The Landing and Take-Off Particulate Matter Standards for Aircraft Gas Turbine Engines

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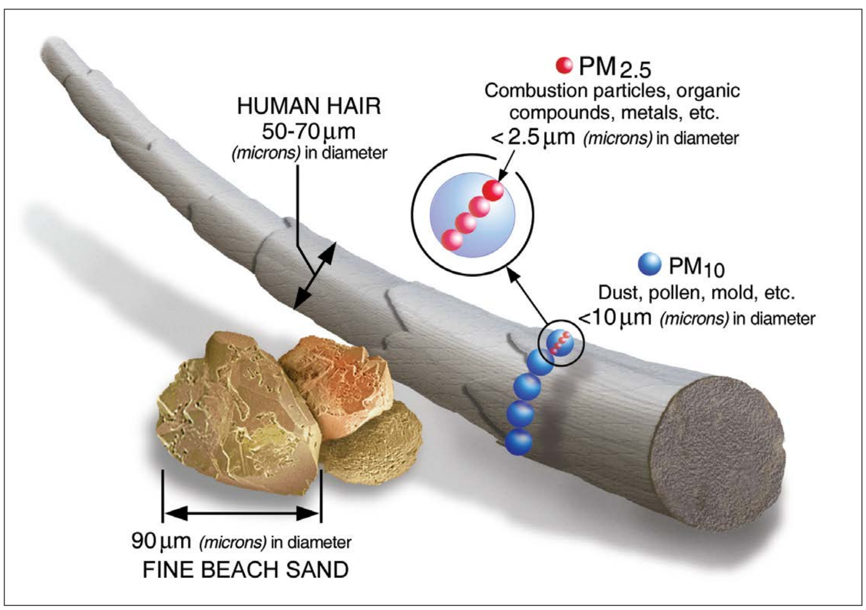
INTRODUCTION

Particulate matter emissions from aircraft gas turbine engines contribute to adverse health and climate impacts. The CAEP/11 recommended particulate matter standards for aircraft gas turbine engines are an important development that will lead to an overall reduction in particulate matter emissions and associated impacts. These new Standards and Recommended Practices (SARPs), which will be considered for adoption by the ICAO Council in March 2020, are the culmination of six years of effort and are a critical milestone contributing to ICAO's strategic objective of minimizing adverse environmental effects of civil aviation activities.

At the engine exhaust, particulate emissions mainly consist of ultrafine soot or black carbon emissions. Such particles are called "non-volatile" (nvPM). They are present at the high temperatures at the engine exhaust and they do not change in mass or number as they mix and dilute in the exhaust plume near the aircraft. The geometric mean diameter of these particles is much smaller than PM2.5 (geometric mean diameter of 2.5 Microns) and ranges roughly from 15nm to 60nm (0.06 Microns)[1]. These are classified as ultrafine particles (UFP). Mass and Number of nvPM emissions primarily depend on the engine technology and the LTO nvPM mass and number standards seek to reduce these emissions in the future with the introduction of cleaner combustor technologies. Synthetic fuels with low aromatics content can also help to reduce nvPM mass and number emissions at low thrust conditions.

Additionally, gaseous emissions from engines can also condense to produce new particles (i.e. volatile particulate matter – vPM), or coat the emitted soot particles. Gaseous emissions species react chemically with ambient chemical constituents in the atmosphere to produce the so called

FIGURE 1: Comparison of particle sizes from different sources (from US EPA)



1 10nm = 1 / 100000 of a millimetre

secondary particulate matter. Volatile particulate matter is dependent on these gaseous precursor emissions. While these precursors are controlled by gaseous emission certification and the fuel composition (e.g., sulfur content) for aircraft gas turbine engines, the volatile particulate matter is also dependent on the ambient air background composition.

The new ICAO standard is a measure to control the ultrafine non-volatile particulate matter emissions emitted at the engine exit, directly related to the combustion technology and fuel burn.

BACKGROUND

Adverse health and climate impacts of particles emitted by various combustion sources have been studied for a long time. For aircraft engines, detailed scientific studies were initiated nearly 15 years ago in the United States and Europe to better understand and quantify the characteristics of their particle emissions. In 2008, first proposals for the introduction of an ICAO particulate standard for aircraft engines were made and subsequently, a plan was developed and agreed at the 8th meeting of ICAO Committee on Aviation Environmental Protection (CAEP/8). This plan was implemented during CAEP/9 and the newly formed WG3 Particulate Matter Task Group (PMTG) was tasked with the development of an nvPM standard first for turbofan engines of rated thrust greater than 26.7 kN. ICAO, through CAEP, also requested the SAE International E-31 Committee to develop a standardized nvPM measurement methodology. Test programmes were developed in North America and Europe through ICAO Member States and through Observers including the industry. These stakeholders also provided most of the man power and funding needed for this development.

Following this request, the SAE AIR6241 documented the specifications of the standardized nvPM sampling and measurement system. These specifications resulted from the establishment of a unique testing opportunity and the construction of a measurement prototype by the Swiss Federal Office of Civil Aviation, followed by a number of unique engine emissions tests performed in Switzerland in international cooperation. Subsequent tests in the USA and the UK validated the AIR6241 specifications and led to further refinements of the calibration procedure of some of the instrumentation used. The knowledge gained from these campaigns formed the backbone of the CAEP/10 nvPM certification requirement and standard as specified in Appendix 7 of the ICAO Annex 16, Volume II, Amendment 9.

THE CAEP/10 NVPM STANDARD

The inaugural engine nvPM emissions standard was agreed to by CAEP/10 in 2016. Any new regulation needs to be informed by the emissions levels of current technologies before future regulatory limits can be established. An important purpose of the CAEP/10 nvPM standard is therefore the mandatory reporting of health and climate relevant nvPM emissions, acquired through a certification process for the in-production engines. Noting that the nvPM mass concentration measurement performed with the new much more sensitive measurement method could be related to the smoke number standard to control non-visibility of exhaust plumes, the CAEP/10 standard was introduced with a maximum nvPM mass concentration limit. This maximum nvPM mass concentration was developed based on a statistical relationship between nvPM mass concentration and the smoke number (SN). Because of this, if an engine passes the current SN standard, by design of the regulatory level, it should also pass the mass concentration limit. As explained above, the CAEP/10 nvPM standard also mandates reporting of health and climate relevant emissions performance: a) the fuel flow at each thrust setting of the certification landing and take-off cycle (LTO); b) nvPM mass and number emission indices (EIs) for the four LTO thrust settings; c) maximum nvPM EI mass; d) maximum nvPM EI number; and e) the maximum nvPM mass concentration. In summary, the new standard is applied to all in production engine types of rated thrust greater than 26.7 kN on or after 1 January 2020. The reported certified parameters will allow comparisons of engine technology and engine type comparisons for LTO nvPM emissions. Furthermore, the maximum nvPM mass concentration obtained from the nvPM certification measurement was expected to help in maintaining the non-visibility criteria of the exhaust and to provide a pathway for ending the applicability of the SN standard for engines of rated thrust greater than 26.7 kN. A graphical representation of the CAEP/10 nvPM mass concentration standard is shown in Figure 2[2]. The CAEP/10 nvPM mass concentration standard and associated reporting were included in the ICAO Annex 16, Volume II, Amendment 9.

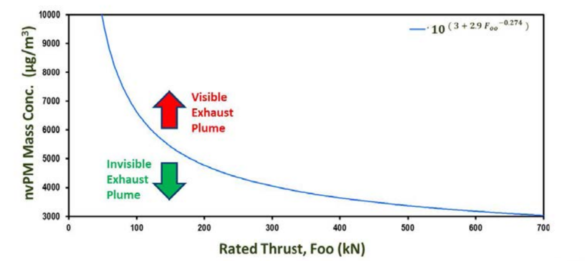
DEVELOPMENT OF THE CAEP/11 LTO NVPM MASS AND NUMBER STANDARDS

Following the development of the CAEP/10 nvPM mass concentration standard, ICAO CAEP continued the development of the LTO nvPM Mass and Number standards. About 25 engines that represented the range of in production engine combustor technologies and a full range of engine sizes were tested to characterize nvPM mass and number emissions. These tests were supported by various Member States, EU and the engine manufacturers. Using these datasets, metric systems for LTO nvPM mass and number emissions were developed. Metric values of nvPM mass and number provide an effective way to characterize and reduce real-world LTO nvPM emissions.

As noted earlier, the nvPM mass and number emissions are affected by aromatics in the fuel. The certification fuel has a small range of total aromatics including naphthalenes. Based on nvPM emissions data from dedicated tests supported by Swiss Federal Office of Civil Aviation (FOCA) where the fuel specifications were very carefully controlled and data from a few other tests, a reference fuel hydrogen content of 13.8% by mass was chosen to be the reference parameter to normalize the nvPM emissions. In addition to the fuel specification, ambient conditions on the test day also affect the measured nvPM emissions and it is desirable to normalize the measured data to International Standard Atmospheric (ISA) conditions at the surface. However, the methodology developed to normalize nvPM emissions to ISA conditions from a dedicated test funded by US Federal Aviation Administration (FAA) did not lead to satisfactory results. Therefore, the lack of ambient conditions corrections was included in the overall uncertainty of the metric value.

Emissions data from the dedicated tests of 25 engines of the same type funded by US FAA along with data from selected repeat engine tests, characteristic factors

FIGURE 2: Graphical presentation of the CAEP/10 nvPM Mass Concentration Standard



$$\textit{Regulatory limit concentration of } nvPM_{mass} = 10^{(3 + 2.9\,F_{oo}^{-0.274})}$$

FIGURE 3A: The CAEP/11 LTO nvPM mass regulatory limits for in-production and new type engines of rated thrust greater than 26.7 kN

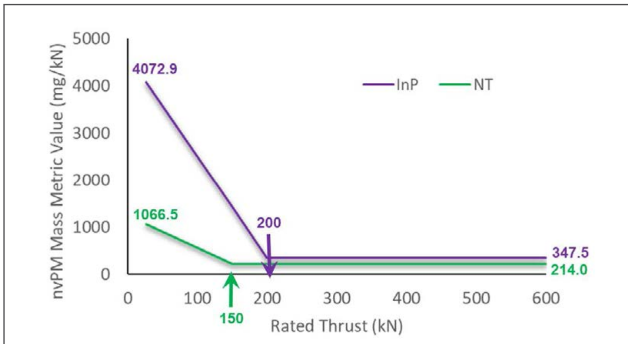
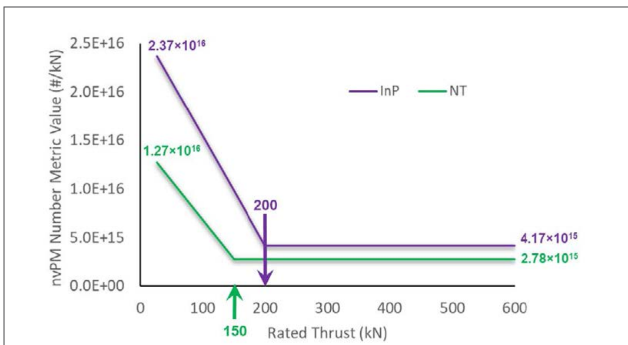
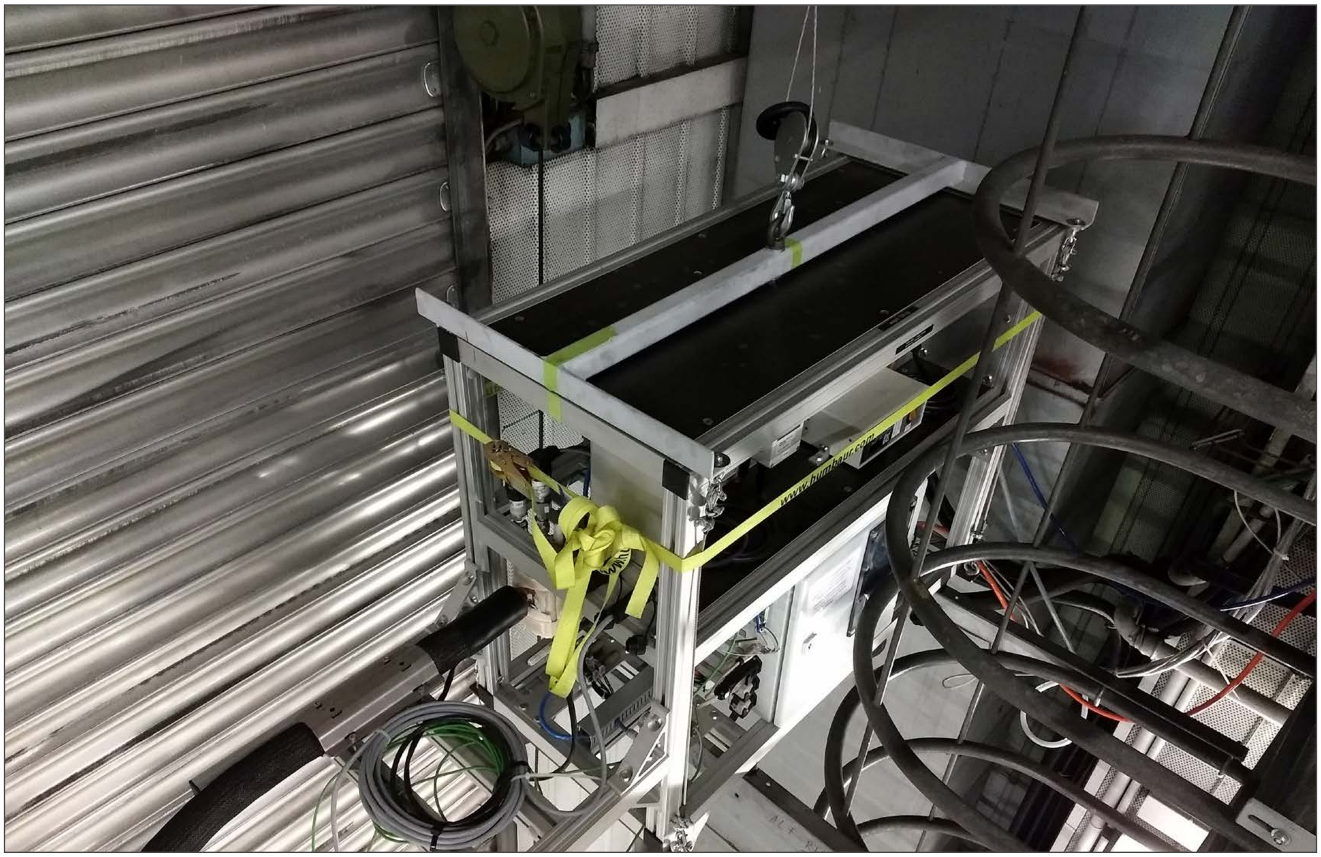


FIGURE 3B: The CAEP/11 LTO nvPM number regulatory limits for in-production and new type engines of rated thrust greater than 26.7 kN



for complying with the regulatory limits were developed. Similar to the factors for gaseous emissions and smoke, these characteristic factors are for adjusting the measured nvPM metric value of an engine type from a small number

2 Please see ICAO Environmental Report 2016 for more details

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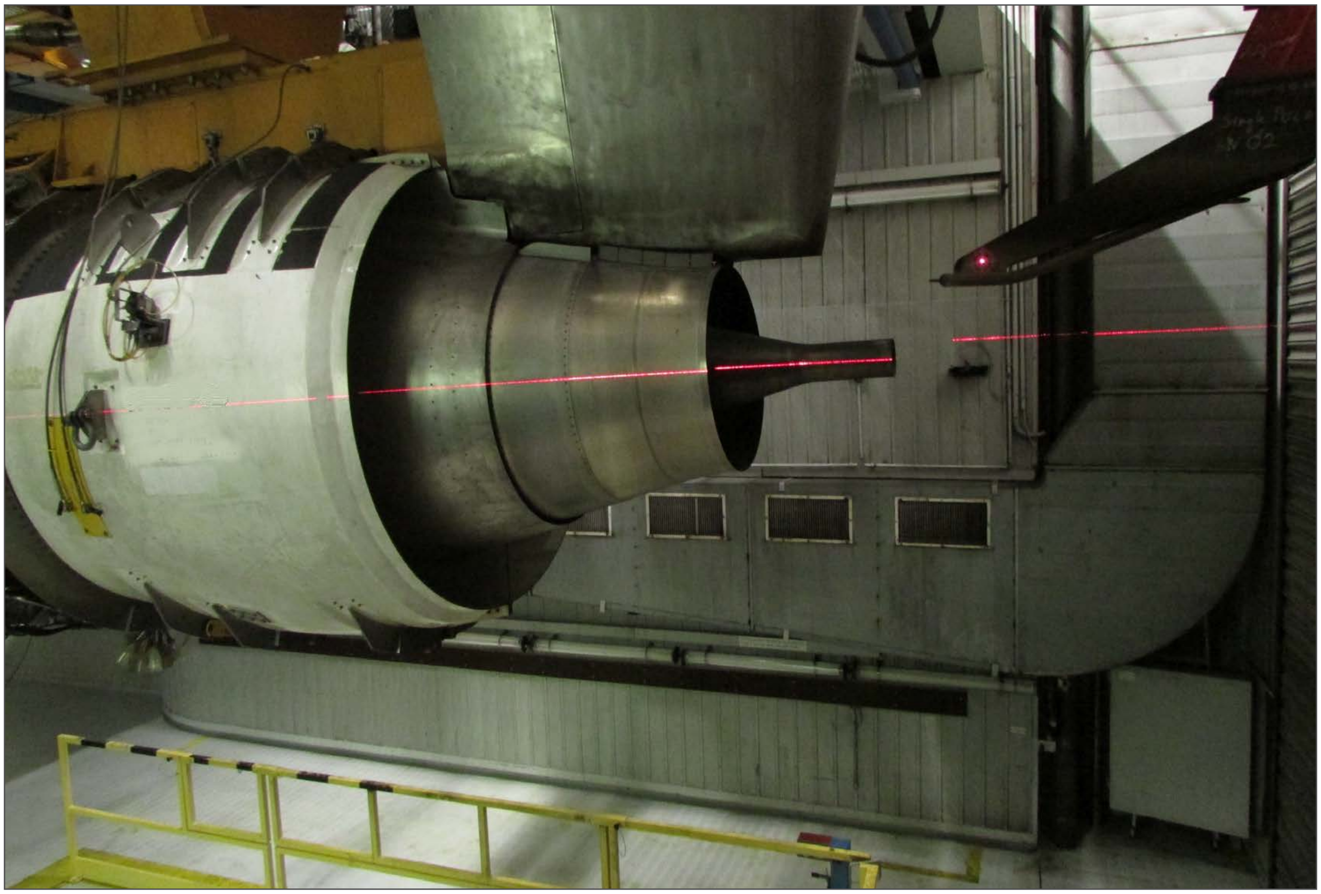

of engines tested (i.e. in most cases only one engine of the type will be tested) to guarantee compliance of the population of that engine type within a certain confidence limit.

Based on the metric values of the representative set of engines, five stringency options for nvPM mass and three stringency options for nvPM number were developed. Using the results of the cost effectiveness analysis and other factors such as technology readiness levels, CAEP/11 recommended the LTO nvPM mass and number regulatory levels for in-production and new engines, which will be considered for adoption by the ICAO Council in March 2020. These regulatory levels are shown in Figure 3.

END OF SMOKE NUMBER APPLICABILITY

With more than 50 years of advancement in our understanding of nvPM properties, extensive calculations were performed by a team from Massachusetts Institute of Technology to ensure that the non-visibility criteria of the SN limit will be maintained by the CAEP/10 nvPM mass concentration standard. It was established that for modern engines with high by-pass ratios, the CAEP/10 limit will indeed provide the necessary limit for light transmission. Because of this, CAEP/11 recommended the end date to the applicability of the smoke number standard for engines of rated thrust greater than 26.7 kN, which will be considered for adoption by the ICAO Council in March 2020. Given that the nvPM standards are not applicable to engines of rated thrust less or equal to 26.7 kN, these smaller engines will still need to comply with the SN standard.

CORRECTION FOR NVPM LOSSES IN THE STANDARDIZED SAMPLING AND MEASUREMENT SYSTEM

A sampling system for gas turbine nvPM will lose a portion of the particles when they travel through the sampling lines because of the very small size of these particles. Therefore, the nvPM emissions measured at the instruments will be lower than the values at the engine exit plane.

The purpose of emission certification is to compare engine technologies and to ensure that the engines produced comply with the prescribed regulatory limits. The ICAO nvPM sampling and measurement system requirements standardise the particle losses in the system such that engine measurements performed by different engine manufacturers and test facilities can be compared directly.

However, for emission inventories and impact assessments, nvPM emissions at the engine exit should include the particle size dependent losses in the sampling and measurement system. The standardized methodology to estimate such system losses described in the Appendix 8 to the ICAO Annex 16 Vol II was updated during the CAEP/11 cycle. This update simplifies the calculation methodology and will allow all engine manufacturers to report loss correction factors using the same procedure. While the ICAO Annex 16, Volume II, Amendment 9 recommends reporting of the system loss correction factors, reporting of these factors is made mandatory through the CAEP/11 update to ICAO Annex 16, Volume II, Part IV. This will enable the engine manufacturers report the system loss correction factors together with the nvPM emissions data as soon as engine data are certified and will lead to more accurate estimates of nvPM emissions inventories.

EFFECT OF THE NEW STANDARDS

So far, aircraft gas turbine engine designs have not been designed for low nvPM emissions. With the implementation of CAEP/11 LTO nvPM mass and number standards, future engine designs will need to consider the full interdependencies between all pollutant emissions and fuel-burn. While there may be trade-offs and constraints, these engine emissions standards will encourage cleaner technologies to be included in engine designs in the future. Significant reductions in nvPM mass and number in addition to NOx are already seen with lean-burn staged and advanced rich-burn combustors. The new nvPM SARPs will result in the implementation of such technologies across the industry and this will lead to significant reductions in emissions from aircraft engines. These new nvPM standards mean that the full complement of ICAO environmental SARPs is now in place that will limit and reduce the impact of international civil aviation in terms of local air quality, noise and CO_2 emissions.