engine manufacturers lean burn technology would seem to be essential to achieve LT goals, especially at high OPRs. Although manufacturers did not explicitly state that RQL has hit a limit, they assessed the potential for meeting the MT Goal as ‘possible but tough’ and did acknowledge that the next 10% reduction below today’s capability would be extremely hard to achieve.

5.1.7 In respect of the LT Goal, the presented data points for the GEnX 1B engine at TRL7 were shown already to lie within the LT band, albeit at conditions well below the maximum design thrust⁷, and this coupled with the fact that a second manufacturer has demonstrated lean burn technology at TRL 6 sitting at the mid-point of the LT band, there is increased confidence that this LT goal will also be met and possibly before the due date.

5.2 Status of LTO NO_x in Certificated and High TRL Uncertified (TRL6 and TRL7) engines and rigs

Larger (higher OPR) engines:

In Summary, the IEs noted that very substantial progress has been made toward both the MT and LT goals; however, at this time, no manufacturer has yet met either goal as defined by having achieved TRL 8. It was noted that considerable progress had been made using RQL combustors but with a significant margin remaining to the MT goal. Data points for the first staged DLI combustors projected from TRL7 (GEnX) showed a remarkable spread of results across both the MT and LT Goal bands together with a (RR) DLI projection from TRL6 meeting the LT band.

5.2.1 GE GEnX. (TRL 7)

Amongst the larger engines, notably one engine, GE's GEnX-1B (using TAPS 1 staged lean burn combustor technology) appears very close to achieving the MT goal and, as depicted in Figure 3 at lower OPRs, of penetrating the LT goal band also. Preliminary certification data shows a range of reductions of 50 to 65% margin relative to CAEP/6 over the OPR range 45 to 35. At ~ 42.7 OPR- the engine design point - the reduction is ~ 50% of CAEP 6. The four points lower than the design OPR indicate data collected at de-rated engine conditions during the preliminary certification test. The IEs were told that the sales potential for the most de-rated engines could be low - a sales figure of less than 5% was quoted. The question of engine de-rates in respect of meeting Goals is discussed fully in section 6.3. The manufacturers noted that this engine was expected to undergo certification very close to the timing of the Review; therefore there is a reasonable degree of certainty that it will achieve TRL8 within the year. On the face of it, this would indicate that the MT goal will be met and that the LT goal could also be met in a lower OPR engine. The GEnX 1B as shown is expected to offer a 50% reduction at 42.7 OPR to lie on the MT goal line in the middle of the goal band. Therefore, given the original definition of a goal, when this engine achieves TRL 8, it will have met the goal for its design OPR. Considering OPRs either side of this 'design' condition, at de-rated conditions, this engine exceeds (is lower than) the MT goal and at the lowest OPR shown (34.8) is shown to be expected to sit at the middle point of the LT goal band. On the other hand, at growth conditions (between 44 to 46 OPR) the data points are shown as lying above (not meeting) even the MT goal band though perhaps poised to meet this goal by 2016. Such a spread of performance against the 2006 Goals raises questions not only about goal definition but also market appeal as at the lowest OPRs there is expected to be only a very limited market for these products. It is worth noting that in thrust terms, the OPR data points presented represent a thrust spread of 52Klbs to 75Klbs. These questions are discussed more fully in Section 6.

5.2.2 GE engines GE90-94B and CP7200

GE 90-94B (PEC) is a GE90-94 engine that has been fitted with a combustor upgrade to reduce NO_x emissions at the highest OPR condition to meet CAEP/6 requirements.

The GP7200 is an Engine Alliance engine designed for the Airbus A380 aircraft in both passenger and freighter versions which will also meet prospective CAEP/6 requirements over its full OPR range.

5.2.3 Rolls-Royce Trent 1000,

The IEs were shown data for recent Trent series of engines (some of which had been certified just prior to the 2006 review). All of these engines featured RQL combustors that had incorporated significant

⁷ The data points relate to the B787 family of aircraft.

improvements in stages from one engine series to the next. For example the progression in NO_x reduction can be seen going from T500 – T800 – T900 – T1000. All of these engine families are easily compliant with CAEP/6, and for the later versions particularly, represent something of a step change in NO_x reduction achieved since the 2006 Review. Data at three OPRs are identified in Figure 5 for Trent 1000 at ~ 44, 41 and 37.9 OPR that show NO_x reductions of ~30, 31 and 36% respectively compared with CAEP 6 and show significant improvements compared with even the Trent 900. The data points shown relate to the Trent 1000 that was certified in August 2007. However engine efficiency improvements have been incorporated, since certification, for which there are no up-to-date emissions data. The engine is expected to be re-certified during the autumn of 2009 or early 2010.

5.2.4 **Rolls-Royce Trent XWB (TRL7) and DLI (TRL6)**

Data for RR XWB engine with further evolved RQL technology is shown at ~ 45.5 OPR (~ 39% reduction from CAEP6). Although higher than GENX TAPS, the performance of XWB at the highest OPR is, unsurprisingly, similar since, in the main combustion zone, both combustors will be operating close to the rich boundary of the lean range. Interestingly the slopes of both GENX TAPS and Trent 1000 data points are close to parallel with the high OPR CAEP 6 line. If extrapolated both would intersect zero Dp/Foo at OPRs higher than 16. As noted elsewhere this indicates the increasing difficulty of NO_x control at high OPRs and combustion air temperatures and indicates a potential for even higher NO_x reductions at moderate OPRs.

5.2.5 **Data for a RR DLI** combustor test at TRL 6 is shown at ~ 39 OPR (29 Dp/Foo - 68% reduction from CAEP 6) – almost exactly at the long term goal line and a little below the GENX data points. This performance may be degraded during development from TRL6 to TRL8 as a result of meeting other engine operating objectives such as handling, durability etc.

Mid OPRs:

In summary, again no manufacturer had met either goal. Improvements employing RQL combustors have been achieved though with a considerable gap still to be closed. At these OPRs, engine data was presented projected to meet the MT Goal using both advanced RQL (TALON X) projected from TRL6, and DLI combustors (CFM TAPS) projected from TRL7. For these OPRs, no specific data was presented projected to meet the LT Goal

5.2.6 **The P&W 4000 Advantage 70** (31 to 34 OPR), with Talon IIb (RQL) combustors has been demonstrated to give ~ 20% reduction in NO_x relative to CAEP 6 (figure 5). Increased, aggressive, exploitation of advanced Computational Fluid Dynamics (CFD) technology was credited with enabling much of this improvement. Further combustor developments identified as Talon X (RQL) have been tested at TRL6. Data points for two tests are shown at ~30 and 35.5 OPR. These points straddle the Mid Term Goal line and indicate NO_x reductions from CAEP 6 of ~45 and 50% respectively. As with the Rolls-Royce TRL6 data this performance will be liable to erosion during development to TRL8. Predictions for this combustor to TRL8 (Fig 5) anticipate NO_x production within the mid-term goal band. This performance also (as with RR) represents a substantial step change compared with the preceding P&W 4000 Advantage 70 technology that is now certificated at ~ 38% reduction from CAEP 6. Future combustor design philosophy is to continue with RQL on grounds of reliability, operability, flexibility and weight.

5.2.7 **The P&W 1217 and PW 1523G** (new geared fan engines) were described briefly. The 1217 engine in the 66 to 76 kN thrust class is intended for application in the Mitsubishi regional Jet (MRJ). A single projected data point was shown for this engine at OPR 30 and 54% CAEP6. The higher rated 1500 engine has been chosen to power the Bombardier C series aircraft with thrusts around 105kN and around 34 OPR. Again a single predicted data point was presented at around 50% CAEP6. Predicted NO_x levels are shown for both engines in Figure 5 marked as TalonX. More specific performance data was not available.

5.2.8 **CFM 56 engines** from CFM International with ‘Technology Insertion’ can also be seen in Figure 5 in the Mid OPR ranges: CFM 56-7B between ~22 and 29 OPR and CFM56-5B between ~22.5 and 32.5 OPR. These are replacement engines for the ubiquitous CFM 56 range that offer all-round improvements including fuel-burn and NO_x. The NO_x reductions therefore are from both cycle and from combustor (GE) improvements. For example CFM56-7B gives a NO_x reduction of ~33.3 % from CAEP/6 at mid way through the OPR range and CFM56-5B produces ~ 27% reduction. These NO_x levels are slightly higher than those achieved with the Double Annular (DAC) combustor versions but involve simpler, probably lighter technology.

5.2.9 **CFM TAPS engine demonstrator:** Also at mid pressure ratios ~28.8 OPR is a data point for the CFM TAPS demonstrator lying close to, but just above, the top of the Mid Term band. Only this single data point was provided though the Review was told that the demonstrator engine had accumulated 900 hours of running over 4000 endurance cycles. No additional information was provided in terms of staging, engine transients etc. Nonetheless the tests appear to demonstrate the ability to scale TAPS DLI technology down to suit Mid OPR engines. This engine is significant in that it represents the only DLI – type combustor at any OPR other than high OPRs.

Lower OPRs:

In summary, data was presented showing considerable activity within four engine manufacturers of smaller low OPR engines using improvements to RQL combustors. Nonetheless, a considerable margin remains to be closed before even the MT goal will be reached. No projected data points were presented for DLI systems for smaller low OPR engines.

5.2.10 **BR725:** A data point for the RRD BR 725 engine is shown at 25 OPR. The RQL combustor produced a NO_x reduction of 34% relative to CAEP 6. This engine was type certificated in June 2009.

5.2.11 **CF34-10A:** (~ 26 OPR) Two data points are shown for this derivative engine that are ~ 29.5 % lower than CAEP/6 and ~ 10% lower than the earlier engine versions.

5.2.12 **SNECMA SAM146:** (~20 to 23 OPR and 15500 to 17500 lbs SSLT) has been demonstrated at about 80% of CAEP6 (again Figure 5). This has been demonstrated in rig tests at TRL6 and in HP engine core tests. Again this uses a re-designed and re-optimized RQL combustor. The stated overall ambition is to achieve performance at about 20 to 30% lower than CAEP6. It is anticipated that the engine will be certificated in late 2009.

5.2.13 **The Honeywell HTF 7000-1:** (around 22 OPR and 7000 lbs SSLT). The baseline HTF7000 engine is to be refitted with the SABER–1 combustor that is, currently, in its development programme. On the basis of one engine test, the SABER1 combustor has produced an emissions index reduction of about 25% compared with the baseline combustor (from a Dp/Foo of ~ 64 to ~ 53). This improved performance is ~ 4% higher than the CAEP/6, high thrust engine characteristic but ~ 25% lower than the CAEP/6 line with the low thrust allowance included. An extensive test program, including flight testing, is planned leading to the incorporation of the SABER-1 combustor into a new engine variant (HTF 7000-1) intended for EIS in 2010. A further development of the combustor -SABER-2 - is in the R&D phase and is intended to provide >40% margin relative to the baseline engine and would, therefore have a ~10% margin relative to the high thrust CAEP/6 line. SABER 2 is intended to be available for EIS from 2013.

5.2.14 **P&W 800** Selected for the Cessna Citation Columbus. General descriptions were presented incorporating a PW Talon II (RQL) combustor. This engine has considerable core commonality with the larger ‘PurePower’ GTF family but itself has a direct drive fan. As a result of the low NO_x combustor and the reduced fuel burn, NO_x reductions of ~ 50% from CAEP 6 are predicted. The engine is expected to be certified in 2011 and enter into service in 2014. No other information about performance was presented.

5.3 Issues Related to Small and Medium Size Engines

5.3.1 A key question is whether the same combustor technologies applied to larger, higher OPR engines could lead to similar reduction of NO_x emission of small and mid-size engines. However there are a variety of possible difficulties as combustor size and OPR decrease. For example, the scaling-down of complex fuel injector geometries is likely to be challenging since strength, tolerances durability, Reynolds number requirements will impose component dimension and manufacturing limitations. In addition, low combustor air temperatures and pressures reduce droplet evaporation rates and drag and therefore reduce the quality of the lean mixture and the precision with which fuel can be placed in the small primary zone.

5.3.2 To date RQL has been the chosen combustor architecture for engines in the small and mid-size categories. At this Review presentations were made showing further improvements in RQL combustors for small and mid-size engines, for example TalonX, fitted to the PW1217 & PW1523 were shown as projected to meet the MT Goal. However, at this Review (as noted at 5.2.8 above) a single predicted data point was presented for the CFM 56 TAPS demonstrator engine using a staged DLI combustor. It is too early to be sure that the TAPS style of DLI combustion is practicable at mid OPRs though if it is then it is likely that considerable emissions improvements should be made over a useful range of mid engine sizes.

5.3.3 Whilst recognizing the very significant technical challenges in applying TAPS technology at even smaller scales and lower pressure ratios, manufacturers felt there was at least the potential to scale the technology appropriate to smaller engines. Specifically, applications of TAPS II technology for GE's eCore engine appears poised for scale across full range of aircraft applications though how far down the OPR/engine size scale this will reach remains to be seen.

5.4 Rate of technology improvement

There appears to be great potential for exploiting TAPS technology to achieve further NO_x reductions. The future of TAPS combustion technology focuses on further development to produce TAPS II, with better mixed, leaner fuel/air mixtures to achieve additional NO_x reductions. There will then be a development program (eCore) to apply TAPS technology over the full OPR range. It is acknowledged that this, technically, is a very ambitious program. However it will certainly be easier to design and demonstrate TAPS at a relatively large scale (and OPR) and then to scale down, than it would have been to start at small scale.

5.4.1 Notwithstanding the impressive DLI results presented at this review the technology does hold some considerable challenges. For example fuel manifolds in zone 3⁸ have to operate in a severe temperature environment. This is especially true when, during staged operation, there will not be a fuel flow through one, or more, manifolds. Stagnant fuel cannot be exposed to such temperatures because of boiling and coke formation. Therefore either the manifold must be emptied of fuel or all the manifolds must, somehow, be cooled by the remaining fuel flow. The fuel staging valves and actuators also need to be cooled in order to survive in the zone 3 environment.

5.4.2 Evidence relating to the future evolution of DLI combustion was presented to the IE's. This expressed confidence that significant further NO_x reductions will be possible through evolution of the technology. Both improved fuel/air mixing and leaner combustion will be required. However the latter is critically dependent on increasing combustion air which must be at the expense of combustor and turbine cooling – areas already under significant challenge particularly in the highest OPR engines. Improved staging and control strategies are also areas that require ongoing work. It is likely that all the innovations such as complex fuel injectors and manifolds and advanced wall cooling designs are increasing the mass

⁸ Zone 3 in the engine is the unventilated space outside of the combustion system pressure vessel wall and inboard of the by-pass duct wall.

associated with the combustion system and it is noted that there will be a continuing focus on weight, cost and performance trades.

5.4.3 P&W and other manufacturers employing RQL technology anticipate the task of achieving further NO_x reductions to be possible but 'tough'. They expect modest evolutionary improvements through refinements rather than through a further 'step change'. At high OPRs progressive improvements using RQL combustors were shown (RR) closing with the MT Goal but with a significant margin still to be achieved. At mid OPRs, the TALON X RQL combustor was shown projected from TRL6 to be straddling the MT Goal band. These two provide confidence that, though a challenge, the MT goal can be met through this development route. No data was presented for smaller low OPR engines using RQL (or DLI for that matter) combustors projected to meet the MT Goal,

5.4.4 The IEs discussed the rate of technology improvement and considered whether the apparently steep reduction in NO_x offered by GEnX might not necessitate making the MT and LT goals more ambitious. However, the history of leading edge combustor technology improvements shows that after the initial step change, the improvement curve substantially flattens (following a classic technology development S curve in the absence of game changing breakthroughs – such as the introduction of mature CFD, which has allowed more rapid design and optimization). Therefore, it appears that lean burn combustor technology is likely to follow the same development curve such that after a revolutionary step change the rate of improvement thereafter will be much flatter. Moreover, as noted in 5.3 the applicability of lean burn technology to smaller engines (< 26.7 kN) is likely to be substantially more difficult.

5.4.5 Ultimately, progress in achieving goals is subject to investment in R&D. Industry appears to be making considerable investment pursuing NO_x reduction technology. Government investments are less certain. In Europe, at the level of individual nations, some significant NO_x reduction research programmes are underway. At the EU level large investments have been promised but were not shown to be forthcoming. In the U.S., NASA appears to be focusing on fundamental technologies and is not investing the considerable resources that supported the technologies that are now near achieving the MT and LT goals (TAPS and TALON-X). The FAA's Continuous Low Energy, Emissions and Noise Program (CLEEN), put in place since 2006 (in 2009), may fill some of this gap, but this is not yet clear.

5.4.6 The IEs also noted that reducing NO_x via combustor changes is getting to be more and more difficult as we are approaching theoretical limits. For example DLI is only possible if there is sufficient engine core air available, after that used for wall cooling, to achieve lean combustion. This requirement is in conflict with the need for the highest cycle temperature to produce the highest thermodynamic efficiency (the result of this conflict can be seen in GEnX TAPS NO_x at the take off condition (Fig 9). It should be noted that the above reductions in NO_x are not in all cases due solely to changes in combustor technology. Where engine cycles have also been changed resulting in improved SFC then the NO_x reductions may have been achieved as a result of both factors. In such cases industry representatives have stated that a significant proportion of the reductions in NO_x will have resulted from engine cycle changes and in some cases roughly in equal measure. Figure 6 was presented by Rolls-Royce using a constant engine cycle as an example from which to compare the NO_x performance of different evolutionary developments of an RQL combustor as well as the impact of a step-change in combustion technology to DLI (labelled as Lean Burn) if it had been applied to this one engine cycle.

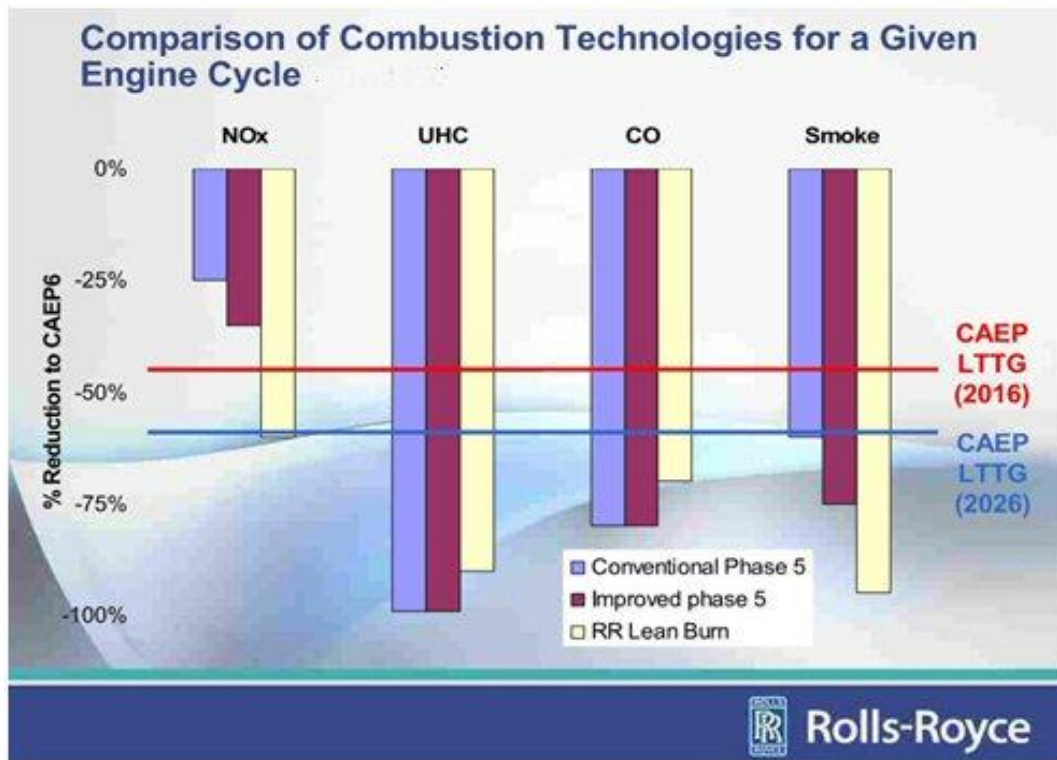


Figure 6. Comparison of Evolutionary and Step-change Combustion Technologies for a Selected Constant Large Engine Cycle .

5.5 Trade-offs

5.5.1 The technologies that are required to address emissions, for example, can have a weight/performance penalty – and hence have some effect in noise. Ultimately, the relationship is indirect. For example, any increase in aircraft weight that requires an engine performance change can result in a fuel burn increase, which could then increase aircraft NO_x emissions. The consequence of, say, noise reductions could result in a NO_x /noise trade-off. Similarly, though not as pronounced, the direct trade between noise and NO_x that can result from the engine design balance i.e. by-pass ratio, OPR etc. will necessarily produce tradeoffs between fuel burn, noise and NO_x emissions, amongst others. The manufacturers have indicated that they always have to reconcile these, and other, trade-offs. One specific example is that of combustor through-flow velocity which, if increased, is likely to increase combustion noise. This is a small example, but can show up as an issue in some cases.

5.5.2 The IEs also explored any weight penalties as a result of advances in combustor technology to reduce NO_x. Manufacturers indicated that when they generate new combustor technology there can be weight penalties. For example, in general terms, combustion section mass increases as a result of innovations required to meet high OPR, high temperature conditions and to reduce NO_x. For example, tiled combustor walls, possibly larger volume combustors, much larger fuel injectors and additional weight of multiple fuel manifolds and associated valves, pumps and control systems are likely to be employed. This additional mass clearly results in a small but necessary trade-off in order to achieve the overall NO_x and fuel burn benefits. Some of these penalties, in DLI combustors, may be offset by reduced SFC resulting from improved combustor exit ‘pattern factor’.

5.5.3 Other potential trade-offs could, for example, result from increased combustor pressure loss needed to drive blade cooling in very hot cycles or from reductions in diffuser performance if combustor heights had to increase or fuel injectors and associated pipe work produced an aerodynamically dirtier

diffuser exit environment. However these have been continuing design concerns throughout the history of the gas turbine and are always the subject of design improvement studies and compromises. The IEs were informed that for CAEP modeling purposes the fuel burn penalty resulting from minimizing NO_x has been assumed to lie in the range between 0.0% and 0.5%. Manufacturers indicated that generally the cost of the combustor technology is not a critical issue. They further noted that the weight “penalty” really comes off gains that new systems generally offer – ultimately the fuel burn reduction in the new product may not be as high as it could have been in the absence of a new combustor.

5.5.4 Overall, Manufacturers point to the overall trade-off involved in the creation of quiet, clean, efficient, competitive engines. Any local, necessary, mass increase may be necessary to meet any objective, such as noise or NO_x but this should be seen in the context of continuing overall mass reductions that are achieved in new engines even when overall improvements are being achieved in all aspects of performance.

5.5.5 Manufacturers who appeared to be less keen to move to lean combustor technology noted that the decision is largely influenced by the weight penalty, complexity and operability of the combustor design. They felt that if by using lean burn combustor technology they could achieve a performance improvement overall, then they could compensate for weight gains associated with the combustor. Ultimately, all manufacturers noted that this weight gain was probably not too significant.

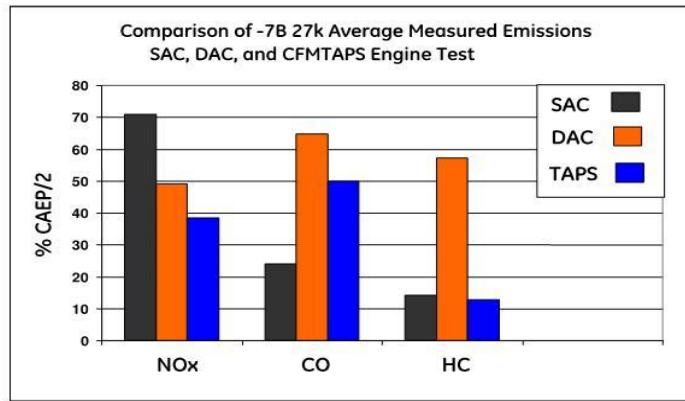
5.5.6 The IEs noted that the need to manage the environmental consequences of design optimization continues to become more complex. However, tradeoffs are a constant factor in design briefs and IEs felt that for some new engine architectures a reduction in LTO NO_x (~10% of total NO_x emitted) may not be reflected at cruise (~90% of NO_x emitted). Under such circumstances more total NO_x could be emitted as a result of such design choices. In particular, some engine designs do not offer as high a NO_x reduction at cruise as those achieved at LTO, for example, Open Rotor designs. This is a potentially significant design trade that should be explored more in-depth at the next review.

5.5.7 IEs noted, from evidence presented, that lean staged burning systems can offer substantial reductions in non-volatile PM (both mass and number). There is some preliminary data that supports this assertion at high power settings, but no information exists to assess performance at lower power settings. One manufacturer did indicate that all PM measurements in lean staged systems were very low. There was no data presented to be able to assess whether this was true also for volatile PM which is largely Sulphur based.

5.5.8 At the 2006 review, manufacturers noted that maintaining combustor efficiency for lean staged burn systems was a challenge, particularly at cruise. The CFM56 TAPS LTO emissions measurements

presented at the 2009 Review would indicate there are still challenges as evidenced by Figure 7. Such challenges are likely to originate as a result of the lean, low temperature combustion producing possible CO and UHC increases particularly at low thrust engine conditions. Manufacturers felt confident that these challenges would be addressed in subsequent developments. At high power there is no issue with efficiency. At cruise conditions, designers have to carefully design, including staging etc for efficiency. Although no details were provided, manufacturers indicated they are making progress toward dealing with the problem. A manufacturer stated that generally they optimize both for cruise combustion efficiency and NO_x emissions, as clearly, combustion efficiency is critical to customers.

CFM56 TAPS LTO Emissions



Significant NO_x reduction with no HC increase
Addressed CO emissions in subsequent development



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Figure 7. Comparison of CFM 56 engine emissions for RQL, DAC and DLI (TAPS) combustor technologies.

5.6 Cruise NO_x

5.6.1 At the previous review, using only RQL evidence, a broad correlation between LTO and cruise NO_x was noted. As LTO improvements were achieved there were, generally, corresponding cruise NO_x improvements. This correlation appears to hold for similar technologies (RQL systems) but the 2006 Review Report noted LTO based correlations from RQL and Rich Burn combustors used for cruise NO_x estimation are unlikely to hold true for lean staged systems where there are substantial fuel placement and air fuel ratio changes as staging occurs.

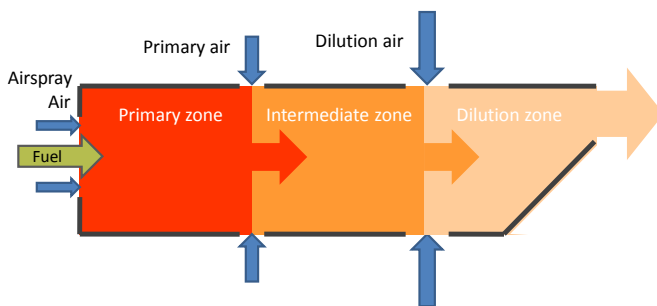


Figure 8. RQL Combustor schematic.

5.6.2 With RQL combustors (shown schematically in Figure 8) there are two useful combustion zones, where the fuel is burned and the product emissions are created, – the primary zone (PZ) and the

Intermediate zone (IZ).⁹ At the Take-off condition the PZ is operated richer than stoichiometric¹⁰. Conveniently, little NO_x is produced in the PZ at these rich conditions because of the low availability of oxygen. Subsequently rich mixture must be diluted with air very quickly to limit the time at peak NO_x production temperatures. However the PZ is operated fuel rich, primarily, to deliver adequate combustion stability over the full LTO and Cruise mission. For example Figure 9 shows possible combustion temperature regimes for a ~ 45 OPR RQL combustor.

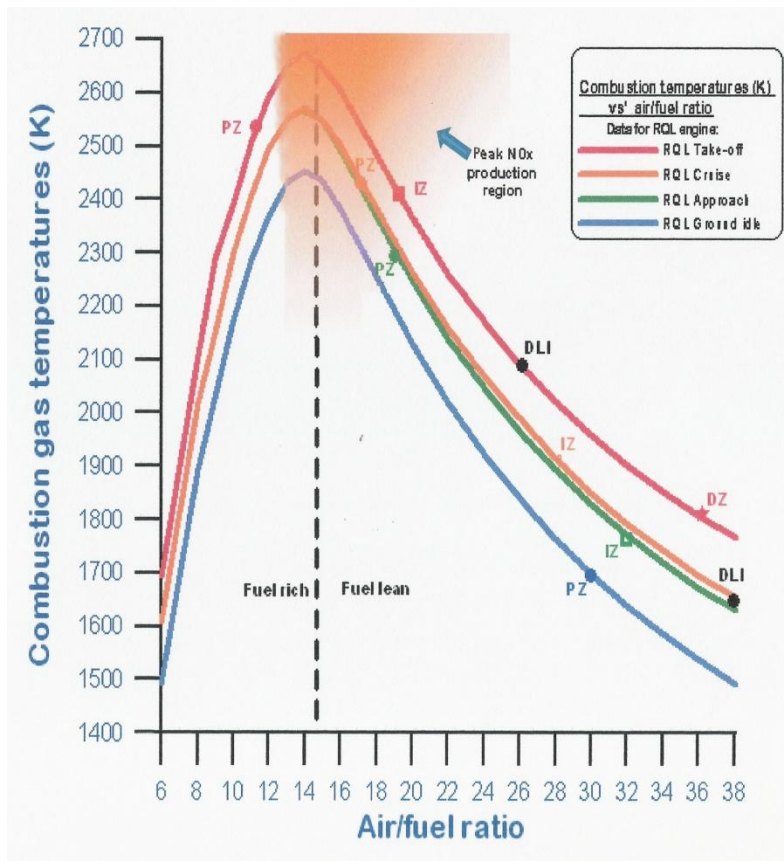


Figure 9. Temperature Regimes for 45 OPR RQL Combustor.

5.6.3 Although the PZ operates at ~ 10 AFR at take-off the PZ temperature at ground idle is only about 1700K (30AFR) which, ideally, is too cool for good idling efficiency. In addition the combustor has to remain stable through even more challenging conditions such as slam decels, and flight idle at start of descent. The reason for this wide operating range is that the combustion zones operate in series such that whatever fuel is supplied to the combustor has to encounter all the air provided for the richest case. A further consequence of the design with the series of non variable combustion zones is in the production of NO_x throughout the LTO/Cruise cycle. The production of NO_x is a function of flame temperature, pressure and time at temperature⁵ (this is the basis for a variety of competent semi-empirical methods for predicting NO_x). Therefore whatever is done at take-off to reduce NO_x, such as improved mixing or

⁹ The Dilution zone (DZ) is responsible for producing a satisfactory pattern factor although it may contribute some residual burnout of CO, H_c and smoke.

¹⁰ At the stoichiometric fuel air mixture all the available fuel burns with all the available oxygen in the air, at conditions richer than stoichiometric there is insufficient air for complete combustion. As a result the products of combustion must include species such as UHC_c, CO, H₂, and smoke.

reduced time at temperature, will also apply at other engine conditions such as cruise. Although the same percentage reductions would not be expected at all conditions. For example (Figure 9): in an RQL combustor at cruise the PZ operates on the lean side of stoichiometric at temperatures where significant NO_x is produced.

5.6.4 Similarly, Direct Lean Injection (DLI) combustors (see Figure 10, schematic diagram) have been devised to operate on the lean side of stoichiometric in order to avoid the NO_x that is produced in the Quick quench zone of the RQL combustor.

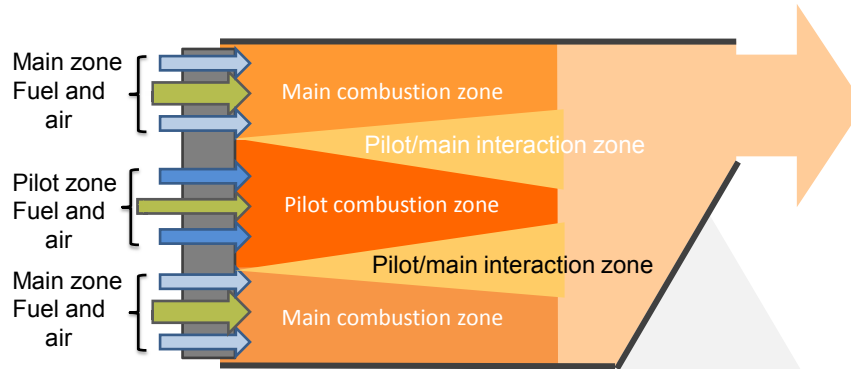


Figure 10. Direct Lean Injection combustor Schematic.

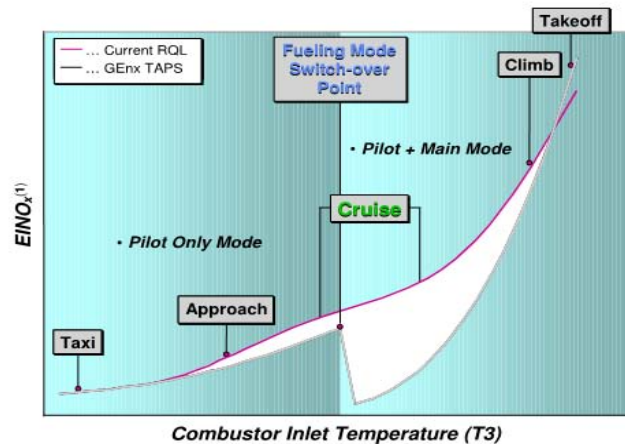
5.6.5 In a DLI combustor at take-off the combustion zones are operated much leaner than stoichiometric to meet LTO requirements and leaner yet at cruise. In many ways DLI combustors are evolutions of the double annular combustor (DAC) philosophy. These were designed with parallel, separately fueled, RQL combustion zones to allow some measure of separate fuel/air ratio optimization of each of the two zones across the flight mission.

5.6.6 Instead of the mechanically separated combustion zones of the RQL the two, concentric zones of the DLI are created aerodynamically in the same combustion space. Each zone is fueled by a separate, independent sprayer so that the fuel air mixture in each zone can be optimized to meet the emissions objectives and the performance demands across the LTO/Cruise mission. Great attention is given to produce the best quality of fuel/air mixing – approaching perfect premix as far as possible. The extent of the interaction between the pilot and main zones is very carefully managed to maintain the independence of the zones whilst, at some conditions, allowing the pilot to support combustion in the main zone and to provide for light-around on staging. If at any engine condition, both zones must be operated very weak or where one zone may be unfueled there is likely to be some system ‘tuning’ required to deliver satisfactory combustion efficiency. Cruise is one such condition where ‘pilot-plus-main’ mode may be switched into ‘pilot-only’ mode. However the IE’s have been advised that the objectives of the tuning are satisfactory efficiency and lowest cruise NO_x that is compatible with the efficiency objective.

5.6.7 Until more experience of certificated DLI engines has been achieved together with the probable differences of approach by several manufacturers it will not be possible to identify a generic scaling relationship between take-off and cruise NO_x similar to that for RQL combustors. On balance it seems unlikely that a scaling relationship will be obtained until the industry evolves the DLI technology to a similar design philosophy (i.e. as has happened with RQL technology). On the other hand there is some evidence, for DLI combustors, that suggests the LTO/cruise relationship appears to be in a positive direction i.e. a substantial cruise NO_x reduction. The issue of LTO: Cruise NO_x is discussed more fully in Section 6.4

5.6.8 Manufacturers with experience of DLI combustor emissions measurements noted that both the size and mass of emitted particulates were very substantially reduced. However Figure 11 (below) illustrates one area of DLI engine operation that often produces problems and often requires considerable design compromises and development effort. As fuel is burned off during cruise the thrust required diminishes and the air/fuel ratio in the combustor that has been operating in Main + Pilot mode becomes very weak. As a result the low NO_x emission performance gets better and better. However at some point, unless the progressive weakening is prevented, lean combustion instability and/or combustion inefficiency would result. Therefore at some chosen condition before this point the combustor is staged to the richer 'Pilot only' mode which, in contrast, may be rather richer than would be optimum and could lead to particulate emissions. Both the smoke and NO_x and possibly CO emissions change very substantially during the staging. This introduces another variable into the design process – where to design the stage point or how the combustor design affects the choice of stage point. This in turn will introduce significant variability into the NO_x emitted during the Cruise cycle and into any LTO/Cruise relationship.

TAPS Fuel Staging



Fuel Staging enables low cruise NO_x levels



(1) EINO_x = Emissions Index to NO_x, measured in Grams of NO_x per lb of fuel

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Figure 11. Fuel staging in a DLI combustor during Cruise.

6. Discussion

6.1 Review of Progress Towards MT & LT Goals

6.1.1 As detailed in Section 5 above, from the 2009 Review the IEs noted that substantial progress had been made towards the achievement of both the MT (2016) and LT (2026) Goals, though neither had as yet been reached using the TRL8 definition.

6.1.2 MT Goal:

Very much in line with the IEs 2006 expectations, progressive significant reductions have been achieved through further developments with RQL-style combustors and also very substantial reductions have resulted from a 'step change' to DLI combustion - though in this latter case not yet quite at TRL8. As a result there is every prospect that the Mid-Term Goal will be met through RQL designs, particularly at mid OPRs, though still a considerable challenge especially at high OPRs, and quite likely more comfortably met with DLI combustor technology. Significantly, lower OPR engines appear to be facing a considerable challenge to meet even the MT Goal with RQL, and it is at least questionable whether DLI architectures will prove practical for engines of this scale.

6.1.3 LT Goal:

For the Long-Term Goal, current evidence suggests that RQL technology will struggle to achieve this level of reduction, and DLI technology will be necessary for this goal to be achieved again particularly at high OPRs. The data presented for the GEnX provides some confidence that this may be achieved ahead of the 2026 date. Beyond the initial step-change offered by DLI, the rate of change of improvement in NO_x reduction is likely to become much slower though with continuing NO_x emission improvements for new engine types as a result engine cycle changes linked to reductions in engine SFC. Step improvements in NO_x performance could be extended to a wider range of engine classes if DLI combustion were able to be applied in medium and small engines. There are, however, concerns at present about possible difficulties working at smaller scale and lower OPRs from various perspectives including weight, cost/complexity, fuel conditioning. If it transpires that DLI staged combustion is more suited to larger high OPR engines and is impractical for smaller engines then it is conceivable that the NO_x characteristic slope across all OPRs will be much flatter than those currently used for Goals (and though outside the terms of this Review possibly also for Stringency).

6.1.4 Step-change improvement through staged LDI:

It is clear that the most radical change since the last Review has been the confirmation of the flight testing of staged lean burn combustion for the GE GEnX-1B family of engines and the resulting evidence presented of measured, though not yet fully certificated, whole-engine NO_x performance showing very significant reductions indeed against CAEP6 and also against current RQL designs – (both were anticipated at the 2006 Review). Fig 5 on page 21 clearly shows these dramatic reductions exhibited by the GEnX-1B family ranging from as much as 67% below CAEP6 at OPR35 (54k lbs SSLT), 53% margin at OPR40 (70k lbs SSLT), and a 45% margin CAEP6 for versions of this engine at OPR46 (75k lbs SSLT). In broad terms relative to the MT and LT goals this translates to the low thrust version of this engine (to be fitted on the B787-3) being expected to coincide with the BOTTOM of the LT goal band, whereas mid thrust versions (for the B787-8) sit between the LT and MT bands, and with the highest thrust version shown (for the B787-9) lying ABOVE the MT goal band. In the light of these results, necessarily, consideration was given to whether to change the Goal bands. A full discussion of the arguments can be found below at section 6.2.

6.1.9 Also presented were data for the CFM56-TAPS (staged LDI) demonstrator engine at TRL7 which was said to have accumulated 900 hours running and 4000 endurance cycles. The NO_x data for this engine was not presented in the same format as for the GEnX (nor incidentally the same as for the 2006 Review), nonetheless it is predicted to lie close to the top of the MT Goal band and close to GE's 2006 prediction.

This single data point gains added importance in the eyes of the IEs given that it represents an early attempt to migrate the DLI concept to mid OPR engines.

6.2 Whether to change the MT and LT Goals set in 2006

6.2.1 The consensus view of the IEs is not to make changes to the Goals during this first Review of the original Goals set in 2006 for the arguments laid out below.

6.2.2 The first question to be addressed was whether the MT [and even the LT] Goal had already been met? The strict answer to this question has been judged by the IEs to be *No* given that no manufacturer had yet achieved TRL8 (full certification) at the time of the Review.

6.2.3 The IEs consider that progress with rich burn combustor concepts, such as RQL on Trent 1000, and anticipated for RR XWB, and P&W Talon X appears to be following the path anticipated in the report of the 2006 Review, namely, progressive improvement towards the MT goal but with the goal remaining a significant challenge. Based on the evidence of progress with RQL combustors alone there would be no reason to even contemplate any change to the position of either of the Goal bands and especially for the MT band as the date of the MT Goal is now only seven years away and can be seen to still represent a considerable challenge particularly for both high OPR and low OPR engines. The two data points for P&W's geared fan engines at mid OPRs (30 and 34.5) have been predicted to lie within the MT band, with this favourable (LTO) outcome being assumed by the IEs to result from a combination of low NO_x RQL combustion and engine cycle.

6.2.4 Moving to consideration of the impact of the first staged DLI combustor system of the GEnX-1B family and the CFM56 TAPS demonstrator, the 2006 Review clearly anticipated this [TAPS] combustor design making an impact within the MT timeframe [for example see 9.5.3.1 of the 2006 Report]. However, the very large flight proven reductions detailed in Section 5.2.1 of this report, (though at the time of the Review not yet having reached TRL8) do pose a greater challenge to both the MT and LT Goals than perhaps was anticipated. A high expectation was expressed at the 2009 Review that certification and achievement of TRL8 for the GEnX-1B would follow soon afterwards in line with B787 EIS expected in 2010.

6.2.5 It is a significant issue that the GEnX-1B NO_x measurements across the range of thrusts presented to the Review span from the bottom of the LT Goal band to the middle of the MT Goal, and even above the MT band at higher indicated thrust developments. In contrast the CFM 56-TAPS appears to lie at around the top of the MT band – though variations with thrust/OPR for this engine were not detailed at the Review.

6.2.6 Clearly, these GEnX-1B results beg the question whether the Goals should be lowered at this Review. The goals chosen in 2006 required a careful balancing between the best anticipated progressive rich burn RQL achievement versus the possibility of significant but less certain (both level and timing) achievement with new 'step-change' lean burn systems (e.g. TAPS). The 2006 Report indeed emphasized that this variety of potential technical solutions increased confidence that the MT goal would be achieved. The impetus for changing the Goals now, clearly, is the prospect of GE TAPS based lean burn staged combustion in the very near future gaining full certification and TRL8 status comfortably in the MT goal band and possibly the LT band also – though see discussion below at 6.3 on Goal definition.

6.2.7 However, pulling in the other direction are a number of factors weighing in the minds of the IEs which have led to the conclusion to desist from changing the Goals at this Review:

1. There is a natural reluctance to change what were intended to be medium and long term goals a little after three years from them having first been set coupled with a feeling that change now could to some extent discredit the Goals particularly if made in haste and requiring later reversion.
2. Strictly, in the absence of TRL8 achievement, the goals, as yet, have not been met, though the prospects do look encouraging that at least the MT Goal will be met in the near future.
3. Staged DLI combustion is recognized as being a step-change in aero-engine combustor technology of a scale that comes along relatively rarely and therefore there is no immediate pressure to change the goals as further improvements remotely close to this magnitude are not expected to be repeated in the next 10 or more years.
4. Given the nature of such step-changes, further elapsed time would provide opportunity for factors to mature that could possibly affect some of the potential reductions. The service experience of the DAC supports this patient approach.
5. It remains questionable whether staged DLI combustion will turn out to be a practical proposition in low OPR/thrust engines and if it is not then such an outcome would likely raise serious questions of the current characteristic slopes of both the Goals (and possibly also Standards Stringency).
6. The IEs recognize that the issue of definition of when a goal has been met has come to the fore [see discussion at 6.3], particularly for families of engines, through the release to this Review of the GEnX engine family data points. As described in detail above, these data points span across both MT and LT goal bands yet there are planned further thrust versions possibly to be developed that would have difficulty meeting even the MT Goal band. The IEs therefore believe that the issue of definition cannot be addressed in isolation and should be coupled with the wider question of re-visiting the goal levels themselves.
7. The IEs understand that the 2006 NO_x Goals are already being used as design targets, in engine bids and competitions and therefore rapid and successive change would not be desirable.
8. The IEs have made a call to the Steering Group for better harmonization of dates within the LTTG process. As a result they are conscious that to make a change to either NO_x Goal at this time with just 7 years remaining, or changing the goal date to 2019, may complicate possible harmonization, for example, when it is understood that the Fuel Burn LTTG Goals are likely to be set at 2020 and 2030.

6.2.8 In summary the IE's have concluded that the Goal bands should not be altered at this Review, either their level or band width, but that these questions should be addressed at a future Review, if one should be held, and in conjunction with consideration of Goal definition (see 6.3 below), and in any case only after TRL8 has been achieved and further in service experience gained with lean burn staged combustion.

6.3 Definition of the achievement of a Goal

6.3.1 At the last review the IEs indicated that a goal is reached when one or more products cross the upper goal band line. The IEs feel that a refinement to that assumption, at the very least requires debate, and may be warranted. This debate needs to consider whether it may be more appropriate that the goal line has to be crossed across a range of engines thrust sizes (OPRs) within one family and/or perhaps even across more than one family.

6.3.2 The IEs believe that the simplicity of the existing definition adopted at the first Review is its greatest attraction, though there are consequent issues of concern to industry and regulators and these

were noted at the time of the 2006 Review. Chief amongst these are difficulties related to the relatively steep NO_x emission characteristic slopes of families of engines (as compared even with the stringency slope) where thrust increase is achieved more through throttle push (increased temperatures) than through substantial re-scaling of the engine. Furthermore, questions could be raised about the implications of perhaps only one manufacturer achieving the goal level, the position and degree of the absence of a certification-style kink in the goal bands, also possible special needs related to small engines. After careful consideration, at the last Review the Panel felt that many of these questions were more appropriate to the debate on regulatory stringency rather than to goal setting, and the ‘simple’ approach served to emphasize the differences between goal setting and standards stringency.

6.3.3 As has been detailed previously the primary challenge at this Review to the Goals set in 2006 comes from data relating to the GEnX-1B though crucially the degree of this challenge depends closely on the thrust/OPR version under consideration as has previously been discussed, the data for this engine covers a strikingly large range across the current MT and LT Goal.

6.3.4 For a more representative picture the IEs turned to Figure 5 previously shown on page 21 of this Report and analysed the characteristic NO_x slopes of the engines shown in that figure. The calculated gradients are shown in Table 2 below together with the associated range of OPRs plotted in Figure 5. Interestingly this analysis shows that the GEnX is not exceptional in terms of gradient and in fact lies centrally within the spread of engine types shown. What is confirmed, however, is that the OPR spread of this engine, lying in the top three, is among the highest of those shown.

MT Goal	Gradient 0.8		
LT Goal	Gradient 0.6		
Engine Type	Characteristic NO_x Gradient	OPR Range Shown	OPR Range Mean +/- (%)
SAM 146	1.6	19.5 – 23	8
CFM56-7B	1.62	21.5 – 29	15
TRENT 900	2.03	39 - 42	3.5
V2500 Select	2.07	25.7 - 33.7	13.5
CF34-10A	2.23	25 – 26.5	3
CFM56-5B	2.3	23 – 32.5	17
TRENT 1000	2.36	38 - 44	7
GEnx-1B	2.47	35 – 45.5	13
TRENT 500	2.67	35 – 36.5	2
TRENT 800	2.72	35.5 – 41.5	8
GE90-94B	3.08	35.5 - 41	7
GE GP7200	3.38	36.5 - 41	6
PW4000	3.66	31.5 - 34	4

Table 2. Analysis of the Characteristic NO_x Slopes & OPR Ranges for the Engines Shown in Figure 5.

6.3.5 Given the strong relationship between OPR /engine temperature and the production of NO_x it must be expected that significant thrust de-rating will, in normal circumstances, produce quite dramatic reductions in NO_x. This raises several complications and possible solutions when trying to re-define when a Goal has been met.

Possible candidates discussed by the IEs for changing the definition include:

1. **To exclude lower thrust or de-rated versions lacking market significance.**

To help investigate this possibility the IEs requested manufacturers' data on the proportion of orders taken for the various thrust versions of GENX powered versions of the B787. The IEs were provided with the summary Table 3 below taken from the ACAS database which was said to show a similar pattern to the proprietary Boeing information. The figures in this table for the market share percentages of orders taken, and also the references to the relative position against the MT and LT Goals have been added by the IEs

B787 Marque	GENx-1B Thrust Marque	Orders for Marque	% of Total GENx-1B orders on B787	GENx-1B Marque Relationship with Goals
B 787-3	GENx-1B53	13	4%	Middle LT Goal Band
B787-8	GENx-1B64	263	78%	Between MT & LT Goal
B787-9	GENx-1B74	61	18%	Above MT Goal Band
B787 GENX Total		337		

Table 3. The Proportion of Orders Taken for Each Marque of GENX Powered B787s – not including 294 orders where engine selection remains undecided. Note – Market Percentages and GENX-1B Relationship with MT and LT Goals has been Added by the IEs - Source ACAS database

It can be seen from Table 3 that orders for the lightest weight version of the B787, the -3, amount to only 4% of total orders, with the -8 being 78%, and the -9 around 18%. It is understood that the nominal SSLTs for these aircraft versions are close to 53klbs (Fig 5 data point at about 35 OPR), 64klbs (data point at about 40 OPR), 74klbs (data point at about 45 OPR) - though the exact engine thrusts ordered are not known to the IEs. In broad terms this means that the version of the GENX1B engine for which there is 4% of the market lies around the middle of the LT Goal and it might be argued perhaps should be excluded; the engine for which there is 78% of orders lies between the MT and LT Goals; and the highest thrust version with 18% of orders lies above the MT Goal.

One possibility put to the IEs for deciding on the significance of a particular engine marque where there is a large family spread of OPR and Dp/Foo, might be to consider an orders 'significance test' whereby versions with less than 5% of total orders might be discounted. This may merit further consideration but was not felt by the IEs to be an immediately attractive solution as often these market percentages evolve and would not be fully clarified until the passage of considerable time.

2. **The calculation of an average, perhaps weighted, OPR vs DP/Foo for all of the types in a family- and perhaps with another layer of complication where the weighted average might be coupled with a maximum Dp/Foo.**

This may merit further consideration but was felt to have some unattractive features as well as it would most likely have an element of retrospection as often it would require some years for

higher thrust versions to be developed. And if weighted by sales, the long term statistical spread of sales might be quite different from those accrued during the launch phase. Also the max Dp/Foo element might be thought to have a ring of stringency about it

3. **The use of a designated or ‘design’ OPR version that could be used for benchmarking the Goals.**

It was felt that ‘design OPR’ was currently insufficiently defined and therefore open to varying interpretations. It was felt that this might offer a way forward for future reviews if some agreed definition could be arrived at.

4. **Whether a stringency – style kink at OPR 30 or elsewhere might be introduced to better cater for the steeper (than the slope of the Goals) engine family slopes.**

It was concluded that such a fundamental change would be better tackled at the same time as consideration of the Goal levels themselves probably at the 2012 Review, should such a Review take place.

6.3.6 None of the above, nor any other alternative definitions were found to have sufficient immediate appeal to be recommended as an outcome of this Review and this reluctance was further reinforced when coupled with the likely need to make changes to the goals themselves at any future Review, should one be held. None of the above appeared to offer an easy fix to the issue of family slopes that did not hold the danger of raising serious future weaknesses or concerns. It was concluded that some of the options may merit further consideration at a future Review but this should be in parallel with consideration of the Goal levels (and possibly the slope of the Goals) themselves. Future progress on the question of definition of an engine when part of a wide family may be made easier if some interim work were to be carried out with perhaps the best candidate for technical investigation being consideration of whether a family of engines can be condensed down to an accepted single design OPR.

6.4 Cruise/Metric

6.4.1 As detailed in Section 5.6 above, at the previous review, using only RQL evidence, a broad correlation between LTO and cruise NO_x was noted. As LTO improvements have been achieved there were, generally, corresponding cruise NO_x improvements. This correlation appears to hold for similar RQL technologies but the 2006 Review Report noted LTO based correlations from RQL experience would be unlikely to hold true for lean staged systems where there are substantial fuel placement and air fuel ratio changes as staging occurs. The 2006 Report also expressed concerns about using historic RQL LTO based correlations to estimate cruise NO_x if applied to future significantly different engine architectures.

6.4.2 Figure 11 on page 35 supplied by GE shows a schematic representation comparing EI NO_x for GENX TAPS as against that for ‘current RQL’ across the various mission segments and a full explanation has already been provided in Section 5.6.8 . In summary, this figure clearly shows the point at which staging occurs, switching from pilot plus main zones to pilot only mode, taking place within the Cruise segment and where EI NO_x is significantly lowered. However, in contrast at the take-off condition which constitutes part of the LTO cycle this Figure shows the TAPS combustor to exhibit a steeper slope than is the case with RQL, and at the highest T3, TAPS is shown with a higher EI NO_x than for RQL.

6.4.3 In response to questioning it was claimed that to a degree the cruise staging switchover point is tunable within limits. The IEs believe it is significant that at present there is no regulatory pressure to influence this tuning to minimize cruise NO_x (where up to 90+% of total mission NO_x may be emitted) nor to arrive at a best compromise between reducing both LTO NO_x and Cruise NO_x . At present, given that regulation is based solely on LTO NO_x if a manufacturer had to optimize it must be expected that reducing LTO NO_x would be given precedence over reducing Cruise NO_x ; this may or may not be the

best scientific outcome. Any future better balancing of LTO and Cruise NO_x would of course require clear scientific guidance. On a positive note, for DLI combustors, the evidence thus far would seem to point to the LTO NO_x: Cruise NO_x relationship appearing to be in a favourable direction i.e. a substantial cruise NO_x reduction. There is of course an additional and different trade taking place at the staging point between the levels of NO_x being emitted and fuel efficiency where at cruise up to perhaps 90% of the fuel is burned and in this particular there is a read-across to the fuel burn review.

6.4.4 The IEs questioned whether cruise NO_x goals might be helpful in guiding combustor design to achieve the maximum possible environmental improvement. The manufacturers noted that design targets were set against certification requirements – and that the question to ask was whether certification requirements are still correct. For MT goals, manufacturers noted that they were too far along in product development to introduce another set of (cruise) goals. However, at least one manufacturer expressed that the nature of the goals and whether to include a cruise element might be considered for the 2026 LT goal.

6.4.5 Some cautioned that if there are too many constraints manufacturers may not be able to achieve a design solution. There was also a concern that a cruise NO_x goal may lead to perverse consequences (for example CO or HC increases). Nonetheless, the general view was that in a goals forum it would be worthy of further consideration but would need carefully to include key trade-offs. Manufacturers noted that the earlier that they have advance notice of any likely change in requirements when designing an engine, the better the outcome they can achieve.

6.4.6 Wider than considerations relating solely to the cruise NO_x characteristics of combustor designs themselves, there are potential wider issues related to possible changes in overall engine architectures such as with open rotors and perhaps also geared turbo-fans. It seems likely that such designs with very high BPRs will exhibit a different LTO NO_x: Cruise NO_x relationship and possibly one where cruise NO_x performance may be adversely affected.

6.4.7 The IEs concluded that any future review should consider additional available cruise NO_x data, and particularly by then any in-service cruise experience with DLI combustors, the latest information with respect to the LTO and cruise NO_x characteristics of geared turbo-fans and possibly open rotor designs also, as well as the latest scientific advice on the impact of cruise NO_x. In the meantime, and necessary before any possible setting of a cruise goal, a significant amount of progress would need to have been made on the difficult task of devising a suitable and practical cruise metric including whether this be aircraft or engine based, as well as the gathering by some means of cruise measurement data. Any chosen metric must be required to be able to have validity for turbo-fans and open rotors as well as for RQL and DLI combustors for the latter it should help inform where in terms of altitude or mission profile lean staging would be most advantageous.

6.5 Trade-offs

6.5.1 Section 5.5 of this report provides a detailed technical discussion of the issues and trades involved, and here it may be useful simply to highlight some key areas where the emphasis has changed since the last Review.

6.5.2 The 2006 Review considered the question of trade-offs in some detail and while it was accepted that, in principle, combustor improvements designed to reduce NO_x production are likely to require some adverse trades with, for example, increased complexity, weight, combustor pressure losses, noise and cost, and in the other direction reduced combustor efficiency, little quantitative evidence was presented then and this remained the case at this 2009 Review.

6.5.3 Chief among potential trades brought in to starker focus at this latest Review was the potential, even if perhaps limited, to trade LTO NO_x for reduced Cruise NO_x with DLI combustors. The IEs believe that with around 90% of total mission NO_x on some flights being produced at cruise as opposed to only 10% during the LTO phase, in future it will be much more difficult to justify continuing to focus solely on LTO NO_x. And this will be especially so if with different engine architectures it is shown, in the future, that cruise NO_x moves in an unhelpful direction relative to LTO NO_x – always assuming that the scientific evidence continues to emphasize the need to control NO_x production.

6.5.4 It appears reasonable to assume that for smaller low OPR engines the trades against increased weight, complexity and cost when considering both improved RQL and DLI combustors are likely to be harder to balance. Given that at this Review the Dp/Foo data for the GEnX DLI combustor was showing levels below those of smaller low OPR engines, therefore the IEs believe that if it transpires that the trades-offs involved with advanced combustor designs are easily justified for larger higher OPR engines but are proven to be insurmountable for small and lower OPR engines then such contrasting outcomes across the full OPR range will need to be carefully considered at any future review.

6.5.5 In general terms it was reported to the IEs that analysis being reported to CAEP8 has been completed on the assumption that adverse trades associated with technologies to reduce NO_x, when combined, have been assumed to result in a fuel efficiency loss of between 0% and 0.5%. At the 0.5% highest level it is felt that this is getting close to what might reasonably be considered to be significant and in which case it is an issue that it is felt the Fuel Burn review team may wish to pass comment.

7. Conclusions

Recorded here are the key conclusions of the 2009 Review. Conclusions from the 2006 Review have not been explicitly repeated but, where relevant, key comparisons between the findings of the two Reviews have been noted.

7.1 Process

1. The Review itself greatly benefitted from receiving a considerable proportion of the presentation material in advance. Only a brief opportunity was available to the IEs ahead of the Review to collectively review the material. For future reviews more time should be allowed for this highly productive activity – half a day would seem an appropriate time allocation.

2. Much of the engine data came in graphical form (such as figures 3 and 4) and considerable time and effort was then required to identify engine ID's and exact Dp/Foo and OPR values. Tabulated data should also be provided for any future review.

3. This Review was expected to be relatively straightforward re-visiting of the findings of the 2006 Review, however, in the event the pace of progress in combustion technologies has been such that challenging questions were asked of the 2006 Goal levels and Goal Definition, as well re-igniting the issue of cruise NO_x related to staged lean burn combustion.

4. With four IEs for this Review, rather than the previous six, IE resources were severely stretched and greater resources would certainly be needed at any future review if it were adequately to address re-visiting the Goal levels, Definition, and Cruise NO_x.

5. The IEs believe a further Review of the Goals around 2012 would be timely as by then the new generation of DLI staged combustors would be certificated. And consequently their in-service performance established, their applicability to smaller/lower OPR engines clearer, further information may be available to assist solving the problem of definition for wide families of engines and finally further information may be available on a metric for cruise NO_x.

7.2 Science

6. The IEs were convinced that the scientific evidence supports continued efforts to reduce NO_x emissions from aircraft. Having explored the state of the scientific knowledge regarding the environmental impacts of NO_x as well as other emissions, and although the Review did not include any quantitative data to evaluate environmental need, the IEs felt there was sufficient evidence to conclude that the environmental need for NO_x reduction appears, if anything, more compelling than during the 2006 NO_x Review.

7. The climate impact drivers appear more urgent, given emerging actions to mitigate (e.g., cap and trade schemes) in place or shortly expected throughout the world. Although NO_x is not a greenhouse gas per se, it is an indirect greenhouse gas and some progress has been made relating its impact to that of CO₂ via Global Warming Potential metrics.

8. Surface air quality constraints are also more compelling. Recent scientific understanding of human health impacts of aircraft emissions appears to indicate that health impacts from particulate matter (PM) may be higher than those from ozone due to NO_x. However, NO_x does contribute to secondary PM formation, making its overall health impact more significant.

9. NO_x and CO_2 appear commensurately important when it comes to climate, though it is dependent on the chosen time horizon. NO_x is very important for air quality – however PM and SO_x appear to be gaining in importance and may even overtake NO_x , CO and UHC continue to be important, but secondary effects.

7.3 Progress towards Goals

10. At the time of the Review no product had as yet achieved a Goal as defined by having reached TRL8 though pre-certification flight test data for a new large engine (GEnX) fitted with a new generation of staged DLI ('TAPS') combustor exhibited a step- change in NO_x performance to the extent that versions of this engine were shown straddling both the MT and the LT Goal bands.

11. Despite straddling both Goals, the gradient of the characteristic NO_x slope for this family of engines was shown not to be exceptionally steep as compared with engines fitted with RQL combustors and therefore the extent to which it straddled both Goal bands was a function of its wide OPR range coupled with the relatively shallow slopes of the Goal bands as compared with, for example, the CAEP 6 stringency slope.

12. The development of the staged DLI combustor solution has been at a pace anticipated at the 2006 Review, however, the data presented to the 2009 Review extending down as far as the LT Goal did present a greater level of achievement than anticipated this early in to the time period. 13. RQL combustor developments appeared to be following very much what was anticipated for them in the report of the 2006 Review with progressive improvements closing on the 2016 MT Goal though with significant challenges still lying ahead.

14. It appears that DLI staged combustors may be needed for the achievement of the 2026 LT Goal and particularly for higher OPR designs.

15. The aggressive GE eCore engine program (DLI/TAPS) holds the prospect at least of very significant NO_x reductions also for Small and Medium OPR engines, particularly in the longer term. However the employment of DLI in some small and medium engine applications may be constrained by issues of weight and complexity.

16. It appears that the improvements in NO_x emission characteristics has been, at least to an extent, stimulated by the presence of realistic, challenging but achievable goals. This seems likely to be further encouraged by the wide, international acceptance of these goals.

7.4 Whether to change the Goals

17. With neither of the Goals having yet been attained to TRL8 level and with them being intended to be medium and long term targets, there was considerable reluctance among the IEs to make modifications a little more than three years on. This was coupled with concerns that to make changes in haste that may require later reversion could discredit the Goals process. It was therefore decided not to make changes at this Review.

18. As anticipated in the 2006 Report, DLI staged combustion has been shown to represent a revolutionary step-change in technology. Such changes come along relatively rarely and therefore it was concluded that there is no immediate pressure to change the goals as further improvements remotely close to this magnitude are not expected to be repeated in the next 10 or more years.

19. Given the uncertainties surrounding wider applicability and in-service performance of staged DLI systems further elapsed time would provide opportunity for experience to be accumulated which will provide vital information for future consideration of any adjustment to the Goals.

20. Having recommended better harmonization of dates and assumptions across the various LTTG Goal activities, the IEs concluded that to make a change to either NO_x Goal at this time (with just 7 years remaining for the MT goal), or changing the goal dates will further complicate any harmonization process.

7.5 Whether to Change the Goal definition

21. The IEs recognized that the issue of defining when a goal has been met has come under the spotlight largely as a result of the wide spread of pre-certification data points presented for the GEnX-1B family.

22. From analysis of the gradients of the characteristic NO_x slopes for several engine families it was concluded that, at about 2.5, the slope for the staged LDI GEnX-1B was no steeper than typically the case for other engine families using RQL combustor systems.

23. From the data presented to this Review a distinguishing feature of the GEnX-1B contributing to its wide spread across both the MT and LT Goals is the wide OPR range shown for this family of engines – from OPR 34.9 to 45.6 – considerably above the average OPR spread of the engine families investigated for comparison.

24. The IEs were reconfirmed in the view that the simplicity of the 2006 Goal bands and definition were a great attraction and any future changes should also aim for maximum simplicity, though this may be harder to achieve.

25. The IEs briefly considered several options for changing the definition and these are detailed in the report, however, it was soon concluded that this topic could not sensibly be addressed either in haste or in isolation from the overall question of the level of the Goals themselves.

26. Future progress on the definition of goal achievement where there is a wide OPR spread in families of engines would benefit from work in the interim to investigate particularly the notion of a design OPR but also of other options, including those listed in this Report.

7.6 Cruise NO_x

27. The conclusion of the 2006 Report expressing concerns about possible future unreliability of the established relationship between LTO NO_x and cruise NO_x was further vindicated by evidence at this Review.

28. For engines fitted with RQL combustors no new evidence was presented to disturb the consensus of a broad correlation between LTO NO_x and cruise NO_x. On the other hand, evidence was presented adding weight to the view that staged DLI systems fundamentally challenge this correlation.

29. From the evidence presented for staged DLI systems, cruise NO_x is expected to be significantly lower than for an equivalent RQL combustor and thus it was concluded that, in principle at least, the LTO NO_x: Cruise NO_x relationship would move in a favourable direction i.e. a substantial cruise NO_x reduction.

30. In contrast, at the take-off condition which constitutes part of the LTO cycle, the illustration presented for the staged DLI system exhibited a steeper slope of EI NO_x than was the case with RQL which, in principle, could lead to a higher EI NO_x at take-off (or a steeper slope at higher OPRs) than for the equivalent RQL design.

31. Given that current regulatory standards apply only to LTO, it would be reasonable to assume to the extent there is flexibility that manufacturers will favour minimizing LTO NO_x performance to the detriment of cruise NO_x despite cruise NO_x on some flights being up to 90% of total mission NO_x.

32. Beyond the question of combustor design, future Reviews will need to consider possible changes in overall engine architectures, such as geared turbo-fans and possibly open rotors, as it seems likely that such designs will exhibit further challenges to the LTO: Cruise relationship for NO_x, and possibly in an unhelpful direction i.e. where cruise NO_x performance may be adversely affected relative to changes in LTO NO_x.

33. For there to be serious consideration of NO_x at cruise, and possibly the setting of Cruise NO_x Goal, a significant amount of progress would need to have been made in the interim on the difficult task of devising a suitable and practical metric, and with any chosen metric having validity for turbo-fans and open rotors as well as for RQL and DLI staged combustors.

7.7 Trade-offs

34. The 2006 Review found no evidence of unmanageable trade-offs in connection with combustor technologies for reduced NO_x. In general terms the present Review has arrived at a similar finding for the bulk of mid and high OPR engines though the suggestion made to the Review of a possible 0.5% fuel burn deficit (proposed range for CAEP modeling 0% to 0.5%) is felt to be at least bordering on the significant and may be something that could helpfully be referred to the Fuel Burn review.

35. There is some evidence that smaller lower OPR engines may suffer more significant adverse trades restricting their ability to fit not only staged DLI but also advanced RQL combustor technologies, though a further passage of time is required to be certain on this point.

36. If in due time the immediately preceding conclusion turns out to be correct then it seems possible that the characteristic rise in NO_x production with OPR across the full breadth of engine types will be flatter than has historically been the case.

37. Trades may emerge between LTO NO_x and Cruise NO_x both for engines fitted with staged DLI combustors and those having new engine architectures that will be likely to alter the current relationship, and not necessarily in a consistently helpful direction.

8. Recommendations of the Panel of Independent Experts

1. That the Panel's conclusion be noted that there continues to be a need to reduce aircraft NO_x both from a surface air quality and climate change perspective and that the evidence of environmental need was judged to be, if anything, more compelling than at the 2006 Review.
2. Given the extent of the remaining uncertainty work should continue to better establish the importance and impact of NO_x on global climate.
3. The emerging, and thought to be growing, importance of PM should be monitored and this should include the role of NO_x in the formation of PM.
4. Despite significant predicted and actual reductions in aircraft engine NO_x since the last Review, the levels of both the MT and LT goals should be retained unchanged for this present round and at least until greater experience has been gained with new staged DLI combustors and their applicability to lower OPR engines has been clarified.
5. That the applicability of new advanced RQL and DLI combustors to smaller/lower OPR engines be better established and the resulting consequences be monitored for the gradients of characteristic NO_x slopes for future Goals (and possibly standards stringency).
6. In the interim period before any future NO_x review it would be helpful if work were pursued to inform how families of engines might sensibly be handled, for example, whether it is realistic to think in terms of a 'design OPR' around which the performance against the Goals of a whole family of engines might be measured, as well as other options.
7. In the interim period before any future review, it would be helpful if work were pursued to investigate the options for a realistic metric, and methods for establishing, cruise NO_x, and with such a metric capable of handling advanced RQL and DLI combustors as well as alternative engine architectures including GTF and Open rotors.
8. Better harmonization be pursued with other parallel Goals activities and particularly with respect to Goal dates, basic assumptions, the provision of consensus information and forecasts of emissions burdens, and other interactions.
9. That a further NO_x Review be conducted so that the present Goals can be refined and updated to take better account of imminently expected step-change combustor systems, likely changes to engine architectures, and associated implications the definition of achievement of Goals as well as for cruise NO_x; an interval of about three years would seem to be appropriate.
10. That a larger IE Panel, than the four members for this Review, be formed for any future NO_x Review if the factors detailed in the immediately preceding recommendation are to be satisfactorily dealt with as to do otherwise would result in too great a burden being placed on individual members.

*IE Panel of the 2009 NO_x Review
Final report November 2009*

APPENDIX A

Technology Readiness Scale

(Excerpted from CAEP/6-IP/4, Appendix A)



Figure 1. Technology readiness levels

APPENDIX B

CAEP-Memo/76
Appendix A

APPENDIX A

TERMS OF REFERENCE FOR THE INDEPENDENT EXPERT PANEL MEMBERS FOR THE NOX TECHNOLOGY UPDATE REVIEW

1. GENERAL

1.1 The WG3 Long Term Technology Goals Update Review will be conducted by a Review Committee comprising a Panel of nominated independent experts, designated members of airlines, airframe manufacturers, NGOs, regulators/air worthiness experts, and the scientific community represented by the RFPs, as appropriate. The review committee will be assisted by additional members drawn from representative trade associations and research establishments, moderators provided by ICCAIA as appropriate, Industry presenters who will present the technical information for the review, an airline specialist nominated by IATA, and CAEP RFPs/SFPs and/or nominated representatives. The Review will be facilitated jointly by BERR and FAA.

1.2 Major elements of the NOx technology Goal Update Review will include:

- a) An overview of the latest scientific understanding of climate and local air quality effects
- b) Progress in development of reported revolutionary technologies for the long term future (to 2026), and
- c) developments of the new technologies reported to the original Review to future products in the middle term (to 2016) for climate and local air quality effects.

2. OBJECTIVITY

2.1 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 relevant to the 2016 goal. Appropriate representatives from the major manufacturing companies will attend the review and present relevant material to the IEs. In addition, material will be presented by representatives of research organisations and industry on the progress with longer-term research activities on emissions reductions.

3. FUNCTION OF THE UPDATE REVIEW TEAM

3.1 To provide CAEP with a consensus view on the progress towards meeting the original medium term and long term NOx reduction goals recommended to CAEP/7.

4. **FORMAT OF THE REVIEW:**

4.1 Subject to Review Committee requirements, the format of the review will cover a science overview, a technology update and programme review, and a research programme review. Proprietary technology development will not be reviewed, thus all sessions will be open to all review panel members. All presentations will be made available to IEs at least 2 weeks before the Review and will be summarised in a written statement for the Review report to ensure accuracy of reporting.

5. **REVIEWERS EXPERTISE REQUIRED:**

5.1 The independent expert review team should comprise technical experts with experience in the following areas:

- a) Product Development
- b) Airworthiness
- c) Customer Requirements
- d) Technology Development and Transition
- e) Broad technical expertise with experience in several industries, including aviation

5.2 Candidates for the independent expert reviewers will 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.

6. **INDEPENDENT EXPERT PANEL DELIVERABLE AND DOCUMENTATION REQUIREMENTS:**

6.1 To prepare a report on the progress and status of technology developments for NO_x emissions reduction and control, from the baseline assessed by the original NO_x technology Review reported to CAEP/7, and the prospects for NO_x reductions suggested by research progress. The Report on the Review proceedings will be for presentation to CAEP SG and/or CAEP/8, and as a preliminary draft for review by WG3. The progress assessment should, where possible:

- 1) assess the possibility of success and trends for the future, based on experience from past research and development programmes
- 2) comment on any changes to the environmental tradeoffs resulting from such NO_x reduction developments – both for emissions and noise
- 3) provide a balanced view of the state of emissions reduction technologies, and in a manner suitable for broad understanding
- 4) comment 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 and on the appropriateness of certification metrics, as necessary

- 5) progress can be 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 C



International Civil Aviation Organization

CAEP-SG/20093-WP/22
27/05/09

WORKING PAPER

COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION (CAEP)

STEERING GROUP MEETING

Salvador, Brazil, 22 to 26 June 2009

Agenda Item 6: Emissions Technical – WG3

INTERIM REPORT OF THE INDEPENDENT EXPERTS TO THE 2009 NOX REDUCTION TECHNOLOGY REVIEW, LONDON, 30TH – 31ST MARCH 2009

Prepared by
The Independent Expert Panel.

(Presented by the Rapporteurs)

SUMMARY

The interim report prepared by the Independent Experts is provided in Appendix A.

Action by the CAEP-SG is in paragraph 2.

1. INTRODUCTION

1.1 The original NOx Technology Goals Review was held in March 2006 and the report presented to and accepted by CAEP/7 in February 2007. This set out Medium [10 year - 2016] and Long [20 year - 2026] Term NOx Technology Goals.

1.2 A second Review was held in March 2009 to assess progress towards achievement of these goals. An interim report of the Independent Experts is provided in Appendix A.

2. ACTION BY THE CAEP-SG

2.1 The CAEP-SG is invited to:

- a) Note the initial comments of the Independent Experts and their plans for preparation of a final report for presentation at CAEP/8;
- b) Consider the recommendation for harmonisation of activities, time lines and baselines for the various Technology Goals as set out in paragraph 2.1(h) of the report.

APPENDIX A

Interim Report of the Independent Experts to the 2009 NOx Reduction Technology Review, London, 30th – 31st March 2009

Prepared by
The Independent Expert Panel

1. INTRODUCTION

1.1 In support of the CAEP Long Term Technology Task Group (LTTG) of Working Group 3 (WG3) a group 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 term [MT] (10 year) and long term [LT] (20 year) goals for NOx control. The IEs conducted the Review in March 2006 in London, UK. The IEs recommended (and CAEP subsequently accepted) MT (2016) and LT (2026) Technology goals. The IEs used the LTO certification metric to define the goals.

1.2 The IEs positioned the MT technology goal at CAEP/6 minus 45% +/- 2.5% at a reference OPR of 30. The bandwidth is relatively small indicating a reasonable degree of confidence of achievement. The IEs positioned the LT technology goal at CAEP/6 minus 60% +/- 5% at a reference OPR of 30. The greater bandwidth as compared with the MT technology goal reflected the greater degree of uncertainty of outcome.

1.3 The criterion adopted by the IEs was that a goal is met when one or more manufacturers achieve a performance within the goal band judged against TRL 8. Thus the goal bands are predicting the leading edge capability.

2. NOX GOALS UPDATE REVIEW - MARCH 2009

2.1 A subset of the original IEs (P. Kuentzmann, L. Maurice, M. Ralph, and J. Tilston) conducted a status Review of the goals [March 30 & 31 2009 in London, UK]. The IEs elected Malcolm Ralph (Chair of the 2006 Review) to Chair the 2009 Review. The IEs were asked to provide a brief preliminary report to the meeting of WG3 also held in London, UK (1 to 3 April 2009), and are currently preparing their Report for presentation to CAEP/8. The following preliminary observations are based on the aforementioned IE report to WG3.

- c) The IEs thanked the Research and Science Focal Points (RFPs/SFPs), representatives from Research Establishments and Industry participants for the excellent information provided.
- d) **Science:** The IEs intend to revisit the state of the science. The IEs felt that the environmental need for NOx reductions from a climate perspective appears, if anything, more compelling than during the 2006 NOx Review. Surface air quality constraints also appear more compelling.
- e) **Questions to RFPs:** The IEs posed the same set of questions to the RFPs and SFPs as in 2006 for update. They also posed a few new questions. The RFPs/SFPs were asked to provide answers by mid-April to inform the draft report.
- f) **Progress to Goals:** At the 2009 Review IEs were provided data on recent certifications (2006-2009) as well as progress on technology development. The IEs noted that substantial progress has been made toward both the MT and LT goals; however, at this time, no

manufacturer has yet achieved the goal (based on a technology achieving Technology Readiness Level (TRL) 8).

- g) **Goal Levels:** Based on the data presented, the IEs intend to assess the goals and determine whether these should remain as is or are made more aggressive. There appears to be no need to relax the goals given the progress made toward achieving them. The IEs did ask ICCAIA to provide historical data on the rate of combustor NOx reduction technology advancement to inform their deliberations.
- h) **Goal Definition:** At the last review the IEs indicated that a goal is reached when one or more products cross the goal line. The IEs feel that a refinement to that assumption may be warranted - not least to accommodate the “family approach” to engine design and development favoured by Industry.
- i) **Trade-offs:** The IEs intend to address the inter-relationships between noise and other emissions given the potential tradeoffs.
- j) **Cruise NOx Goals:** The IEs questioned whether cruise NOx goals might be helpful in guiding combustor design to achieve the maximum possible environmental improvement particularly given the characteristics of staged combustors. They will explore this subject and address it in their report.
- k) **Harmonisation:** For the future, the IEs recommend the need to consider how to harmonise the CAEP technology goal activities in NOx, noise and fuel burn, adopt common timelines and common baselines to ensure that all CAEP technology goals are mutually compatible

3. **TIMELINE FOR DEVELOPMENT OF FINAL REPORT**

3.1 The IEs understand that they will work to the following timeline:

- a) The IE report to be offered as a draft to Review participants in June 2009.
- b) Final Report to be presented to the final meeting of WG3 in Montreal, September 2009.
- c) Final Report to be presented to CAEP/8 in February 2010.

APPENDIX D

List of presentations:

Conclusions from the 2006 Review. M. Ralph.

ICCAIA Recent engine certifications summary, D Allyn

ELECT-AE. Technology Progress in Europe. R von der Bank.

GE. 2009 Recent Emissions Certification Test results with GE Aviation Combustor Designs. W Dodds.

GE. Combustion Technology Progress on LTTG NOx Goals. M Foust.

Honeywell. SABER – Low-Emissions Combustor Development. R. Dudebout.

LTTG NOx Technology Goals. P Newton.

NASA. Progress toward aviation's environmental goals and objectives. F Collier. D Bulzan. M Wadel. R D Rosario.

P&W. Dependable Combustor Technologies For Environmentally Responsible Aircraft Engines – Update. D Sepulveda.

P&W. NOx Review Update. D Sepulveda & R McKinney.

P&W. Recent P&W/IAE Engine Upgrades for Improved Environmental Performance. D Sepulveda.

Rolls-Royce Low Emissions Combustion Technology Programme Update. K Young.

Rolls-Royce. Developments of Rolls-Royce Engines and the Phase 5 Combustor. P Madden.

Science Group. Aviation and NOx impacts: overview of issues. D Lee, R Miake-Lye, M Ko.

Snecma. Near term: Technology of SAM146, An Environmentally Friendly Engine. Rollin.

APPENDIX E

List of Attendees for the CAEP NOx Goals Update Review BERR Conference Centre, London, UK 30, 31 March 2009

Industry Representatives

ICCAIA (9)

Madden, Paul	R-R	paul.madden@rolls-royce.com
Dodds, Will	GE	willard.dodds@ge.com
Sepulveda, Dom	P&W	
Allyn, Dan	Boeing	daniel.m.allyn@boeing.com
Dudebout, Rudy	Honeywell	rudolph.dudebout@honeywell.com
Foust, Michael	GE	
Rollin, Gilles	Snecma	
Olivier Husse	Airbus	
Christophe Plaisance	Airbus	christophe.plaisance@airbus.com
Florentina Viscotchi	Bombardier	
Ken Young	R-R	kenneth.young@rolls-royce.com

IATA (3)

Betty Hawkins	IATA	bhawkins@airlines.org
Thomas Roetger	IATA	
Delphine Dantec	AF IATA	dedantec@airfrance.fr

Science Community (2)

David Lee	MMU	
Rick Miake-Lye	Aerodyne	

Independent Experts

Lourdes Maurice	FAA - USA	lourdes.maurice@faa.gov
Malcolm Ralph	Independent Consultant - UK	malcolmralf@hotmail.com
John Tilston	Independent Consultant - UK	jrandml@tiscali.co.uk
Paul Kuentzmann	ONERA - Fr.	paul.kuentzmann@onera.fr

Research Community

Fayette Collier	NASA	
Ralf von der Bank	EC (R-R)	ralf.von_der_bank@rolls-royce.com

Attendees for the CAEP NOx Goals Update Review
BERR Conference Centre, London, UK
30, 31 March 2009

CAEP WG3

Government (26)

Dave Lister	WG3 Rapp. UK	
Curtis Holsclaw	WG3 Rapp. USA	curtis.holsclaw@faa.gov
Theo Rindlisbacher	FOCA Switzerland	
Cesar Rodrigues Hess	Brazil	
Marcelo Batista Saito	Brazil	
Roger Worth	DfT UK	Roger.Worth@dft.gsi.gov.uk
Steve Arrowsmith	EASA	stephen.arrowsmith@easa.europa.eu
Erick Herms	EASA	
Peter Newton	Representing BERR - UK	Peter.john.newton@gmail.com
Mohan Gupta	FAA - USA	Mohan.L.Gupta@faa.gov
Tetsuya Tanaka	CAEP Secretariat	
Hélène MANZONI	French CAA (rep. CAEP Member)	
Matt Spears	EPA US	spears.matt@epa.gov
Illimar Bilas	Germany (rep. CAEP Member)	
Jenny Ryman	Swedish Transport Agency	Jenny.Ryman@transportstyrelsen.se
Antonio Andreini	Università degli Studi di Firenze	
Ed McQueen	FAA - USA	
Ralph Iovilelli	FAA - USA	
Martin Plohr	DLR Germany	
Dan Rutherford	ICSA	
Chris Eyers	QinetiQ	cjeyers@qinetiq.com
Werner Hoermann	EASA	
Wieger Dijkstra	Ministry of Environment, NL	
Ted McDonald	Transport Canada	
Frank Wetzel	UBA, Germany	
Urs Zeigler	FOCA Switzerland	

APPENDIX F

List of Acronyms and abbreviations.

AIC	Aircraft Induced Cirrus
AQ	Air Quality
AR4	IPCC 4 th Assessment Report ¹¹
CAEP	Committee on Aviation Protection
CFD	Computational Fluid Dynamic (modelling)
CFM	Joint Snecma/GE company
CH ₄	Methane
CO ₂	Carbon Dioxide
DfT	Department for Transport (UK Gov.)
DAC	Double Annular Combustor
DLI	Direct Lean Injection (combustor)
DLR	Deutsches Zentrum für Luft und Raumfahrt
Dp/Foo	NO _x characteristic (grams/kN thrust)
DZ	Dilution Zone (of combustor)
EINO _x	Emissions Index of NO _x (grams per kilogram of fuel burned)
EIS	Entry Into Service
EPA	Environmental Protection Agency
EU	European Union
FAA	Federal Aviation Administration
GCC	Global Climate Change
GE	General Electric
g/kN	Grams of pollutant per kilo Newton of thrust
GTP	Global Temperature change Potential
GWP	Global Warming Potential
H ₂	Hydrogen
HAPs	Hazardous Air Pollutants
Hc	Hydrocarbons (generic)
IAE	International Aero Engines
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCAIA	International Coordinating Council of Aerospace Industries
IE's	Independent Experts
IPCC	International Panel on Climate Change
IZ	Intermediate Zone (of combustor)
klb	Thousand pounds (thrust)
kN	Kilo-Newton (thrust)
LAQ	Local Air Quality (sea level)
LOSU	Level of Scientific Understanding
LT	Long Term

¹¹ The Synthesis Report can be accessed at.
www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

LTO	Landing, Take-off (cycle) ¹²
LTTG	Long Term Technology Group
MMU	Manchester Metropolitan University
MT	Medium Term
NASA	National Aeronautics and Space Administration
NO _x	Oxides of Nitrogen (NO and NO ₂ aggregated)
O ₃	Ozone
OPR	Overall Pressure Ratio (engine)
Optim.	Optimised
P&W	Pratt and Whitney
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate material (generic particulates)
PZ	Primary Zone (of combustor)
RF	Radiative Forcing
RFP	Research Focal Point
RQL	Rich burn, quick Quench, Lean burn (combustor style)
RR	Rolls-Royce
SAQ	Surface Air Quality
SFC	Specific Fuel Consumption (g/kN.s) or (lb/lbf.h)
SFP	Science Focal Point
Snecma	Société National d'Étude et de Construction de Moteurs d'Aviation
SO _x	Oxides of Sulfur (aggregated: mostly SO ₂ and SO ₃)
SSLT	Static Sea Level Take-off Thrust
TAPS	Twin Annular Premixing Swirler (combustor style)
TRL	Technology Readiness Level
UBA	Federal Environment Agency (Germany)
UHC	Unburned Hydrocarbon
UK	United Kingdom
VOC	Volatile Organic Compounds
WG3	CAEP Working Group 3
Wm ⁻²	Watts per square metre
Π _{oo}	Engine Overall Pressure Ratio (i.e. as OPR)

— END —

¹² Taxi, Take-off, Climb-out, Approach

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