NEW PARTICULATE MATTER STANDARD FOR AIRCRAFT GAS TURBINE ENGINES

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Particulate matter (PM) emissions from aircraft gas turbine engines are known to adversely impact both health and climate. The proposed new particulate matter standard for aircraft gas turbine engines is an important development that will lead to an overall reduction of the PM emissions and associated impacts. This new standard is a critical milestone that contributes to ICAO's strategic objective to minimize the adverse environmental effects of civil aviation activities.

At the engine exhaust source of an aircraft, particulate emissions mainly consist of ultrafine soot or black carbon emissions. Such particles are called "non-volatile" (nvPM). They are present at high temperatures in engine exhaust and they do not change in mass or number as they mix and dilute in the exhaust plume behind an aircraft. The geometric mean diameter of these particles is extremely small and ranges roughly from 15nm to 60nm (0.06 Microns).

Additionally, gaseous emissions from engines can also condense to produce new particles (i.e. volatile particulate matter – vPM), or coat the emitted soot particles. Other gaseous species react chemically with ambient chemical constituents in the atmosphere to produce the so-called secondary particulate matter. Volatile particulate matter is dependent on precursor emissions, which are controlled by gaseous emission certification and the fuel composition (e.g. sulfur content).

The new ICAO standard is an attempt to control the ultrafine non-volatile particulate matter emissions.

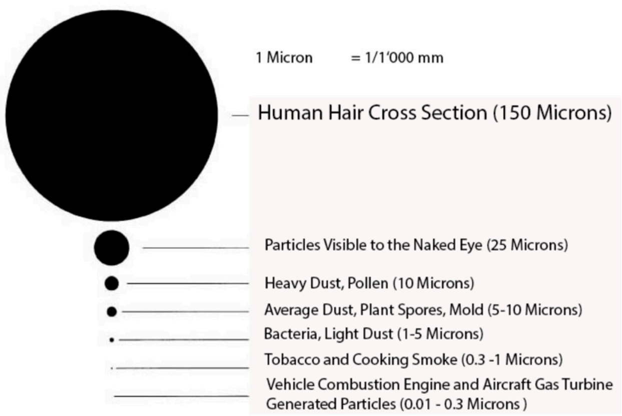

Figure1. Comparison of Particle Sizes from Different Sources.

Historical 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). That plan was implemented during CAEP/9 and the newly formed Working Group (WG3) Particulate Matter Task Group (PMTG) was tasked with the development of a nvPM standard, first for turbofan engines of rated thrust > 26.7 kN. WG3 also asked the SAE International E-31 Committee to develop a standardized measurement methodology. ICAO Member States, the European Union and the industry provided both the human resources and funding needed for this development.

By late 2010, the SAE E-31 Committee had agreed to a conceptual system for nvPM measurements. The key element for testing of such a system was the availability of an engine test cell and frequent engine runs. In order to keep costs low, the CAEP was searching for an engine maintenance facility to make use of test runs performed after engine maintenance. SR Technics, a private company in Zurich, Switzerland agreed to make their test cell available for this purpose and the Swiss Federal Office for Civil Aviation (FOCA) built and installed the first complete system prototype, including a retractable sampling probe, in their engine test cell. Led by the Swiss Federal Laboratories for Materials Science and Technology (Empa), the prototype system then became the permanently installed reference system used for the development of the nvPM sampling and measurement system (see **Figure 3**). In parallel to the Swiss effort, the SAE E31 Committee tested a prototype of the system and instrumentation in March 2011 during the National Aeronautics and Space Administration (NASA) led Aviation Alternative Fuels Experiment-II (AAFEX-II).

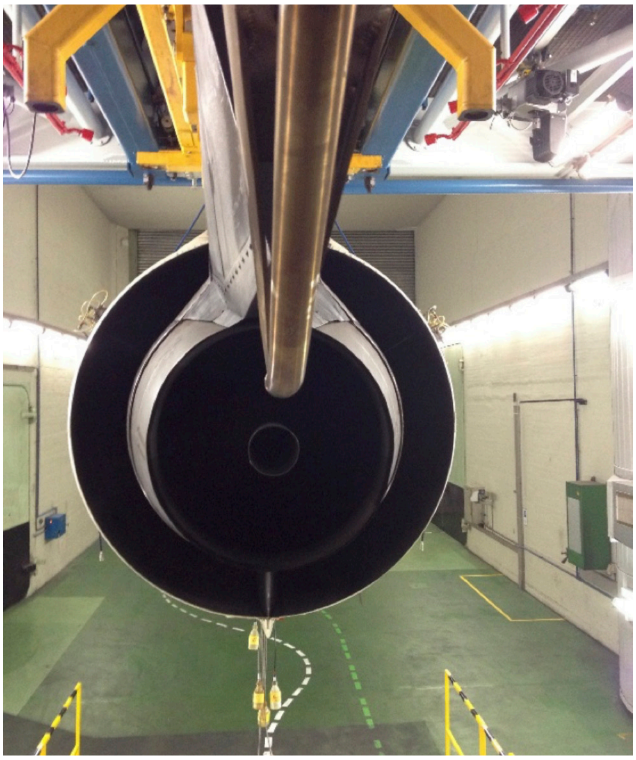

Figure 2. Turbofan Engine Seen From Behind With Tube of a Sampling Probe.

After these initial system tests, many campaigns followed, as detailed in an article in Chapter 3 of this report titled: "From smoke to nanoparticles: international campaigns for the establishment of a new nvPM regulation". Results of those tests led to the publication of the SAE Aerospace Information Report (AIR 6241) in 2013. The AIR6241 report documented the specifications of the standardized nvPM sampling and measurement system. Subsequent tests in Switzerland, USA and UK, all 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 forms the backbone of the CAEP/10 nvPM certification

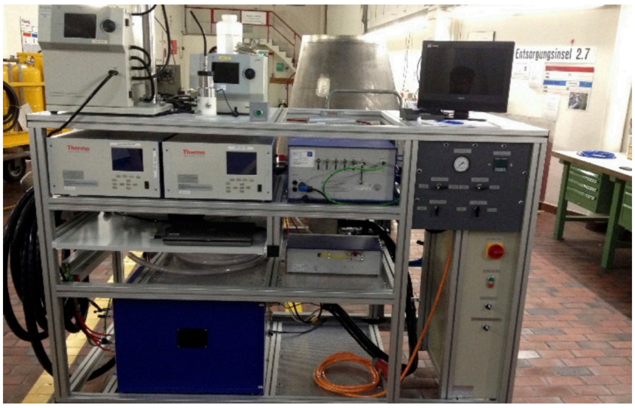

Figure 3. Sections of the Swiss nvPM Sampling and Measurement System With Added Particle Sizing Instrumentation. (Sections 4 and 5 in **Figure 4**).

requirement and standard, as specified in the new proposed Appendix 7 in the ICAO Annex 16 Vol. II (**Figure 4**).

The New CAEP/10 nvPM Standard

The CAEP/10 nvPM standard uses a mass concentration limit that is equivalent to the smoke number regulatory level in the following sense: if an engine passes the current smoke number standard, by design of the regulatory level, it will pass the first nvPM standard. Therefore, a new stringency is not introduced through the CAEP/10 nvPM standard. However, it sets the stage for health and climate relevant nvPM standards.

The new CAEP/10 nvPM standard mandates the reporting of:

- The fuel flow at each thrust setting of the certification landing and take-off cycle (LTO).
- The nvPM mass and number emission indices (EIs) for the four LTO points.
- Maximum nvPM EI mass.
- Maximum nvPM EI number.
- Maximum nvPM mass concentration.

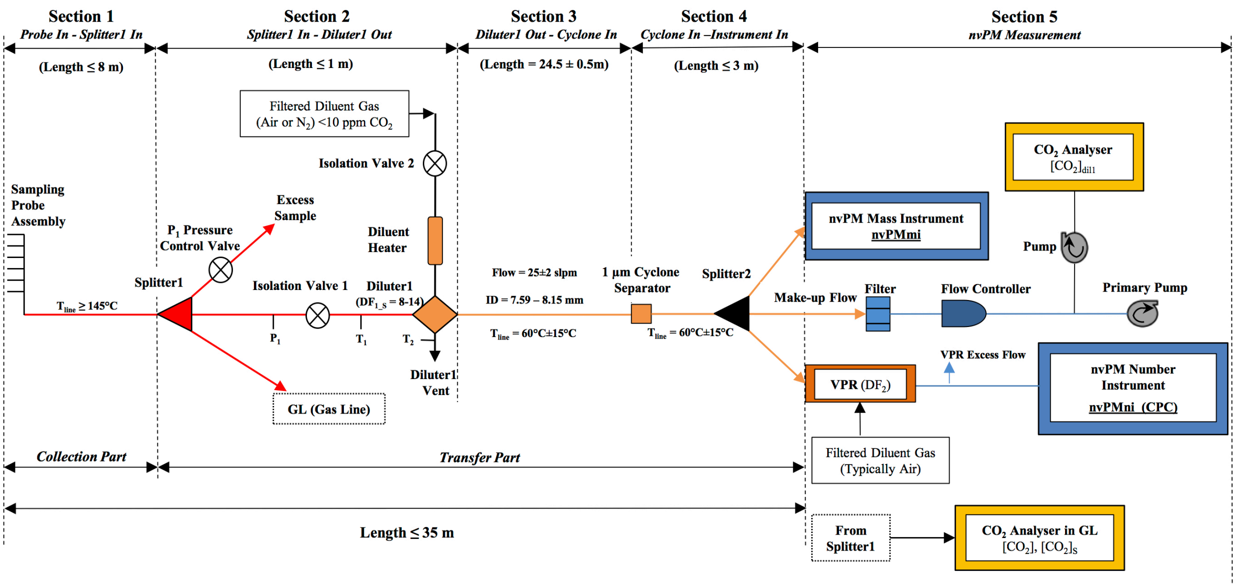

Figure 4. nvPM Sampling and Measurement System (ICAO Annex 16, Vol, II, Appendix 7).

The new standard applies 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 health and climate relevant nvPM emissions. Furthermore, the maximum nvPM mass concentration obtained from the nvPM certification measurement is used to maintain regulation of the non-visibility criteria of the exhaust and provides a pathway for the potential removal of the old smoke number standard for engines of rated thrust > 26.7 kN as early as 2020.

The regulatory level for the CAEP/10 maximum nvPM mass concentration was developed based on a statistical relationship between nvPM mass concentration and the smoke number. A graphical representation of the CAEP/10 nvPM regulatory limit for maximum nvPM mass concentration is shown in **Figure 5**.

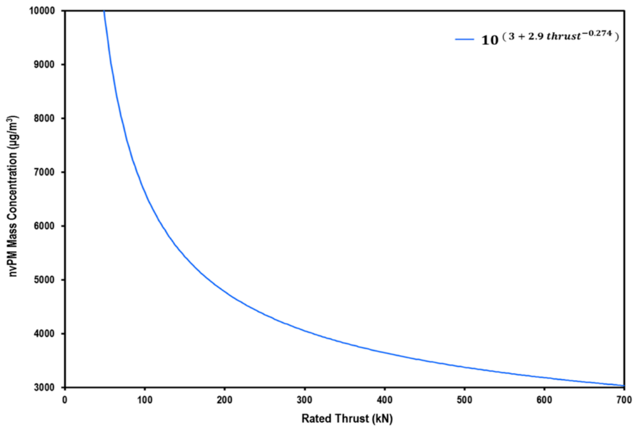

Figure 5. CAEP/10 nvPM Standard Regulatory Level.

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. A standardized methodology to estimate such system losses is described in the new proposed Appendix 8 to the ICAO Annex 16 Vol II nvPM update so that all engine manufacturers can report loss correction factors using the same procedure. The CAEP/10 update to the ICAO Annex 16 Vol.II includes a recommendation that engine manufacturers report the system loss correction factors together with the nvPM emissions data as soon as engine data are certified.

CAEP/11 Outlook

The CAEP/10 nvPM standard is a first step in the development of a mass and number nvPM standard for aircraft engines. The CAEP/10 standard requires the reporting of health and climate relevant nvPM mass and number while maintaining equivalency to the smoke number based visibility standard. A nvPM mass and number standard requires data from around 25 in production and project engines that will represent the current and future aircraft fleet. Work has already been undertaken during CAEP/10 to acquire nvPM emissions data from these engines.

Data from the representative aircraft engines will be available to CAEP by February 2017 and will be used in the development of LTO-based nvPM mass and number metric systems, stringency options, technology response, and cost effectiveness analysis. In addition, plans are in place to develop corrections to measured nvPM emissions for ambient conditions and fuel sensitivity. Similar to gaseous and smoke emissions, factors to determine characteristic nvPM mass and number emissions will also need to be developed. These efforts will inform the development of a health-based mass and number nvPM standard during CAEP/11.

The maximum nvPM mass concentration and smoke number emissions data from the representative engines will also be used to update the mass concentration-smoke number relationship. Based on this update, efforts will be undertaken to potentially replace the smoke number with the maximum nvPM mass concentration.

Figure 6 shows a roadmap of CAEP/11 activities of CAEP WG3 Particulate Matter Task Group (PMTG).

New nvPM Standard in Context of Evolving Gas Turbine Combustor Technology

Gas turbine engine combustor technologies continue to evolve, leading to significant reductions in exhaust emissions. To accomplish medium and long term NOx reduction goals, engine manufacturers are developing advanced rich burn and lean burn combustor technologies. In particular, significant reduction in nvPM mass and number is seen with the lean burn staged combustors. So far, this technology has been implemented by one engine manufacturer in medium to large commercially available turbofan engines.

Implementation of such technologies across the industry will lead to significant reduction in nvPM emissions in the future. The potential impact of the future technology implementation is shown in **Figure 7**.

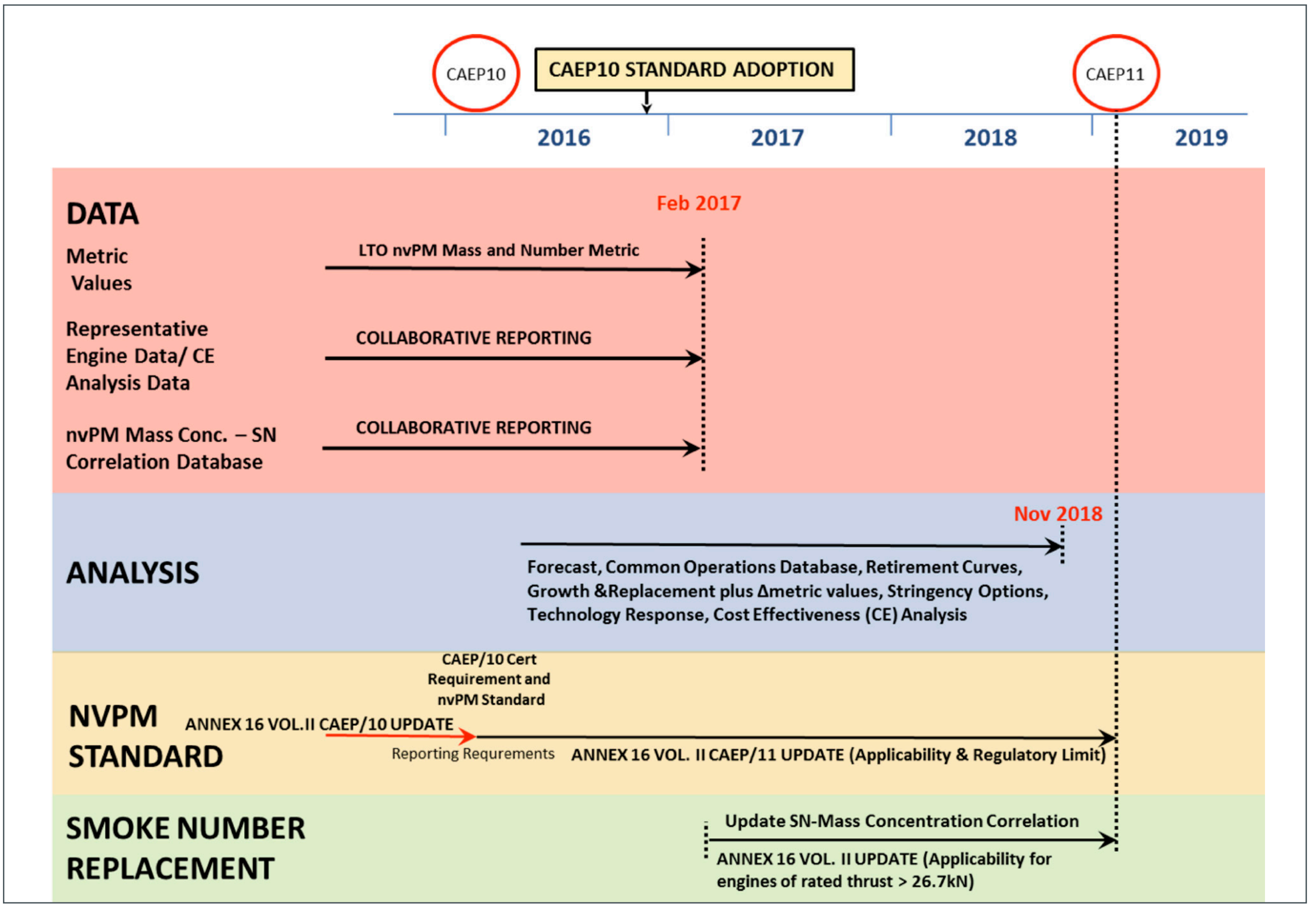

Figure 6. Roadmap of CAEP/11 Activities Toward the Development of a Health-Based Mass and Number nvPM Standard.

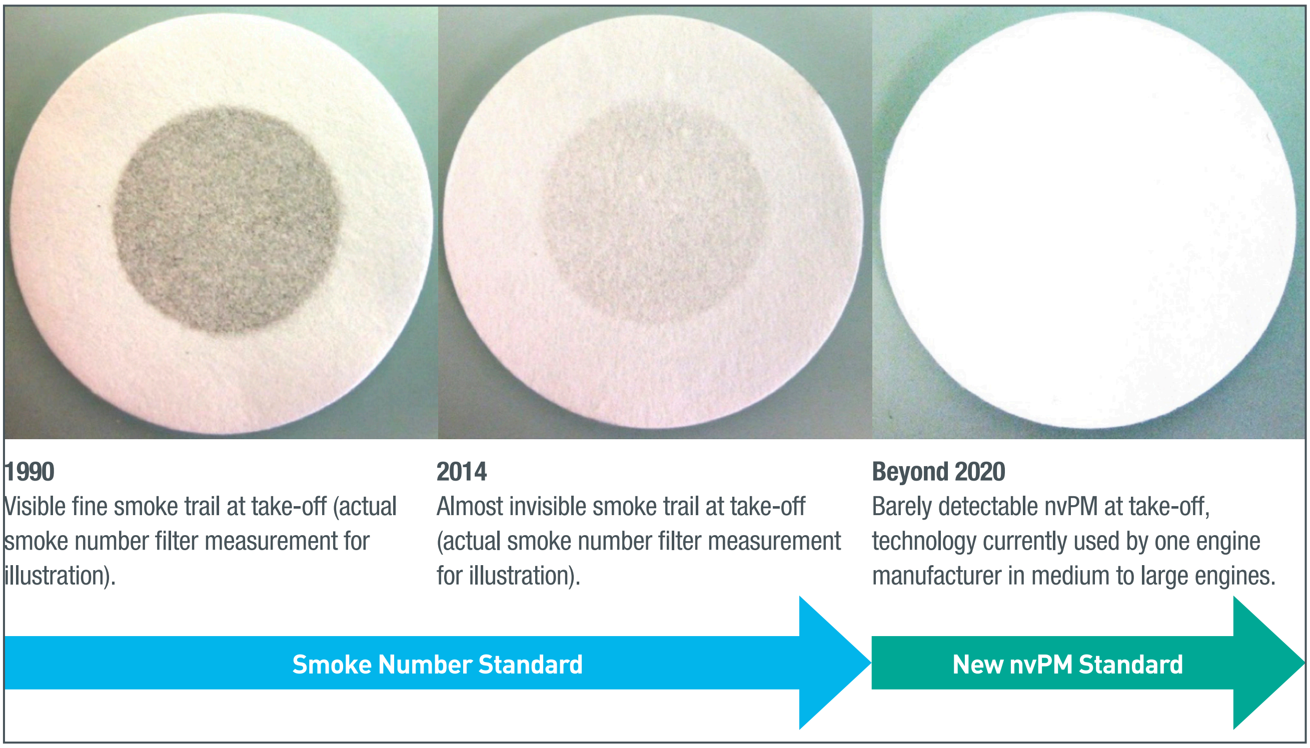

Figure 7. From smoke number standard to the new nvPM standard.