FROM SMOKE TO NANOPARTICLES: INTERNATIONAL MEASUREMENT CAMPAIGNS FOR THE ESTABLISHMENT OF A NEW nvPM REGULATION

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Particle emissions of civil aviation aero engines have been the focus of much scientific research prior to the establishment of the new non-volatile particulate matter (nvPM) standard. Examples of such research efforts include the NASA campaigns APEX and AAFEX[1] and the DLR PartEmis[2] studies. The latter resulted in the EASA supported Studying, sAmpling and Measuring of aircraft ParticuLate Emissions (SAMPLE) studies[3], which drew the attention of regulatory agencies to sampling and measurement issues associated with a new standard (**Figure 1**). Developing a standard requires the collaboration of scientists, engineers, regulatory agencies, and instrument and engine manufacturers in an international and multi-institutional effort. The Society of Automotive Engineering (SAE) International E-31 Aircraft Exhaust Emissions Measurement Committee played an essential role by elaborating the measurement and calibration procedures in the aerospace information report "Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines" (AIR 6241)[4]. The applicability of the developed procedures was tested in numerous field campaigns, which are the main focus of this article.

A particularly difficult challenge in nvPM measurements is due to the absence of a direct way to calibrate PM instruments and the lack of a clear chemical definition of the material that composes the nvPM. For gases, a precise mixture can be prepared that simulates gaseous emissions in the exhaust, which can then be used to calibrate measurements of species like NOx, HC, and CO. Conversely, particle standards are neither easily prepared nor referenced. The lack of a robust calibration standard is compounded by other challenges such as particle losses within the sampling system and instruments, which had to be considered in the establishment of the method and required field testing and evaluation. Furthermore, all of these challenges are compounded by the need to make the measurements in the high temperature, high velocity, and high vibrational environment of an aircraft exhaust.

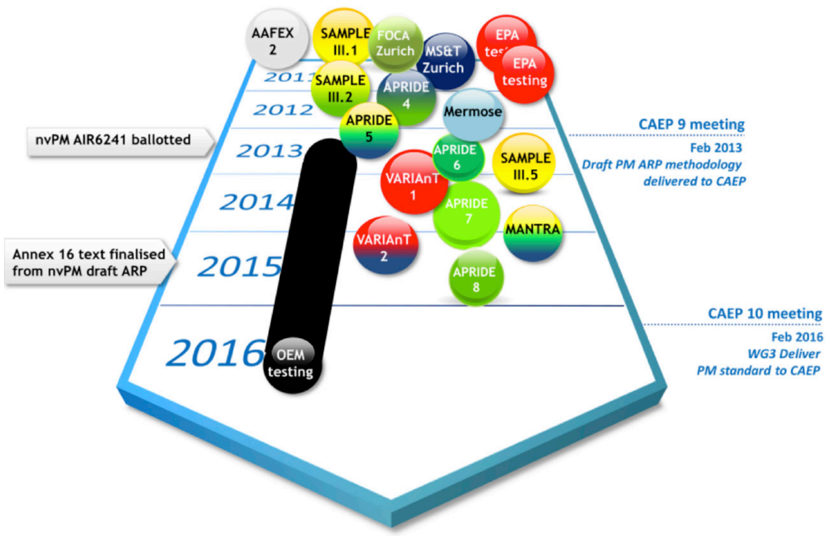

Figure 1. nvPM Methodology Standard Campaigns and Milestones (Courtesy of Cardiff University Gas Turbine Research Centre).

Aviation Particle Regulatory Instrumentation Demonstration Experiments (APRIDE)

Access to in-production aircraft engines for emissions measurements is rather difficult. A unique measurement opportunity was established in 2011 in collaboration between the Swiss Federal Office of Civil Aviation (FOCA) and SR Technics in the engine test cell of SR Technics at Zurich Airport. This facility performs maintenance service on in-production engines, A permanently installed retractable single orifice probe (**Figure 2**) was developed that allows the sampling of PM-laden exhaust for various engine models and variants.

Figure 2. Single Orifice Probe nvPM Measurements in the Test Cell of SR Technics, Zurich Flughafen (Courtesy of SR Technics).

The initial APRIDE campaigns focused on studying and identifying suitable measurement equipment. For example, various models of particle counters and volatile particle removers were tested and evaluated. After these initial efforts led by FOCA with the participation of DLR Stuttgart, the unique measurement platform and the FOCA support funded by the Swiss domestic fuel tax saw the contribution of various Swiss institutions and partners from the SAE E31 Committee, including the FOCA supported Swiss Federal Laboratories for Materials Science and Technology (Empa), the EASA funded SAMPLE consortium, the FAA supported Missouri University of Science and Technology and Aerodyne, Transport Canada supported National Research Council of Canada and U.S. EPA.

Systematic investigations were performed on particle counters and system operability parameters which determined instrument and system specifications (APRIDE 3/SAMPLE III.2)[5]. System to system variability was the main focus in APRIDE 4[6]. This effort continued in APRIDE 5/ SAMPLE III.3[7] with a three way system inter-comparison [**Figure 3**]. APRIDE 5/SAMPLE III.3 further investigated the effect of various dilution factors on the particle number measurements and measured relevant nvPM characteristics for particle losses within the sampling system, such as particle effective density and particle size distributions. In addition, the particle chemical composition and internal structure were examined with online and offline measurement methods.

Figure 3. The APRIDE 3/ SAMPLE III.2 Campaign Team (Courtesy of SR Technics).

The APRIDE 5/SAMPLE III.3 campaign was the greatest effort at SR Technics to date, with more than 35 participants, 95 hours of dedicated engine operation, and more than 130 tons of jet fuel burned [**Figure 4**]. An important highlight of this major effort was the "certification-like" engine test, which was a dedicated "mock" engine nvPM certification test that followed the draft standard specifications as would be performed in the facility of an engine manufacturer. The first commercial nvPM measurement system prototype was evaluated in a cooperative effort with the manufacturers in APRIDE 6. Empa, SNECMA, GE Aviation and FOCA further investigated the effect of total fuel aromatic content on nvPM emissions[8]. This campaign also collected SN data in parallel, allowing SN nvPM mass correlations, and investigated the spatial variability of nvPM and gaseous pollutants at the engine exit plane.

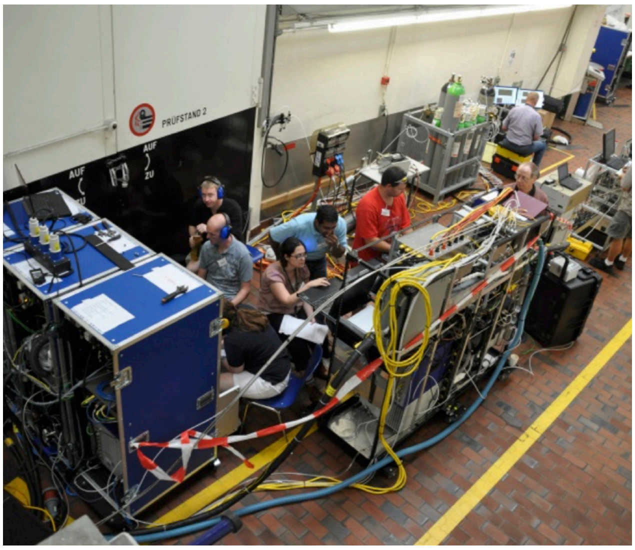

Figure 4. nvPM Measurements of the SAMPLE Consortium and Missouri University of Science and Technology In Action During the APRIDE 5/SAMPLE III.3 Campaign (Courtesy of SR Technics).

VARIAnT and MANTRA

APRIDE provided much needed data and experience with these nvPM measurement systems, but these studies also raised some specific questions. Most notably, the issue of system-to-system variability is critical for regulatory measurement systems used across the industry. In order to better understand and quantify this system-to-system variability in general, the VAriable Response in Aircraft nvPM Testing (VARIAnT) program conducted campaigns in the summers of 2014 and 2015 at the US Air Force Arnold Engineering and Development Complex (AEDC) in Tennessee, USA [**Figure 5**].

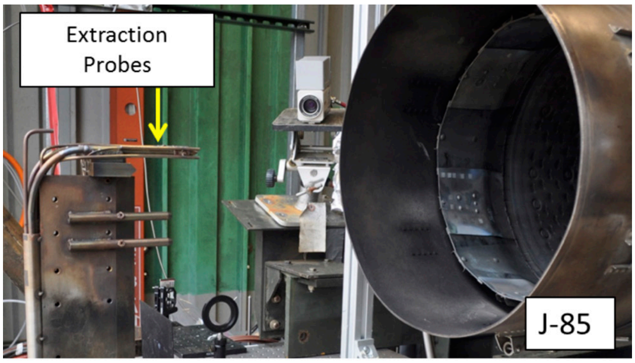

Figure 5. The VARIAnT Probe System (Courtesy of AEDC).

The 2014 VARIAnT1 campaign, as well as APRIDE and the engine manufacturer testing described below, highlighted measurement variability in the nvPM mass measurement instruments in particular, and a campaign that focused specifically on this variability, called Mass Assessment of nvPM Technology Readiness for Aviation (MANTRA), was carried out in early 2015 at Rolls-Royce in Derby, UK [**Figure 6**].

Figure 6. The MANTRA Experimental Set-up (Courtesy of Cardiff University Gas Turbine Research Centre).

The objectives of the VARIAnT1 study were to perform a systematic evaluation of the sources of variability in the measurement of nvPM mass and number and, where possible, determine the largest sources of variability and methods to potentially reduce these to the lowest degree possible. The second campaign, VARIAnT2, continued to assess the variability between two independently assembled, compliant nvPM measurement systems, but had an additional goal of conducting more detailed investigations of particle losses in those compliant sampling systems.

The VARIAnt1 test campaign showed little effect on measurements within the range of conditions for a wide variety of operating parameters of the sampling system defined by the draft ARP. This confirmed that the sampling system was robust. Multiple sampling systems with multiple instruments gave confidence in the resulting comparisons performed. However, the reliability of one of the mass instrument types was brought into question, which resulted in a lack of confidence in a single instrument suite, as would be used in routine testing in the future. VARIAnT2 data analysis and interpretation is ongoing. However, differences in repeated pre-test mass calibrations have already been identified. This was unexpected and is being further investigated. Both mass instrument types responded differently to the laboratory calibration soot aerosol as compared with the engine, and the same instrument that raised questions in VARIAnT1 showed greater variation. Thus, the issues raised by VARIAnT1 require ongoing study, and cast doubt on the nvPM mass measurement in particular.

The differences in the response of mass instruments over ranges of nvPM size, elemental to organic carbon ratio, and mass concentration, were the focus of the MANTRA study. Laboratory diffusion flame sources and a turboshaft engine were used in the study. Soot optical and structural properties, as well as chemical composition, were investigated in parallel to the mass instruments as a function of fuel air equivalence ratio or engine power setting. The data analysis of this campaign is still ongoing but a better understanding of calibration and gas turbine nvPM properties is expected, which will lead the way to an improved calibration procedure for the mass instruments.

Engine Manufacturer Testing and Comparison

As details are being worked out in APRIDE, VARIAnT, and MANTRA, a parallel effort has begun to ensure that these systems can be used by engine manufacturers in their facilities during certification test scenarios. In coordination with an ad hoc group on measurements (MEASURE) of CAEP Working Group 3, and with the International Coordinating Council of Aerospace Industries Associations (ICCAIA), a series of "demonstration" tests and "comparison" tests are being pursued.

The goal of these tests is to deploy one of the reference systems that was characterized in APRIDE such that every engine manufacturer can gain experience and obtain data using these reference systems on their engines. In a "demonstration" test, either the North American Reference System or the European Reference System is transported to the engine company's test facility and used to collect data in a certification-like test environment. If all of the certification requirements are met, there is agreement with the regulatory authorities that the data will subsequently be acceptable as nvPM certification test data once an nvPM emissions standard has been put in place. In this way, the engine manufacturer can learn how the system is used and can obtain important and costly nvPM certification data at the same time.

In a "comparison" test, one of the nvPM reference systems is used in parallel with the engine manufacturer's own nvPM measurement system. For a "comparison" test, all of the same experience and data are obtained as in a "demonstration" test, but in addition, the results of the engine manufacturer's system can be compared with either the European or North American Reference systems. This comparison will provide more system-to-system consistency data and will show how the individual systems operated by engine manufacturers compare with these extensively deployed reference systems. A "comparison" test is required for each manufacturer. While a "demonstration" test is available as a convenience, and for obtaining nvPM data sooner, a "demonstration" test is not required once a "comparison" test is done.

A number of tests with engine manufacturers have already been conducted and additional tests are planned. Together, this will build an nvPM base of a few dozen engines in the coming years, including several repeats of some engine model types. All of the major engine manufacturers have now gained some experience in operating these new nvPM measurement systems, and nvPM data from representative engines are currently being accumulated.

Additional Studies and Future Work

Much progress has been made in advancing the research measurement technology to a standardized system that can be used in regulatory certification for nvPM emissions. The focused field campaigns described here have taken the recommendations of the SAE E-31 Committee, and tested and refined those procedures such that Appendix 7 to Annex 16 can be the basis of the new nvPM standard.

Nevertheless, additional work is still needed and ongoing. The variability in mass measurement, in particular, needs to be understood and reduced. The ability to accurately account for nvPM losses in the probe and sampling system needs to be finalized and fully documented. The current Appendix 7 standard is based on a maximum PM concentration metric, yet there is interest in going further and developing a more detailed PM standard based on a Landing Take-Off (LTO) cycle as is done for gaseous emissions. To do that, the effects of ambient conditions and fuel effects on PM levels need to be more fully understood. However, the extensive efforts already performed in these many field campaigns have provided ICAO with the strong technical support needed for the new nvPM standard of Appendix 7 of Annex 16.

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