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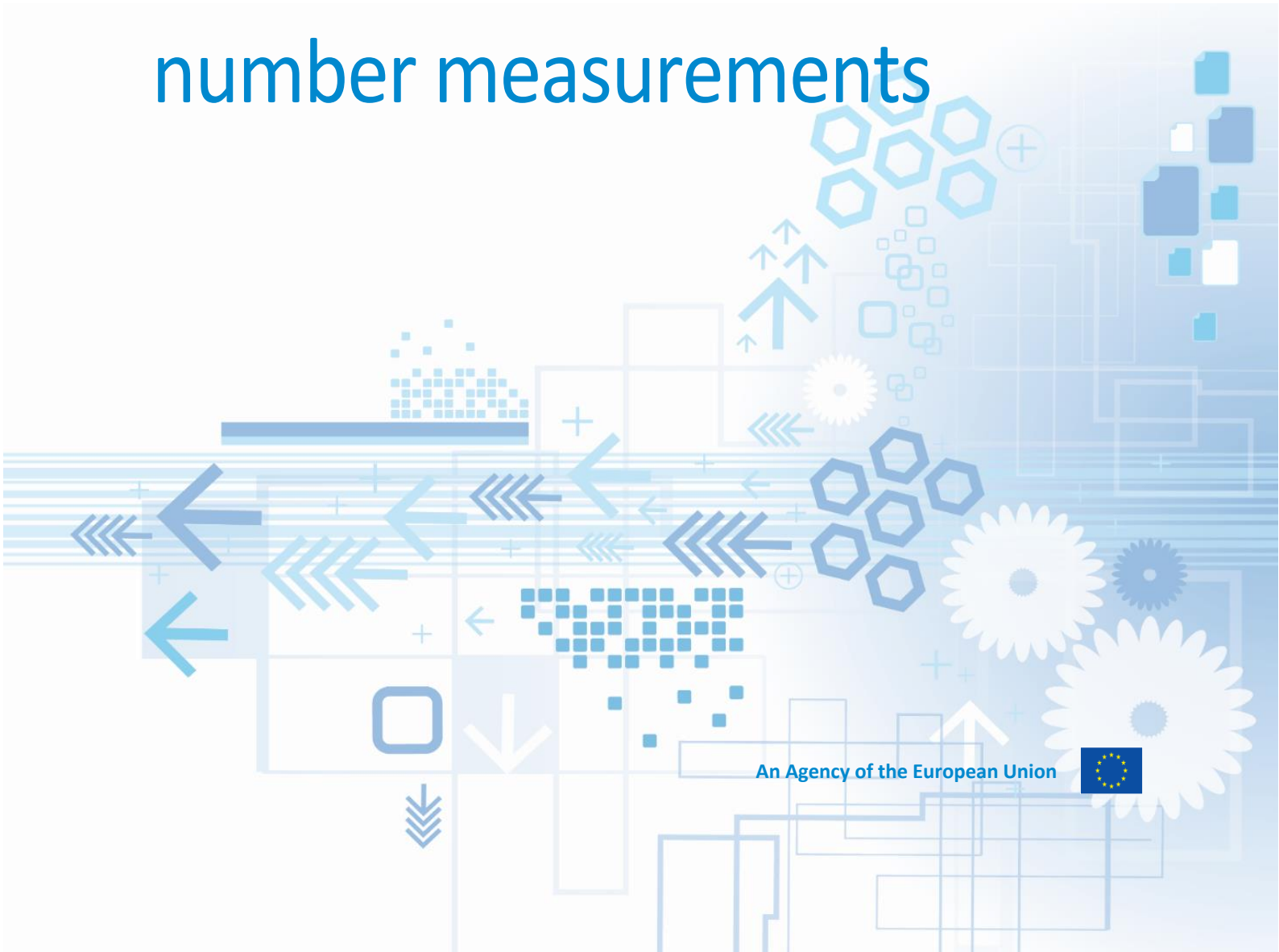
SAMPLEIV [EASA.2020.FC05]

[DELIVERABLE 2: REPORT]

Solutions for regulatory aviation nvPM mass and number measurements



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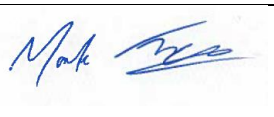
Lead author	27/10/2024	Dr M Johnson	
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EXECUTIVE SUMMARY

This report provides a review of the state-of-the-art aircraft engine ICAO regulatory Annex 16, Volume II nvPM emissions sampling and measurement system. Included are the historical approaches adopted in establishing the baseline system, and the current status of the methodology for nvPM mass and number measurement in a regulatory context.

An overview of the historical development of the sampling system together with the nvPM mass, number and size instruments is presented, with the scientific thoughts, compromises considered and data that was available to understand the impact of the adoption.

Potential improvements to the ICAO regulatory nvPM sampling and measurement system could reduce uncertainty in reported aircraft engine nvPM emissions. Optimisation of the methodology is possible as more information becomes available. High priority improvement items for nvPM sampling and measurement, perceived to have the biggest impact in reducing uncertainties, are presented.

Now well over a decade after the development of the initial nvPM measurement approach, scientific and operability knowledge has improved, and new/improved instrumentation is commercially available. 'Outside-the-box' consideration is provided based on 'what we now know' without having to comply with existing system boundary constraints. Novel measurement solutions are presented which could potentially provide the best possible/optimum nvPM measurement for regulatory use.

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LIST OF ABBREVIATIONS

BC – Black Carbon

CAEP – Committee of Aviation Environmental Protection

CPC – Condensation Particle Counter

cPTFE – carbon loaded Polytetrafluoroethylene

CPMA – Centrifugal Particle Mass Analyser

CS – Catalytic Stripper

DF – Dilution Factor

EC – Elemental Carbon

EI - Emission Index

(US) EPA - (United States) Environment Protection Agency

FAA – Federal Aviation Administration

FOCA – Federal Office of Civil Aviation

GMD – Geometric Mean Diameter

GSD – Geometric Standard Deviation

ICAO – International Civil Aviation Organization

LDSA – Lung-Deposited Surface Area

LII – Laser Induced Incandescence

LOD – Limit of Detection

LOQ – Limit of Quantification

MSS – Micro Soot Sensor

nvPM – Non-Volatile Particulate Matter

OC – Organic Carbon

OEM – Original Engine Manufacturer

PCRF – Particle Counting Reduction Factor

PM – Particulate Matter

PSD – Particle Size Distribution

SAF – Sustainable Aviation Fuel

STP – Standard Temperature and Pressure

TC – Transport Canada

TOA – Thermal Optical Analysis

VPR – Volatile Particle Remover

ZHAW – Zurich University of Applied Sciences

1. State-of-the-art and the historical approaches of ICAO regulatory nvPM sampling and measurement system

1.1. Introduction

Information on the historical development and approaches of smoke and gas sampling and measurement systems for aircraft engine emissions certification for the 1st edition of ICAO Annex 16 Volume II (in 1981) and up to 2003, is contained in the NEPAIR report[1].

This report provides a review of the state of the art in nvPM ICAO regulatory sampling & measurement and the establishment of the baseline of the system, in respect to the detailing of historical approaches adopted, and the current status of the methodology for nvPM mass and number measurement in a regulatory context.

As of CAEP/10 (February 2016) an inaugural engine nvPM certification requirement and emissions standard for engines of thrust >26.7kN was adopted into the ICAO Annex 16 Volume II as a new Chapter 4 & Appendix 7. This required compliance for in-production engines on or before January 2020 and is applicable to engines produced subsequently. The certification requirement specifies a standardised sampling and measurement system and requires mandatory reporting of LTO and maximum EI's of nvPM mass and number. The new maximum nvPM mass emission limit translates to the smoke number visibility metric and sets a new standard for permissible limits of nvPM mass concentration. To enable reporting of engine exit nvPM, for emissions modelling and inventory purposes, a system loss correction methodology was also included as Part IV and Appendix 8 to Annex 16 Volume II.

As part of CAEP/11, a new metric system was developed representing nvPM emissions, in order that new regulatory limits will ultimately translate to 'real-world' reductions in emitted nvPM. Based on datasets acquired using the aforementioned CAEP/10 standards, new LTO nvPM regulatory limits for both nvPM mass and number have been implemented, with 'new type' engine applicability required from January 2023.

In-line with the adoption of these new nvPM standards, the smoke number metric applicability for engines of thrust >26.7kN has ended.

The detailed schematic of the nvPM sampling and measurement system provided in Appendix 7 of Annex 16 Vol II is provided below in Figure 1.

[1] Lister et al. 'Aircraft Engine Emissions Certification: A Review of the Development of ICAO Aneex 16, Volume II.' EC-NEPAir: Work Package 1, QinetiQ/FST, CR030440, GRD-CT-2000–00182 (2003)

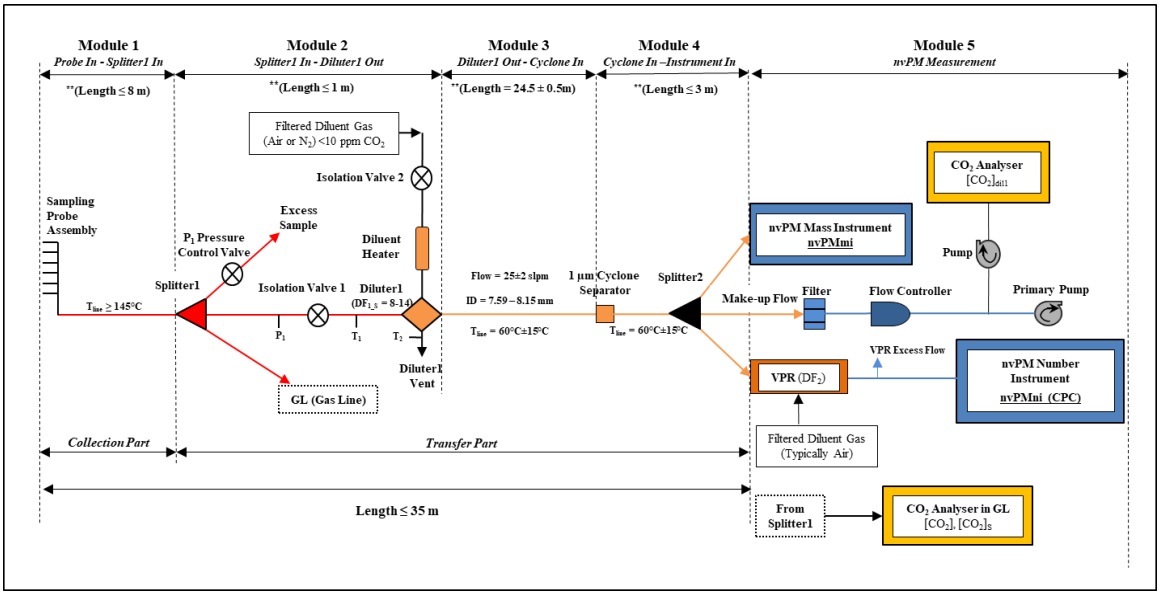

Figure 1 ICAO Annex16 Vol II nvPM sampling and measurement system

To obtain measurements at the engine exit of large-scale civil aviation gas turbines, where high temperature (>500°C), high flow field velocities and high vibrations are typically witnessed, it was deemed necessary to adopt a complicated and relatively long (≤35m) sampling system. This was required to transfer representative engine exhaust from the existing (gas and smoke) Annex 16 Vol II compliant sampling probes to a safe distance away, typically through test cell walls, to the relevant nvPM mass, number and gaseous analysers. This is different to the automotive regulatory methodology which attempts to collect the entire engine exhaust sample and uniformly dilute, in a constant volume tunnel, before a very short sampling system delivers sample to nvPM analysers. Aircraft engine exhaust mass flowrates make the automotive dilution methodology impractical to implement at the engine exit of a large-scale gas turbine. However, sampling downstream of the engine exit, in the de-tuner/stack of a test cell, could be considered in the future and would be more analogous to automotive sampling methodologies.

The development of the nvPM sampling and measurement system was conducted by the SAE E31 International Technical Committee, responsible for Aircraft Engine Gas and Particulate Emissions Measurement, with details of its development, make-up and usage offered in three Aerospace Information Reports (SAE AIR5892B, AIR6037A & AIR6241A) and an Aerospace Recommended Practice (SAE ARP6320B). As with the development of any new measurement methodology there were several compromises made between practical usage and scientific rigour which are to date not fully documented. These compromises were in part necessary to meet the timeline requested by the regulators to implement the new nvPM standard.

As such, the aim of this report, is to detail historical approaches adopted and the current status of the measurement methodology for nvPM mass and number measurement in a regulatory context. Documented are the compromises and relevant assumptions made supported where available by the the data used to make these decisions. With these decisions suitably documented, it is then possible to propose a scientific optimum for nvPM mass and number measurement capability moving forwards.

A “Review of the chosen approaches and compromises made” was undertaken towards providing an “Elaboration of proposals for improved and novel nvPM measuring concepts”. It is perceived that potentially such an assessment, could be added to SAE AIR6241B or in an SAE Technical Paper (as was performed for the automotive nvPM methodology SAE Technical Paper 2009-01-1767) to traceably document the historical reasoning.

1.2. Participation discussion of historical approaches of nvPM measurement

Over 30 technical international participants from engine manufacturers, regulators, scientific researchers, academics and instrument manufacturers, were instrumental in the development approach for regulatory aviation nvPM measurement. For the purpose of documenting the historical approach detailed in this report, a small subset of these participants, who have been instrumental throughout the nvPM system development process, held several discussions. These participants included European academia, engine manufacturer and regulators who offered significant leadership in the development of documents produced by SAE E31 and CAEP WG3 for the first aircraft engine nvPM standard. In addition, they were instrumental in the delivery of a number of relevant nvPM measurement projects including;

SAMPLE I to III (2009 to 2014) Studying, sAmpling and Measuring of aircraft ParticuLate Emissions

APRIDE 1 to 8 (2011 to 15) Aviation Particle Regulatory Instrumentation Demonstration Experiments

AAFEX2 (2011) Alternative Aviation Fuel Experiment

MANTRA (2014 to 2015) Mass Assessment of nvPM Technology Readiness for Aviation

DG-MOVE (2015 to 2017) System intercomparisons on multiple OEM tests

RAPTOR (2019 to 2022) Research of Aviation PM Technologies, mOdelling and Regulation

These programmes included the first demonstrations of prototype nvPM sampling and measurement systems which took place at SR Technics, Zurich and Rolls-Royce Derby in 2010.

1.3. Milestones and Timeline of nvPM measurement system development

A historical overview of the SAE and ICAO nvPM measurement system development timeline is shown in Figure 2, which details the development of relevant documents and specific experimental test campaigns undertaken. The international collaborations are shown by the multi-colouring shading. Many of these test campaigns are referenced in the historical approach discussion below.

The top two diagrams show the timeline up to the implementation of the nvPM standard. The bottom diagram shows work since the implementation, noting that there have been many other (mostly SAF related) research engine test campaigns where trials of nvPM system improvements have piggybacked these existing test campaigns.

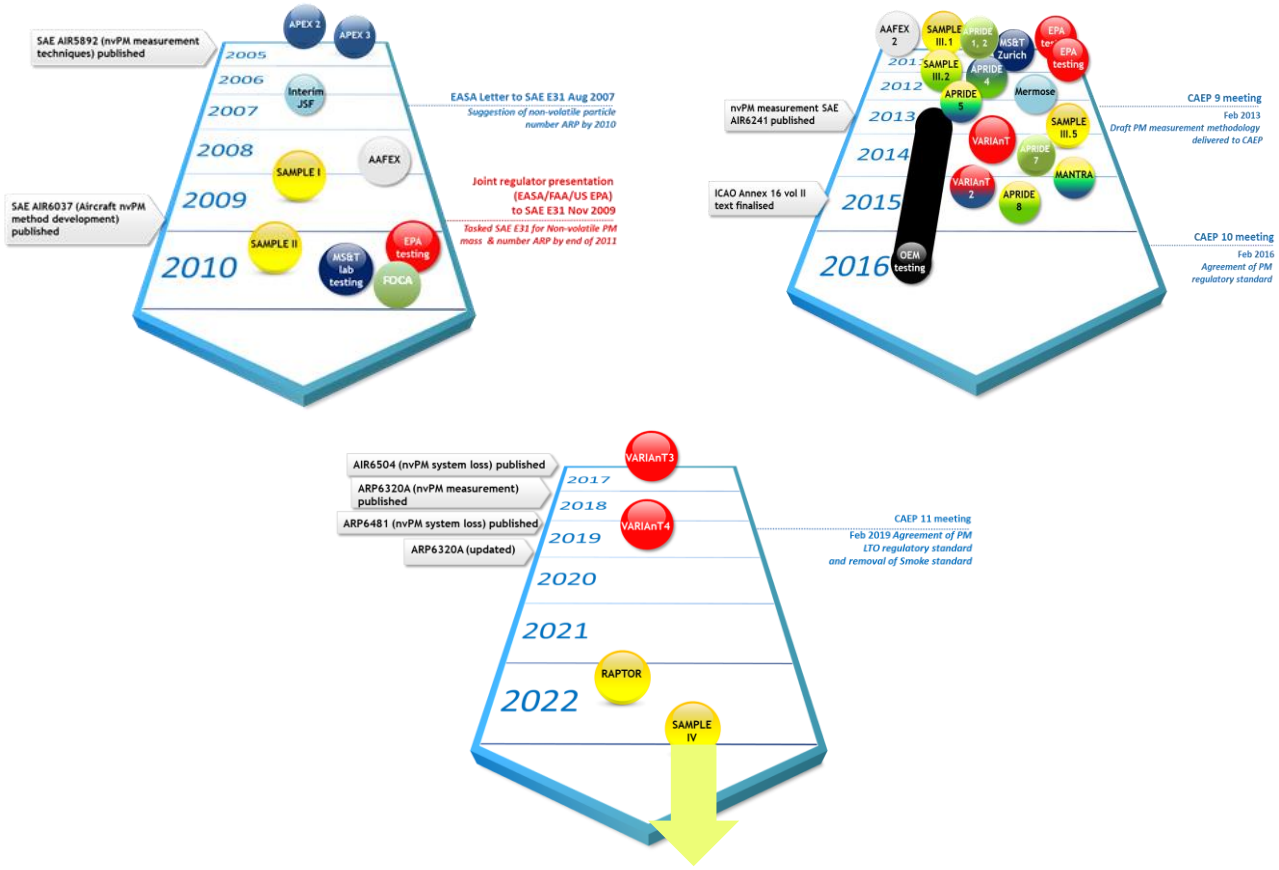

Figure 2 Timeline of nvPM system development – documents and research projects. Colour coding indicates participation/collaborations of funding sources (yellow = EU, green = CH, red = US EPA, dark blue = North American, white = NASA, light blue = other)

1.4. Sampling Methodology

An overview of the history of development of the sampling system is discussed below highlighting the scientific thoughts, compromises considered and data that was available to understand the impact of the adoption. For simplicity, the discussions are broken into the relevant 'modules' of the sample system as defined by ICAO and presented in Figure 1.

It should be noted that there have been two changes of nomenclature of the nvPM system during SAE and ICAO document development. Namely initially 'PTS' (Particle Transfer System) in SAE AIR6421, followed by 'Section' and 'Part' in Annex 16 Vol II and SAE ARP6320, followed by 'Module' in Annex 16 Vol II Amendment 10. These different terms exist across historical reports or manufacturer nvPM system descriptions which are all equivalent but could possibly cause confusion.

1.4.1. General considerations

During the SAE E31 AGM held at Cardiff (2010), it was agreed that the sampling system should be standardised as much as possible, with the regulators specifying that the same sampling system should be used for both nvPM mass and number measurements. This contrasts with Annex 16 Vol II smoke sampling system which allows a range of sample line geometry (ID and length), material and temperature (smoke visibility is

dominated by the larger emitted particles which are substantially less affected by size dependant particle loss mechanisms compared to nvPM). It is noted that the existing Annex 16 Vol II 'standardised' sampling and conditioning was much simpler (no chemical reactions, loss of gas molecules) for gaseous emission measurements as there were no known impacts of sampling system geometry other than sampling time.

It is thought that the decision for a more 'standardised' approach for nvPM sampling was taken towards ensuring particle losses would be similar system to system and to each of the nvPM mass and number analysers, within a given measurement system. This standardised loss was to be supported with calculated penetration efficiencies (akin to VPR penetrations) being reported to allow a potential assessment of system loss, which was known to be difficult without PM size knowledge. However, as discussed further throughout this report, tolerances in the subsequent sampling and VPR specifications have meant that differences within systems are permissible, hence particle losses are not precisely identical/standardised between or within sampling systems. In addition, it has been observed that there are a range of size distributions of nvPM emitted from different engines, which are impacted by engine power and fuel composition. Given major loss mechanisms are size dependant, this leads to large differences in witnessed particle loss across different sampling systems and for the same sampling system across a given engine test.

The concept of a 'standardised' approach is analogous to that employed in the EURO regulation of automotive nvPM through the PMP (Particle Measurement Programme), with the advantages of this approach presented by Jon Andersson (Ricardo & PMP Golden Engineer) at the SAE E31 Ottawa meeting (Andersson, DP04 SAE E31 Ottawa 2011). It was discussed that. during the development of the automotive regulatory nvPM number measurement system, a golden/ reference measurement system and engine were transported and operated at multiple OEM (Original Equipment Manufacturer) automotive laboratories for comparison. The recommendation of Jon Andersson, based on the experience of PMP, was to apply a standardised sampling system as far as practical. This confirmation cemented the SAE E31 decision to apply a similar route with the creation of the portable European (EUR, formally referred to as EASA), North American (NA) and fixed Swiss (subsequently becoming also portable) reference nvPM sampling and measurement systems which were operated analogous to the automotive PMP golden system. These systems were first intercompared at SR Technics[2] then comparisons were made to OEM nvPM sampling and measurement systems[3]. However, due to the practical nature of large gas turbine engines and OEM specific sampling probes it was not possible to replicate the 'Golden engine' at different OEM facilities as was used by the automotive PMP.

The rationale for a standardised system for both nvPM mass and number measurements, removed the ability to consider nvPM mass measurements on the existing raw, smoke and gas, sample line. Requiring in-parallel measurements with the nvPM number instrument on a diluted sample line. However, in making this decision, it was subsequently found (initially around the time of AIR6241 publication in 2013 from SAMPLEIII & APRIDE measurements at SR Technics and then much later by OEMs, Bachman DP25 SAE E31 Florida 2018) that nvPM mass measurements were sometimes found to be measuring at or below the Limit of Detection (LOD) of regulatory compliant nvPM mass analysers. Clearly if this compromise was revisited, then nvPM mass analysers would effectively have an accurate measurement range at ~10 times lower engine exhaust concentrations (corresponding to Dilution Factor 1, which is specified as being 8-14). It should be noted that simply obtaining nvPM mass measurements on a raw undiluted sample line requires consideration for potential issues associated with water condensation and gas cross interferences (for example water or NOx), in addition to particle shedding.

[2] Lobo et al. 'comparison of standardized sampling & measurement systems' DOI/10.1016/j.jaerosci.2020.105557

[3] Due to IP restrictions these comparisons are not reported in the public domain

If nvPM measurements are deemed required at concentrations near or below ambient nvPM levels, then a possible correction for ambient nvPM mass and number entering the engine may be needed. This may be especially required for existing and future staged combustion systems, which are seen to produce very low levels of nvPM (at or lower than ambient) at higher thrusts.

For current system loss correction calculations which uses a number to mass (N/M) ratio to predict a particle size, based on assumptions of GMD, GSD and particle effective density, an accurate nvPM mass is required (Annex 16 Vol. II Appendix 8). In the future, if particle size distribution (PSD) measurements are performed e.g., to facilitate system loss correction calculation, this method would remove the requirement for accurate low level nvPM mass measurements.

Currently, only thermophoretic loss is considered from probe inlet (engine exit plane temperature) to diluter 1 inlet in regulatory reported nvPM Emission Indices (EI). This accounts for differences in engine exit exhaust temperature and is considered particle size independent and therefore can be simply calculated. Empirically based numerical models are used to predict size-dependent loss in the sampling system for airport inventory modelling (Annex 16 Vol II Appendix 8). It was thought that correction for system loss could not be validated empirically on individual systems since there is high uncertainty in measuring full sampling system loss, and currently it is not feasible to measure particle losses in the Annex 16 Vol II sampling rakes under witnessed real-world temperature and velocity conditions. Similarly, it is noted that the system loss in a given sampling system, is highly dependent on the particle size distribution (and potentially morphology & charge). Hence, particle loss determined using a polydisperse challenge aerosol may not be fully representative of a given engine exhaust measured during an engine emissions certification test.

1.4.2. Module 1 – Probe inlet to Splitter 1 inlet

As seen in Figure 1, Module 1 contains the sampling probe assembly and sampling lines to the inlet of splitter 1. A compromise made by the committee early in the development process (SAE E31 Cardiff 2010), was to use existing Annex 16 Vol II sampling probes and rakes (designed originally for Smoke and gas measurement). It is thought that this compromise was accepted in the knowledge that OEMs have developed a variety of different (very expensive and complex) probes, designed and optimised for specific engine exhaust designs. The time to develop new multi-hole nvPM probes for all engine types would have added significant delay (>5 to 10 years) to implementing a new nvPM standard. Both gaseous and smoke measurements are obtained with the same probe/rake (either fixed or rotating) and typically achieve representativeness using multiple ≥12 sampling points, which are subsequently mixed, or by using a traversable single point probe at ≥12 sampling locations.

To try and help standardisation of future probe designs for the nvPM system, the sample residence time from probe inlet to diluter 1 inlet (residence time through probe & sample line is specified) is recommended as <3s (SAE ARP6320, not a requirement in ICAO Annex 16 Vol II). This recommendation does not exist for smoke and gas emission measurements.

However, in choosing to utilise these existing probe/rake designs, a number of compromises have been made in terms of nvPM measurement as discussed below.

Compromises in using the existing probe/rake sampling hardware, originally developed for representative sampling of smoke and gas emissions, are that there are a large range of flow rates in the module 1 sampling section. Designs of sampling systems also employ different expansion and mixing plenums. However, these variations were assumed to have negligible impact on measured nvPM at end of the >25m sampling system from probe outlet to instrument inlet. This assumption was supported by, UTRC line loss tool (SAE AIR6241), modelling studies performed by Dr David Liscinsky. The work assessed a variety of OEM (Rolls Royce, GE,

Honeywell, Pratt & Whitney) sampling probe/rake geometries, indicating that particle losses in probes/rakes were different (up to ~15% at 10 nm). However, when also including the losses encountered in the 25 m sampling line, nominally similar particle size dependent total losses were within 5% (Liscinsky, DP06 SAE E31 San Diego 2012). As research moves towards a better understanding of particle loss in the regulatory sampling system, and potential for system loss correction, the fact that the sample velocity is not consistent or measured in the sample line from inlet to splitter 1 across different engines and/or power conditions means, that the calculation of particle loss requires an unsubstantiated assumption of residence time. It is now understood, this likely impacts nvPM number measurements more than nvPM mass measurements in terms of both diffusion particle loss to the sample line walls and coagulation. System loss correction equations have been empirically validated for relatively simple sample tubing, however for a more complex sampling system geometry, for example understanding of nvPM diffusion and inertial loss in diluter 1 and splitter 1, system particle loss calculations may not be fully robust (Kittelson, DP09 SAE E31 Halifax 2017, Silvis, DP14 SAE E31 Florida 2018).

Additionally, during early system development it was perceived that 'tip dilution' probes were scientifically preferred for extractive sampling. This thought was based on consideration that early dilution limited 'coagulation', nucleation of volatile fractions and thermophoretic loss through quenching of the sample. For these reasons 'tip dilution' probes were employed in the APEX/ AFFEX[4&5] research programmes and subsequently compared during SAMPLE II[6]. As is still the case, manufacture and operation of a multi-point 'tip dilution' probe would be significantly more difficult/complex than existing designs. However, given new understanding of particle loss correction and recent volatile nucleation/ line contamination experiences from OEM[7]& ZHAW data (Durdina, DP18 SAE E31 Saclay 2019), it may be an area to reconsider moving forwards. Similarly, consideration of downstream diluted stack measurements should also be assessed moving forwards, though this would require a fundamental change to engine exit being the definition of certification sampling location. Research programmes such as AVIATOR and AGEAIR will help to provide data to assess if this is a suitable methodology moving forwards.

By using the existing Annex 16 vol II probes/rakes and module 1 sample line systems, another compromise was reducing and maintaining sample temperature >145 °C (existing Annex 16 Vol II requirement for gas measurement). This reduced temperature, potentially allows volatile matter to condense or nucleate prior to dilution, which from a scientific viewpoint may not be optimal, given it would likely be preferable to maintain all vPM in gas phase prior to dilution (>350 °C) as is consistent with nvPM definition which was formulated from filter burn-off thermogram analysis[8]). Similarly, not reducing the gas temperature may potentially offer reduced thermophoretic losses. This would be the case if it is demonstrated that thermophoretic loss is negligible if the cooling, of the exhaust gas, is performed via dilution. Historically it was assumed that this was the case in diluter 1 (Figure 1). However, as discussed in detail below (Section 1.4.3) a recent update of ARP6481A, recommends an approximation of Module 2 thermophoretic loss (including diluter1) as an 'interim fix' until improved understanding of particle loss resulting from high thermal temperature gradients between splitter 1 and diluter 1 outlet are better understood. Some initial SAMPLE II data investigated maintaining the sampling lines to 350 °C to the point of dilution, however it is noted this was on a combustor rig exhaust hence volatiles potentially stemming from lubrication oil systems etc. would not have been present.

Another potential issue, if sample line temperatures were maintained at 350 °C, is in the case of mixed flow engine exit sampling, where the exhaust gas temperature at sample probe inlet is always <350°C, as is also

[4] Wey et al 'APEX NASA Technical report' https://ntrs.nasa.gov/citations/20060046626
[5] Lobo et al 'Physical Characterisation of aerosol exhaust from commercial GT engine' DOI:10.2514/1.26772
[6] Marsh et al. 'SAMPLE II report Section 5.3' www.easa.europa.eu/en/document-library/research-reports/easa2009op18
[7] Proprietary information observed on a research staged combustion engine
[8] Petzold et al 'Evaluation of Methods for Measuring PM Emissions from GT' doi.org/10.1021/es103969v

typically the case of core flow sampling at idle type thrust levels. In these cases, by increasing sample line temperatures beyond that of probe inlet temperatures could induce additional thermophoretic loss hence needs to be carefully considered.

If moving forwards, it is conclusively shown that volatile nucleation from any engine type is not an issue, the above discussions regarding keeping volatiles in the gas phase may not be a compromise. However, conversely if it is still deemed that care is required with respect to volatiles - a future option compatible with maintaining (or in the case of cool exhausts, heating) exhaust sample temperatures to 350 °C, would be that the CS could be housed close to engine exhaust prior to the dilution stage. This may offer the potential to significantly reduce overall thermophoretic loss prior to nvPM number measurement, which currently requires the sample to be cooled from engine exhaust temperature to 60 °C before the sample is re-heated to 350 °C before re-cooling to near ambient temperatures, post CS, to allow measurement by the CPC (condensation particle counter).

Finally, the maximum allowed length of module 1 is set at 8 m. This is a compromise to allow all OEMs practical installation of their systems, which stems from the previously discussed initial 2010 compromise regarding the use of existing Annex 16 Vol II rakes and probes.

1.4.3. Module 2 –Splitter 1 inlet to diluter 1 outlet (Dilution box)

Module 2, often referred to as the diluter box, contains splitter 1 and dilutor 1. Splitter 1 is required to feed both the nvPM and 'raw' gaseous sample lines, along with enabling excess flow to be spilled through a pressure control valve. The eductor diluter methodology provides near-ambient pressure at Diluter 1 exhaust preventing over pressuring of the sample to the mass and number instruments irrespective of engine condition. Also, the diluter actively pumps the nvPM exhaust sample from the probe/rake, without the use of mechanical moving parts, which would induce nvPM loss. In addition, performing dilution as close as possible to the probe inlet aims to supress nvPM coagulation whilst also supressing volatile and water condensation whilst cooling the sample to 60 °C prior to entry to module 3. As discussed earlier historically, it was assumed that the particle loss within the eductor is negligible, due to the cooling being brought about by dilution and the walls being significantly removed from the centreline of the mixing zone. This theory was initially supported by experimentation (Lobo, DP05 SAE E31 Cardiff 2010). Similarly, it was assumed that the dilution of gases and nvPM in the diluter are consistent, with CO_2 measurement pre & post the diluter being used to validate the dilution ratio. However, laboratory-based studies[9] (; Kittelson, DP09 SAE E31 Halifax 2017) have indicated that there are potentially size dependant loss or dilution issues within eductor type diluters as prescribed for Diluter 1. Notwithstanding it is noted that these experiments were performed at atmospheric pressure using non-soot particles, hence further investigation is warranted.

OEM specific probe & splitter geometry, engine thrust, and gaseous raw line flow rates result in non-standardised, unquantified, and variable unbalanced flow splits in Splitter1. The compromise, as discussed in Section 1.4.2, is brought about due to the adoption of existing rakes which results in variable flow rates into splitter 1. Highly variable and unbalanced flow splitting has been previously shown to lead to variable penetration of differently sized particles. Generally, small particles are assumed to follow streamlines, whereas larger particles have more potential to carry straight on through the splitter or be lost via impaction from relatively lower flow splits. As such, typical gas turbine particle number weighted size distributions should not be affected (10 to 100 nm), however particle mass weighted size distributions with a wide GSD potentially could be. Such issues were witnessed in initial NRC mass instrument calibration studies, noting that mass calibration particle sources typically have larger number weighted particle sizes (100 to 150 nm) than aircraft

[9] Giechaskiel et al. 'Effect of ejector dilutors on measurements' doi:10.1088/0957-0233/20/4/045703

engines (10 to 100 nm). Details of the physics presented to the SAE E31 by Dr William Silvis (DP18 SAE E31 Koln 2019) highlighted that the Stokes Number of a given particle needs to be within a specified range to ensure uniform splitting. A more recent OEM campaign has also indicated that imbalance in Splitters may lead to increased uncertainty in nvPM mass measurement (DP28 SAE E31 Paris 2024). Potentially, this could be corrected for with measurements of flow velocity.

Recent observations reported by the SAE E31 operability team (and reported to CAEP WG3 CAEP12_WG3-6_WP04), are that the use of bespoke and 'commercially available' module 2 'dilution boxes', in some circumstances lead to thermal gradients in the sample line and diluter inlet which do not conform to the Annex 16 Vol II >145 °C specification[10]. By definition, cooling of the sample occurs from >145 °C to 60 °C within diluter 1. It has been demonstrated (Whitefield, DP34 SAE E31 Virtual January 2021; Silvis, DP16 SAE E31 Torrance 2018) that at given flow conditions and inlet sample gas temperatures the specified >145 °C requirement in the sample line to the diluter inlet is not adhered to or monitored using the specified temperature measurement protocols. In other systems (Durand, DP35 SAE E31 Virtual January 2021), it has been seen that to fulfil the requirement the gas temperature is sometimes increased before cooling back towards 145 °C possibly resulting in increased thermophoretic loss.

At present, further research (CFD modelling & empirical temperature surveys) is being carried out to determine 'real-world' witnessed system loss in Section 2. Until this data is fully collected and appraised, as an 'interim fix', ARP6320B now recommends reporting nvPM data using T1, which is now specified as the metal temperature of Splitter 1 (not diluter 1 inlet). Therefore, the currently reported thermophoretic loss is only corrected to splitter 1.

To account for the known additional thermophoretic loss, experienced between splitter 1 and diluter 1 outlet, an additional thermophoretic system loss calculation has been included in ARP6481A. This calculation recommends an assumed diluter 1 outlet temperature of 60 °C, which given dilution cooling may be an overestimate of the witnessed thermophoretic loss in diluter 1. However, there are additional loss mechanisms within diluter 1, hence the new additional thermophoretic loss term is thought to be a reasonable estimate for the total loss (thermophoretic, diffusional and inertial) incurred in dilutor 1. As diffusional loss from probe inlet to diluter 1 inlet is already calculated in the system loss tool, the addition of this new thermophoretic term ensures the known nvPM losses from probe inlet to diluter 1 outlet are corrected.

1.4.4. Module 3: diluter 1 outlet to cyclone inlet

Module 3 is typically a single length of heated anti-static PTFE line, which initially was defined to be 'standardised' in line with discussions presented in Section 1.4.1. As such a 25 m, 3/8" OD line was proposed as the shortest possible sample line which could practically reach from the sampling probe outlet to the measurement equipment outside large OEM test beds. The 25 m length having been previously defined in the 1970's as maximum sample line length for Smoke measurements. However, due to tolerances in wall diameter and inconsistencies between metric and imperial dimensional units, typically used in Europe and the US respectively, eventually the standardised approach had tolerances allowing deviations in length of up to 1 m (4% of length) and 0.56 mm in the inner diameter (7% inner diameter 15% cross sectional area).

The sample flowrate specification of 25±2 sLPM was defined based on the fastest robust flowrate available using a Dekati DI-1000 or PALAS VKL10E (or equivalent) diluter across the allowed range of dilution, which was successfully demonstrated on a large modern engine[11]. This sample flowrate value prevented 'over-pulling' of sample, which would cause additional pressure drop in the sample line and could lead to further unknown

[10] As discussed further in SAMPLE IV Deliverable 1 report

[11] Marsh et al. 'SAMPLE II – Section 7.4' www.easa.europa.eu/en/document-library/research-reports/easa2009op18

dilution by pulling ambient air through the diluter 1 vent as well as the diluted exhaust sample. It has also been demonstrated that the addition of a particle size analyser is possible within the 25 sLPM. Potentially, faster sample flowrates could be obtained, with less of a safety factor, which would reduce particle loss.

The diluted sample line temperature 60±15 °C was defined as the lowest temperature which could be standardised across global testbed locations, with stability tolerance set as the same as existing smoke and gas emission requirements (likely due to temperature variation across a long 25m line controlled from a single thermocouple). However, for improved system standardisation, tighter tolerance for sample line temperature control could be specified with empirical validation of commercially available sample lines.

Higher sample line temperatures of 160 °C were initially dismissed for practicality reasons (in terms of unheated sample line junctions). This decision was further supported by empirical studies of particle loss in sample lines used during engine testing[12] and from laboratory studies presented by Dr Claus Wahl (DP19 SAE E31 Interlaken 2010). Given the nvPM number system now typically employs a heated CS and the aforementioned issues of the diluter temperature gradient in module 2 (discussed in Section 1.4.3), revisiting this decision may warrant further investigation, to reduce thermophoretic loss, particularly where analysers (e.g., DMS 500 and LII-300) are able to sample directly at 160 °C.

Numerical analysis of size dependant loss across these sampling system tolerances has been performed[13&14] (DP34, SAE E31 Boston 2014) and this analysis indicated that these deviations can be modelled and hence could be corrected using a system loss calculation. This highlights that standardisation of sampling systems may not be optimal in the future if system loss correction is deemed appropriate.

The sample line diameter was selected based on existing in-use emissions sample lines (again with tolerance range across metric and imperial units). Part of the development of the nvPM system proved that the required sample flowrate of the nvPM reference systems, which caused a pressure drop across the 25 m line, was not too low such that 'commercially available' VPR and nvPM mass instruments were able to draw sample[15] and meet cleanliness/ leak tight tests. It is perceived that potentially higher sample flow rates and smaller sample line ID's may in theory reduce diffusional loss. Hence, they could be considered should measurement analysers be capable of sampling at a vastly reduced inlet pressure or sample lines were permitted to become shorter with implementation of system loss correction. However, due to the specified cyclone detailed in module 4 a constant specific flowrate (of 25 sLPM) in the sampling line is required.

During the early stages of system development, sample line material and line temperature were considered and investigated. For reasons concerned with the practicality of installation of non-permanent sample lines , flexible antistatic cPTFE (The same material specified for smoke measurements to facilitate flexibility) was adopted even though it was known that stainless steel lines potentially offered lower particle loss[16]. This could be further explored with bendable stainless-steel lines commercially available. Currently the antistatic specification is based on ISO8031. Further data is likely required to determine the uncertainty exhibited in sample lines of different earth potential, particularly if aviation soot cannot be assumed to hold neutral charge (DP27 SAE E31 Albuquerque 2024).

[12] Crayford et al. 'SAMPLE III.02 : Section 6.7.2' www.easa.europa.eu/en/document-library/research-reports/easa2010fc10-sc02

[13] Durand 'PhD thesis – towards improved correction methodology' https://orca.cardiff.ac.uk/id/eprint/126400/

[14] Crayford et al. 'SAMPLE III.01 : Section 6.3.2' www.easa.europa.eu/en/document-library/research-reports/easa2010fc10-sc01

[15] Crayford et al. 'SAMPLE III.02 – Section 5' www.easa.europa.eu/en/document-library/research-reports/easa2010fc10-sc02

[16] Marsh et al. 'SAMPLE II – Section 6' www.easa.europa.eu/en/document-library/research-reports/easa2009op18

1.4.5. Module 4: cyclone inlet to measurement analyser inlets

Module 4 contains the 1 µm sharp-cut cyclone, Splitter 2 and sampling lines to the specific mass, number, gas and ancillary analysers and mass-flow make up system. The cyclone was deemed required as an outcome of large discrepancies in nvPM mass measurement witnessed during combustor rig testing[8]and as a robust way to prevent sampling blockages in instruments. The requirement was implemented to decouple the impact of large particles thought to be shed from the probe and sampling system. In order to ensure that 'standardised' cyclones were adopted, a 1 µm rather than 0.3 to 0.5 µm specification was adopted to ensure 'commercially available' cyclones with a 25 sLPM specification were available. In addition, to reduce the impact of measured particles above 1 µm the cyclone sharpness was defined to be more sharp (steeper cut efficiency) than older style cyclones (which transmitted a greater number of particles > 1 µm). More recent studies (Durdina & Durand, DP15 SAE E31 Virtual June 2021) have indicated that the cyclone, if not suitably clean, potentially sheds large >100 nm particles which may significantly impact the uncertainty in mass measurement, particularly at very low mass loadings (at or below the limit of quantification of the mass analysers 5 µg/m^3). This may also explain the findings on an engine with a lean burn combustion system discussed by Dr William Silvis (DP25 SAE E31 Florida 2018).

Regarding the compromise of unbalanced flow ratios in Splitter 1 in Section 1.4.3, splitter 2 is not optimised for the known variations in flow between different splitter legs that may exist due to the specific requirements of flow rate of the number and mass instruments used in any given compliant nvPM sampling system. Again, the physics presented by Dr William Silvis (Silvis, DP18 SAE E31 Koln 2019) could be used to assess the impact. However small ultrafine (<100 nm) particles as witnessed in the exhaust of a large commercial gas turbine are not thought to be significantly affected by flowrate discrepancies witnessed by existing instrument types, which result in significantly smaller velocity bias compared to those witnessed in Splitter 1. The impact of Splitter 2 flow uncertainty could be preliminary investigated numerically, for different instrument and flow splitter geometry setups (for example inclusion of a PSD instrument) to indicate if further empirical validation is required. Depending on specific splitter design configuration and instrument type, splitter 2 leg sample flowrates can vary from 1 to 24 sLPM, hence further recommendation to balance flow splits in Splitter 2 could be added to the relevant ARPs and the ETM, regarding the design of Splitter 2.

1.5. nvPM Mass Instruments

Prior to CAEP 9, there were frank discussions between the different regulators as to the relative merit of what fraction of PM should be measured and regulated on. Initially (circa 2009), European regulators (EASA/FOCA) favoured that the new nvPM standard should be based on number, $nvPM_{num}$, (in-line with other recent nvPM regulations e.g. the automotive PMP/ EURO standards). From a health perspective, the particle surface area of ultrafine particles was considered important. A well-established measurement method (Condensation Particle Counter) for determining the number concentration of particles already existed and given the relevant size range of particles with high lung deposition rates, particle number measurement was considered a good surrogate for particle surface area. US based studies led by NASA[17] along with a DLR/FOCA Zurich Airport[18] field campaign, analysing aircraft plumes on ground (2004 – 2009) revealed the existence of high numbers of extremely small soot particles in aircraft exhaust, which contained very little mass. However, extremely low mass does not guarantee a low number of emitted particles, but very low $nvPM_{num}$ does guarantee low mass given the small size of the Ultra Fine Particles (UFPs) emitted. In 2008, the Swiss FOCA presented a guidance document on the requirements for characterisation of aircraft engine PM in future certification measurements

[17] Moore et al. 'Synthesis of aerosol emissions data from NASA APEX, AAFEX & ACCESS missions' DOI:10.1021/EF502618W
[18] Wahl et al. 'Determination of aircraft engine nanoparticle emission' www.nanoparticles.ch/archive/2009_Wahl_PO.pdf

to ICAO CAEP. Ultimately, it expressed that it is $nvPM_{num}$ that could be used to control aviation gas turbine emissions. However, as historical health studies report their findings linked to the measured total-PM mass with many existing LAQ/health standards being built on total-mass, US EPA requested that a traceable measure of total-mass would be required - suggesting gravimetry as a preferred method. The US-FAA suggested $nvPM_{mass}$ plus volatile PM gas precursors may therefore offer a sensible approach.

After further discussion in 2009, the regulators EASA, US EPA, FAA, TC & FOCA provided a joint statement to SAE E31 that a traceable measurement of $nvPM_{mass}$ & $nvPM_{num}$ should be developed moving forward, which as discussed earlier (agreed at E31 Cardiff 2010) would be performed using existing standard Annex 16 probes and a common sampling system (Section 1.4.1).

Other technical issues were raised, for example how condensable material would be measured (e.g. requirement to freeze samples on test stand and ship cryogenically to certified laboratories) and that volatile precursors would consist of many elements, some of which are independent of the combustion technology (HCs, lubrication oil, Fuel Sulphur content etc.). This is in contrast to nvPM, which is directly related to combustion technology, affording continual improvement to be attained through successively lower nvPM concentration standards. The adopted approach to use real-time nvPM measurements therefore holds as a valid regulatory control concept.

Initially, it was proposed that a gravimetric approach should be considered due to its proven use in emission regulation and traceability (SAE AIR6037). However, this was quickly dispelled as impractical due to the very long sampling times (hours) that would be required to collect a sufficiently large mass loading for traceable measurement.

Similarly to gravimetric measurements, Thermal Optical Analysis (TOA) measurements were also not further considered due to their long collection times (3 x 15 min per test-point) and requirement for off-line analysis which could require days/ weeks till results were generated. Based on the findings of SAE E31 Aerospace Information Reports (AIR5892B & AIR6037A) real-time optical Black Carbon (BC) instruments were proposed as commercially available instruments, capable of measuring carbonaceous mass from aviation gas turbines. However, it should be noted that there is no universally accepted measurement methodology definition for BC.

The definition of aircraft nvPM emissions is “Emitted particles that exist at a gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to a temperature of 350°C”. There is no direct mention of nvPM being composed of only carbon. It was assumed in 2010 that nvPM was primarily composed of BC given the 350 °C threshold. Further, it was assumed that elemental carbon (EC) was an adequate surrogate for BC, even though it only represents the mass of the carbon in the nvPM particles. However, more recent bulk measurements of mass of other compounds (hydrogen & oxygen) bound within soot particles have been shown to contribute of the order of 5-10% of nvPM mass (Smallwood, DP27 SAE E31 Virtual January 2021). There is also a small amount of organic matter that does not volatilise at 350°C, typically <5% of the nvPM mass (Smallwood, DP29 SAE E31 Virtual January 2021). This is in addition to the BC mass.

Discussions have therefore highlighted that BC, and to a greater extent EC, may only be a subset of $nvPM_{mass}$. In the early nvPM mass calibration development (2010), the US-EPA suggested traceability should be attained though calibration to EC using existing standard commercial filter measurement approaches, namely Thermal Optical Analysis (TOA), which were developed for ambient mass monitoring. It was proposed that the NIOSH5040 protocol (used in the US) would be more acceptable to US regulators as compared to other newer European protocols (e.g. EUSAAR/IMPROVE) for the calibration of real-time BC instruments. However, as mentioned, more recent data (Smallwood, DP29 SAE E31 Virtual January 2021) has shown that hydrogen and oxygen are bound within nvPM which are not measured as part of the TOA measurements. This finding results

in a compromise, whereby nvPM is currently equated to EC during calibration. It is noted that this would still be a compromise even if another TOA protocol had been chosen. Newer mass calibration methodologies[19,] (CPMA - CERMS) would enable a true definition of measured nvPM to be achieved. It is noted that, as per the ICAO definition discussed above, nvPM mass should include bound hydrogen and oxygen at >350 °C. In addition, the CERMS method offers reduced $nvPM_{mass}$ calibration uncertainty[20&21], calibration at much lower mass concentrations which are representative of the actual nvPM emissions levels witnessed at a significantly reduced calibration time (Smallwood, DP27 SAE E31 Virtual January 2021).

To ensure availability of analysers for the lifetime of the standard, early in the development process it was decided (SAE E31 Interlaken 2010 meeting) that commercially available optical BC analysers would be utilised. Therefore, performance-based specification, rather than specified analyser technologies are used to qualify the instruments, with Thermo-scientific MAAP, Artium LII-200/300, AVL MSS/MSS+/MSS2 & Aerodyne CAPS PMssa all having been considered since this time. Initially, Laser Induced Incandescence (LII) and optical absorption photometry – two of the four online extractive measurement technologies highlighted in AIR6037A were cited, with photoacoustic technology and an additional optical absorption instrument added to the list later in the nvPM system development in 2011. It was anticipated that the response to BC of each analyser would be comparable within the calibration uncertainties. As discussed further below with appropriate calibration it is still thought this is a sound assumption. However, optical absorption instruments initially designed for an ambient monitoring purpose (i.e. Thermo-Scientific MAAP), were observed by ZHAW to contaminate quickly, which is not practical for OEM engine testing. As such given the MAAP is also no longer supported by the manufacturer, it is now not considered as a viable mass instrument for aviation regulation.

Inclusive of the practical consideration that these real-time BC mass instruments could also be used on combustion rigs as well as engines, OEMs made investment in nvPM mass instruments based on the AIR6241 (prior to development of Annex 16 Vol II and then ARP6320). Since then, nvPM mass data from OEMs and the three aforementioned nvPM reference systems started becoming available, particularly for the AVL MSS and Artium Technologies LII-300. Unfortunately, discrepancies in the form of a bias in reported $nvPM_{mass}$ between the MSS & LII-300 were observed in test campaigns such as APRIDE[2&22] and VARIAnT[23] (CAEP10-WG3-PMTG8-WP13). Subsequent studies including MANTRA and VARIAnT2 indicated the issue was a function of the relative response to the specified 'diffusion' combustion calibration source (e.g., Jing mini-CAST, inverted flame propane burner etc.) and the real-world particulate emissions produced by a gas turbine engine. This again highlighted the concerns that BC, EC and $nvPM_{mass}$ are not the same measure of the carbonaceous solids exiting the gas turbine. As such, the specification of the $nvPM_{mass}$ instrument calibration source was suggested to be changed based on the APRIDE data, with the addition of an applicability (this terminology was later changed in Annex 16 Vol II to verification, 2023) performance requirement such that an additional test confirming TOA agreement on a modern gas turbine (± 16 %) is required when calibrated on a given source. To meet this applicability requirement, Artium Technologies LII-300 instruments were subsequently calibrated on a small-scale helicopter gas turbine instead of a benchtop atmospheric pressure flame (A-PRIDE 8, CAEP11_WG3-03_CTG-03_IP06 Rev 1). Since then, comparison on multiple certification engine types (Johnson, DP10a SAE E31 Halifax 2017) and with more recent comparisons in studies such as RAPTOR[24] have shown good correlation between LII-300 and MSS. However, it should be noted that other campaigns such as

[19] Dickau et al 'demonstration of the CPMA-electrometer system..' doi.org/10.1080/02786826.2015.1010033
[20] Titosky et al 'repeatability & intermediate precision of a mass..' DOI: 10.1080/02786826.2019.1592103
[21] Corbin et al 'Closure between particulate matter concentrations..' doi.org/10.1080/02786826.2020.1788710
[22] Brem et al 'PM & Gas Phase Emission Measurement of Aircraft Engine Exhaust' www.bazl.admin.ch/dam/bazl/de/dokumente/Politik/Umwelt/PM%20Measurement%20of%20Aircraft%20Engines_Swiss%20Research%20Public%20Results_2012-2015.pdf
[23] Kinsey et al. 'Assessment of a regulatory measurement system….' doi.org/10.1016/j.jaerosci.2020.105734
[24] Crayford et al. 'RAPTOR WP4 final report' https://zenodo.org/records/7385796

VARIAnT3&4[25] need to be appraised for apparent differences between instrument types after the change in calibration source. More recently bias has also been observed between $nvPM_{mass}$ calibration sources for the AVL MSS (CAEP/12-WG3/4-IP/08 Appendix A), showing that the additional calibration source applicability requirement was the correct approach to implement for all instrument methods.

From a purely technical point of view, selecting a single nvPM mass measurement methodology would have made the nvPM mass measurement simpler to implement. However, unlike gas analysers with multiple vendors competing with the same technology, in BC measurements, each technological approach is somewhat proprietary and held by one vendor only. In this circumstance, there is the possible risk of a company leaving the market and if one instrument was selected, the aviation sector would create a monopoly. For gas analysers, for example, the stated chemiluminescence technique is used as the standard measurement method for NOx. However, there are many manufacturers building gas analysers with this technique and SAE E31G is now assessing the implementation of performance-based measurement specifications (like nvPM) since there are other NOx measurement technologies that can achieve and out-perform chemiluminescence operability and accuracy. As such, it appears that performance-based specifications are preferred over a single methodology in achieving minimised uncertainty.

As a result of NRC calibration measurements and OEM year to year confidence, more recently calibration procedures including better defined splitters and calibration interval have been revisited, with SAE E31Working Papers (WPs) presented to CAEP WG3 highlighting suggested modifications to text in Annex 16/ ETM (CAEP12_WG3-6_IP06), based on the updatedARP6320A (2021), which now recommends the use of plenum type splitters for mass instrument calibration.

1.6. nvPM Number Instruments

As discussed previously, nvPM number concentration is better placed to control UFP produced by a gas turbine, European regulators were insistent that a metric of number concentration was required. As highlighted by the automotive PMP, total-PM number concentrations are difficult to reproducibly measure given that particles produced by volatile nucleation physics are dependent on both sampling methodology (dilution, temperature, pressure etc.) and combustion technology. As such, aligned with the PMP, $nvPM_{num}$ was defined as the metric by which aviation standards would be set. However, consideration was given for the need to measure to the relatively smaller particle sizes emitted by aircraft gas turbines compared to reciprocating automotive engines. To simplify development and availability of commercially available instruments, existing automotive volatile particle removal (VPR) methods and Condensation Particle Counters (CPCs) were proposed for number concentration measurement. Specifications rather than prescribed technologies are used to define the VPR and as such a CS is not mandatory and different dilution strategies are permissible. However, in the case of the CPC this is prescribed in terms of the working fluid (butanol), single count mode and non-sample flow splitting.

In contrast to the PMP, a particle correction reduction factor (PCRF) was not proposed for the aviation VPR as it was demonstrated that assumed standard particle losses for any given aerosol size distribution are not correct and would not address different particle loss variations across sampling and measurement systems, engine powers and technologies. As such the VPR specified in Annex 16 Vol II is based on a minimum penetration requirement (at four different sizes namely 15, 30, 50 and 100 nm) with gas dilution factors used to correct measured nvPM number concentrations for dilution only. The minimum penetration requirements were based on what commercially available VPR systems, with catalytic strippers (CS), could achieve based on

[25] Giannelli et al. 'Evaluation of methods for characterizing fine PM..' doi: 10.1016/j.jaerosci.2024.106352

SAMPLEIII[26] and instrument OEM laboratory data. The minimum penetration requirement was therefore set to allow AVL VPRs (with CS) to also be utilised. 15 nm was chosen as the lowest size for penetration determination, due to difficulties in creating high numbers of small particles in VPR calibration laboratories. Note that only minimum penetrations were defined in the same manner as the PMP automotive specifications. This means that there are a range of penetrations witnessed when using different VPR technologies. Using VPRs with higher penetration (such as Dekati DEED) means that a higher EI_{num} is currently reported, than would be the case if a VPR with lower penetration was used (such as AVL APC). The impact of this was not understood in early nvPM system development and would be improved should system loss correction be implemented in the future[27].

Note that EI_{num} reporting is also impacted in the same way by the CPC cut-point chosen in any given system. Again, this specification is defined by a minimum counting efficiency only ($D_{50} \leq 10$ nm). In addition, by not using the PCRF method, it was recognised that particle loss would need to be calculated and SAE AIR6241 included calculation of sampling system penetrations including VPR penetration and CPC efficiency.

CPC technology was suggested based on AIR6037 and their successful use in automotive particle number regulation. In addition, the findings of SAMPLE[8] showed that CPCs offer reproducible results with limited uncertainty by allowing only single count mode and butanol as a condensation agent (water CPCs were also investigated[26]).

Considering nvPM observed in aviation gas turbine exhaust is typically smaller than automotive nvPM emissions, commercially available CPCs meeting new technical requirements, which were different to PMP, were sought. To ensure aviation nvPM was satisfactorily measured, these technical specifications mandated no sample flow splitting (to minimise uncertainty of volumetric flowrate traceability) and counting efficiency cut-points of down to 5 nm, even though it was hypothesised the sampling system had >90 % nvPM loss at these low sizes. A steep efficiency slope was also desired rather than the higher and flatter CPC efficiency cut-points used in PMP automotive (D_{50} at 23 nm, D_{90} at 41 nm) ensuring maximum detection of the smallest particle sizes.

Based on analysis of a combustor rig, APU and large engine data collected in the SAMPLEII, III.1 and III.2 campaigns, a maximum cut-point performance specification of D_{50} <10nm and D_{90} <15nm was proposed by Andreas Petzold (DP16 SAE E31 Zurich 2012) as detailed in the SAMPLE III SC02 report[26]. It is noted that although commercially available CPCs were recommended, not many single flow CPCs were available in 2011. However, a CPC with a <15 nm cut-point was made available by TSI, who modified the internal temperature setpoint of a PMP CPC. This performance based minimum counting efficiency threshold allows any CPC with better counting efficiency at the smallest sizes, such as the Grimm 5420 (D_{50}=7 nm) to be used. This was documented as a DLR memo to SAE E31 dated January 2012 “Lower cut-off diameter for Condensation Particle Counters”. Note that at this time only CPCs with internal flow splitting could measure the smallest particles. The CPC market and types of instruments have grown significantly since the nvPM system was developed. The automotive community are reducing their CPC cut-point to be similar to aviation, to account for smaller particles generated by petrol (GDI) engine technologies with 10 nm particles prescribed in the new EURO 7 light duty standards[28] .

Given the mid-cut point efficiency of the aviation CPC compared to pre-EURO 7 automotive CPC (10 vs 23 nm), CS are often employed, even though they may not be required. Given the mid-cut point efficiency of the

[26] Crayford et al. ‘SAMPLE III.01 : Section 4.4’ www.easa.europa.eu/en/document-library/research-reports/easa2010fc10-sc01

[27] As discussed further in SAMPLEIV Deliverable 3 report

[28] Dornof et al. ‘policy update – Euro 7’ https://theicct.org/wp-content/uploads/2024/03/ID-116-%E2%80%93-Euro-7-standard_final_v2.pdf

aviation CPC compared to pre-EURO 7 automotive CPC (10 vs 23 nm), CS are often employed, even though they may not be required. As part of the SAMPLEIII.1[29] programme CS were demonstrated as able to remove rather than shrink particles <23 nm. There is ongoing SAE E31 discussion on the relative merits of CS, balancing the benefits of protection of measuring volatile particles against the additional particle loss observed in the CS. Current thoughts are erring caution on the side of ensuring volatile removal against known additional diffusion and thermophoretic nvPM losses.

However, notwithstanding the additional nvPM loss resulting from the use of a CS, it's use confirms the definition of nvPM (heating to 350 °C), hence CS use is still employed in all commercially available aviation nvPM VPRs. The requirements do not specify the hardware, only the volatile removal efficiency of the VPR, hence an evaporation tube could in theory be used. This may be supported if it can be shown that there is insignificant particle loss difference between CS VPR's and non-CS VPR's or loss differences can be accurately corrected for.

Due to the specification of CPC's being in a single-count mode along with the requirement to cool the sample from the VPR temperature (350 °C) to below the CPC saturator temperature, a dilution stage is required.

Again, traceability of measurement was of key importance to the nvPM number emissions metric. An existing calibration protocol for the VPR and CPCs, as used by the automotive community, was adopted. This approach resulted in non-standardised calibration materials which are not necessarily fully representative of the morphology of nvPM or vPM, e.g., emery oil for CPC calibration (aviation have specified emery oil compared to automotive regulation which permits any material), propane burner PM, salt, silver, gold, Tetracontane nanoparticles for VPR calibration. Given the current difficulties in producing repeatable and stable concentrations of solid particles, in calibration laboratories, currently 15 nm is the lowest size used in the VPR calibration, which is not aligned with the lower cut-point required in the CPC performance-based specifications. Hence, there is the drive towards further VPR calibration points at lower sizes (e.g., 5 & 10 nm)[30].

At present the lowest calibration linearity concentration point specified in the CPC calibration method is higher than nvPM number concentrations typically witnessed and measured on certification gas turbine engine tests. Current thought being that CPC counting is inherently linear, which at times has been in slight contradiction to the calibration sheets provided for commercially available instruments.

Therefore, it would be prudent to re-visit the VPR and CPC calibration specification (particle sizes <15 nm, particle material & CPC conc. at <1000 p/cm^3) and VPR performance penetration on representative particle sources.

1.7. Size Instruments

SAE E31 knew that particle loss in sampling systems is size dependent (SAE AIR6037) and hence to accurately correct for this loss requires knowledge of particle size. nvPM sizing instruments were initially discounted due to issues associated with the definition of $nvPM_{size}$, representativeness of the highly fractal nvPM witnessed in gas turbine exhaust, traceable calibration of size measurements and particle count due to particle charging efficiency. These are especially problematic for real-time (1 Hz) PSD measurement devices which are required to minimise data variability within a practical sampling period on an engine test, particularly at higher engine powers.

[29] Crayford et al. 'SAMPLE III.01 : Section 4.4.2 ' www.easa.europa.eu/en/document-library/research-reports/easa2010fc10-sc01

[30] Discussed further in SAMPLE IV Deliverable 3 report

Subsequently, given the experience that the 'standardised' sampling approach may not adequately control uncertainty associated with size dependant particle loss, across different engine technologies and powers, it is being determined whether there is merit in including a specified particle size measurement to assist with reducing the uncertainty of the current system loss correction methodologies[31,32&33]. Such an adoption would afford a more reliable calculation of engine exit nvPM emissions (SAE ARP6481 and ICAO Annex 16 Vol II. Appendix 8). As presented by Dr Eliot Durand, (DP36 SAE E31 Cardiff 2020; DP24 SAE E31 Virtual January 2021), it is currently thought that significant reductions in system loss correction uncertainty may be brought about by removing the current required assumptions of lognormality, GSD, particle density and particle cut-off at 10 nm. Three methodologies to use particle size measurements for system loss correction have been proposed[34] (Durand DP26 SAE E31 Albuquerque 2024) and are planned to be included in AIR6504A for trialling. In addition, issues for current loss correction methodology associated with low measured nvPM mass concentrations (near or below the LOQ) could be solved using a bin-by-bin correction methodology using empirically derived particle size measurements. On-going research studies are further informing whether a particle size measurement method based on performance specifications is achievable, with SAE E31 preparing a Particle Size Distribution (PSD) Measurement Aerospace Information Report.

[31] Durand 'PhD thesis – towards improved correction methodology' https://orca.cardiff.ac.uk/id/eprint/126400/
[32] Kittelson et al. 'verification of principal losses in regulatory system' doi.org/10.1080/02786826.2021.1971152
[33] Crayford et al. 'RAPTOR WP4 final report – section 5' https://zenodo.org/records/7385796
[34] Durand et al. 'correction for particle loss in regulatory system' doi.org/10.1016/j.jaerosci.2023.106140

2. Potential improvements to the ICAO regulatory nvPM sampling and measurement system

Previously, state-of-the-art improvements were discussed in the context of the nvPM system historical approaches and compromises. However, towards continued optimisation of the methodology, as more information becomes available, the SAE E31P (Improvement team) listed the highest priority items for nvPM sampling and measurement system improvement, which is presented in Table 1. Table 1 documents the specific details of improvements that are currently perceived to have the biggest impact in reducing uncertainties of the existing ICAO regulatory nvPM system.

It is noted that nvPM system improvements can be implemented within an existing ICAO regulatory measurement system, hence are not to be confused with alternative sampling and measurement practices which are termed 'novel' and could provide the scientific optimum which are discussed later in this report2.

It is noted that aspects of empirical work informing the proposed improvements listed in Table 1, have recently been undertaken in delivering the EASA funded SAMPLE IV programme[30], with other EU funded programmes (e.g. RAPTOR, AVIATOR etc.) and North American programmes (e.g. ASCENT project 69) also providing further knowledge of the system and potential routes to reduced uncertainty.

Table 1: Highest priority nvPM system improvements (as agreed by SAE E31P, Alburquerque 2024)

Task	Sub-task(s)
Reduce nvPM mass calibration uncertainty	Covered by detail in Table 2
Reduce system loss correction factor uncertainty	
Reduce nvPM number uncertainty & size dependent particle losses in VPR	
Reduce nvPM number uncertainty	
Reduce system loss correction factors uncertainty by reducing particle losses in sampling system	Understand/Improve Module 2 (including Diluter1) thermophoretic and diffusion loss
	Minimise Splitter1 particle loss by recommending design rules
Measure nvPM at or near current Limit of Detection (LOD)/Limit of Quantification (LOQ)	Minimise re-entrainment of particles caught in the cyclone, frequency and timing of system zero/cleanliness tests
	PSD system loss correction methods
Understanding limitations of historic gas and smoke probes	Document historical approach to gas & smoke sampling
	Future nvPM probe concepts
large (>250/300 nm) particles understanding	Understand composition/source generation
	Impact on PSD method
Reduce system loss correction factor uncertainty	Improve nvPM density assumption
	Diluter1 penetration

Further specific details of the three highest priority items for improvement at the top of Table 1 are further described below in

Table 2 (as per SAE E31 CAEP paper: CAEP12_WG3-6_WP06) including the uncertainty benefits. Some limited international work is on-going in programmes to address these improvements.

The uncertainty task references in Table 2 relate to CAEP11-WG3-PMTG04-WP09 and are defined as:

Task 0: Variability in repeating two engine tests using the same measurement system and identical nvPM emissions source

"If the same 'ARP Compliant' sampling and measurement systems was used to measure the same identical stable source twice, 12 months apart with measurement system use and a calibration cycle in between, how different could the results be at the measurement plane be if the only corrections made were for DF1, DF2 and Collection Part thermophoretic loss?"

Note that this is a variability question not an uncertainty question. Any systematic errors that are constant across both tests need not be considered. Also not considered are technology differences that may exist among ARP6320 systems nor systematic differences among calibration vendors since only a single system calibrated twice at the same vendor is used.

Task 1: System-to-System Measurement Uncertainty at the Measurement Plane

"If several people brought their own 'ARP Compliant' sampling and measurement systems to the same place, and measured the same identical stable source, how different could the results be if the only corrections made were for DF1, DF2 and Collection Part thermophoretic loss?"

Task 3b: **System-to-System Measurement Uncertainty at the Engine Exit Plane**

"If several people brought their own 'ARP Compliant' sampling and measurement systems to the same place, and measured the same identical stable nvPM emissions source, how different could the results be if the measurements are corrected back to the engine nozzle exit plane using AIR6504 system loss method?"

Table 2: nvPM mass, number measurement and particle size (system loss) improvements

nvPM Mass Improvement	Benefit	Improvement detail
nvPM mass calibration existing reference method	Improve confidence of Task 0 calibration-to-calibration variability and determine real calibration lab vs calibration lab uncertainty. Potentially reduce (with high confidence) Task 0 to within 10 %. Note, source uncertainty is in addition to this	Quantify OC-EC method uncertainties both within the same analytical laboratory and between different laboratories
		Resolve differences between manual and semi-continuous OC-EC methods
		Resolve OC-EC method split point and temperature ramp variances
nvPM mass calibration new reference method	Potentially reduce uncertainty, especially at the actual engine measurement range. Potential method for drift determination across nvPMmi types. Potentially reduce (and with high confidence) Task 0 to ~5 % Source uncertainty is on top of this	Develop Centrifugal Particle Mass Analyser (CPMA) mass measurements as reference method
nvPM mass calibration source	Determine and reduce calibration laboratory vs calibration laboratory variability. By reducing variability from a single source setting across different calibration laboratories (part of Task 0) to less than 10%	Standardise operations for commercially available DFCAS nvPM sources to generate more consistent source aerosols across testing and calibration laboratories
		Identify additional nvPM sources for all nvPM mass instrument types
		Develop manufactured black carbon particles as standardised nvPM source
nvPM Number Improvement	**Benefit**	**Improvement detail**
VPR penetration & CPC efficiency	Improve confidence of Task 0 number measurement variability: currently yellow (low confidence) at 10 %	Quantify penetration drift (loss and dilution) for types of VPR
	Task 1 uncertainty understanding needed to establish Task 3a uncertainty:	Quantify VPR penetration uncertainties (loss and dilution) across all VPR types
	Improving confidence in system loss calculation uncertainty Task 3a, there are significant differences in particle loss between VPR types – is this due to design or calibration method. Difficult to quantify uncertainty to within 20 % without this work	Quantify penetration/efficiencies for VPR/CPC at smallest particle sizes <15 nm
Removal of VPR (dilution stage still needed for CPC)	Reduce complexity, and potential to reduce Task 3a system loss and associated uncertainties	Assess and quantify removal benefit vs variable diluter loss, establish if volatile material exists at end of nvPM system across wide range of engine source types
DF2 uncertainty	Reduce nvPM number uncertainty; DF2 uncertainty (10%) is the largest component of nvPM number Task 0 uncertainty; potentially reduce from 10 to <5 %	Establish observed drift and assess using 'measured' DF2

Particle Size Improvement	Benefit	Improvement detail
Particle size distribution (PSD) measurement	Reduction and confidence of Task 3a system loss correction factors uncertainty by using measured particle size distribution. Potentially provide a methodology when nvPM mass instrument is close to Limit of Detection.	Quantify the measurement uncertainty of the PSD including data inversion GMD (Geometric Mean Diameter) and GSD (Geometric Standard Deviation)*
		Quantify the options to use measured PSD for system loss calculation
		Establish Calibration methodology & uncertainty
		Establish Sampling methodology including potential conditioning – e.g. CS or additional neutraliser (particle charge impact)
		Particle loss understanding inside analysers
		Potential LOD/LOQ level for fast PSD
		Evaluate very large mode impact on PSD
		Establish method when mass is close to system & instrument LOD

*PSD derived particle number count uncertainty would also be needed if use of PSD considered for potential simplification for nvPM number measurement

VPR's are currently used for nvPM counting devices in order to remove volatile particles, dilute sample down to single count mode and cool the sample to ambient temperatures compatible with butanol CPCs. However, it is also noted that the temperature employed in the volatile removal stage (usually a CS) is prescribed at 350 °C, which ensures that the nvPM definition is met.

Moving forwards there will need to be consideration as to whether VPRs are required for PSD measurement. Depending on the use of the PSD will impact use of VPR or not. It is noted that VPR use increases particle loss (both diffusion and thermophoresis) and dilution uncertainty, with different design approaches leading to significant differences in particle penetration (circa 15 to 20 % between 15 to 100 nm particle diameter comparing two different VPR manufacturers), which are currently unaccounted for in regulated EIs. However, VPRs ensure that nucleated volatile particles, which do not meet the nvPM definition, are not counted. If a VPR was not present, additional volatile particles may be present at the end of the sampling system in cases such as a contaminated sampling system, highly inefficient combustion system or issues with the engine oil system, which have all been noted in very rare cases across the last decade of testing. As such, trade-off between the pros and cons of increased loss/uncertainty over nvPM definition, will need to be determined.

If the PSD is only to be used for system loss correction factor calculation, then theoretically the actual PSD (no VPR) should be used, since larger particles (with volatile coating) will preferentially penetrate the sampling system. Nucleated particles could be accounted for (removed) via employing suitable PSD fitting at the small particle sizes. Similarly in the case of PSD nvPM number counting, nucleated particles can be removed during PSD fitting. However, particles that do not meet the definition of nvPM if present at sizes of 15 to 1000 nm, would lead to an overcounting (e.g. oil aerosol). However, if volatile material is only present as coatings on nvPM and PSD system loss correction had been undertaken, this would not impact the number count.

3. The scientific optimum of nvPM mass and number sampling and measurement methods for aircraft emissions

3.1. Introduction

Section 1 of this report documented the adopted historical approaches, detailing the current status of the measurement methodology for nvPM mass and number along with compromises made. Now well over a decade later from the initial nvPM measurement approach, scientific and operability knowledge has improved, and new/improved instrumentation is commercially available. 2This section considers 'what we now know' and without existing system boundary constraints ('outside-the-box'), what the current potential sampling and measurement solutions could be to provide the best possible/optimum nvPM measurement for regulatory use, which balances accuracy of reported emissions, robustness of measurement system and the practicalities of operation and installation of the sampling system.

Existing nvPM mass and number and system loss uncertainties have been estimated by SAE E31 (CAEP11-WG3-PMTG10-WP12). It is now thought that using measured particle size distributions will improve the uncertainty of system loss correction calculations. However, the full uncertainty benefit has not yet been quantified, given a fully determined knowledge of measured particle size distribution uncertainty would be required (for example charging efficiencies and electrometer inversions). If, for example, particle losses in future sampling systems are significantly lower than are currently experienced, then performing a particle size measurement for regulatory use may not help reduce uncertainty in reported system loss correction factors. In such a circumstance the uncertainty in correction maybe higher than the actual particle loss in the sampling system, with the VPR in this case contributing significantly to the overall loss experienced.

An optimum measurement design concept aims to reduce overall nvPM uncertainties compared to the existing regulatory nvPM measurement system.

Beyond existing nvPM mass and number regulation, for future regulatory considerations, an optimum measurement system may need to reflect:

- *Optimal nvPM number and mass sampling systems maybe different from one another and are likely very different to an optimum total-PM number and mass sampling system (which would be a contradiction to the original agreement (Cardiff 2010) that both nvPM mass & number are to be measured on the same sampling line.*
- *There are COTS (Commercial-off-the-shelf) instruments that can measure directly/ determine nvPM surface area. Which potentially offers an additional useful measurement metric supporting particle number for the determination of human health and climate related non-CO_2 impacts.*

3.2. Perfect optimum concept for nvPM aircraft engine emissions measurement:

To achieve the perfect optimum for aircraft engine nvPM emissions reporting requires:

i) All relevant nvPM parameters measured to quantify human health and climate impact:

Number concentration, (LDSA/specific) surface area concentration, mass concentration, size (both electrical mobility for diffusion loss correction and aerodynamic for health)

ii) Minimal or accurately known particle loss

Very short sampling system

System parts with accurately quantified particle losses

iii) Simplification

Single (or minimum number of) instrument(s) that can measure multiple nvPM parameters with a known low (<5 %) uncertainty

Single instrument method/technology type

Simple/Robust instrument calibration

Simple sampling & control (no dilution/temperature change interface/splitters)

The most elegant concept solution to the above is to use fully non-intrusive optical measurement systems with built-in self-calibration. Such systems are in development for nvPM mass and surface area /size (Paul Wright DP26a SAE E31 Saclay 2019 & Roman Ceolato DP25 SAE E31 Paris 2024). However, their technology readiness is low and likely greater than 10/15 years from being considered a COTS measurement system for aircraft engine nvPM emissions certification.

Another consideration is that it is difficult to operate aircraft engines at the highest powers for long periods. Even at engine stable steady-state operation, to account for slight variations in nvPM emissions, current best practice is to sample and average a minimum of 30 samples. Therefore, real-time (1 Hz) measurement systems are still practically required.

As such, the below system boundary constraints are included for 'out of the box' concepts discussed here.

Concept Design Boundary Constraints:

a. *Current regulatory reporting metrics*

nvPM number and mass concentration output EI parameters

b. *Use COTS measurement analysers and calibration systems*

c. *Practical analyser installation*

Robust operation in known environmental conditions

Physically integrate with engine test facilities

d. *Use extractive probe sampling*

Probe location - engine exit or downstream in a testbed stack

Obtaining nvPM measurements downstream in a testbed stack has potential benefits:

i. *reduce nvPM sampling losses, whilst still employing high fidelity and vibration sensitive instrumentation.*
ii. *enable standardisation of ALL sampling geometry from probe tip to measurement analysers.*

However, it should be noted there could be significant cost to OEMs to implement (retrofit) such new probe, sampling & measurement infrastructure across multiple testbeds (multiple testbeds needed for operational flexibility). Also, not all OEMs use indoor testbeds for emissions testing. Testbed stacks for large engines can be large (5 x 5 m), so reductions in sampling line length will likely be limited to similar benefit to sampling within 8m of engine exit (e.g., on engine Pylon).

e. *Representative sampling* – Needed at either engine exit or stack location
f. Maximum 1 minute collection time for steady state measurement data (minimum 30x measurement samples)

3.3. Optimum sampling and measurement system concepts

For fullness, optimum concept options can be considered under different implementations of measurement location:

1) Simplification optimum with instruments still located 33 m (25 + 8 m) from probe tip (in benign, carefully controlled environmental conditions)
2) Simplification optimum with minimised particle loss with instruments located either using:
    a) close to engine <8 m sampling from sample probe tip (more adverse environmental conditions)
    b) Testbed stack sampling <8 m of sampling system length (in relatively benign environmental conditions)

It is noted that option 2 solutions are more optimum compared to option 1 due to the reduced size dependant particle loss. However, they require more complexity to integrate either at Engine exit (due to instrument location) or in exhaust stack (test-cells vary significantly in design and geometry often with wide diameters (>5 m) and containing detuners etc.) Similarly, mixing within the distance to the stack sampling is not guaranteed across different thrusts and by-pass ratios prior to any perceived representative sampling location.

Optimum concepts for 1): Using **long ~30 m** sampling system

Table 3 – Optimised Instrument Solutions for a long sampling system:

New method design concept	Simplification	Considerations
Real time (at least 1 Hz) electrical mobility particle size distribution	**Reduce number of instruments** - replace CPC by combining particle number and size into a single instrument	Likely higher number measurement uncertainty ~30 % (instrument OEM) vs ~17 % (existing SAE E31 estimation)
	Single instrument and type – replaces mass and number instruments	Potentially high uncertainty with unknown effective density
Real-time electrical mobility particle size distribution with CS and with Centrifugal particle mass analyser	**Single instrument type** – more accurate than PSD alone	CPMA not a simple instrument

Table 4 Optimised Sampling Solutions for a long sampling system

New method design concept	Simplification	Considerations
Standardise Splitter 1 geometry and flows **Example: use Dekati eDiluter & fixed gas line flow**	**Reduce particle loss difference between engine types** - Standardise Splitter1 particle losses	Need to ensure probe representativeness at highest power conditions, especially mixed flow sampling
Remove dilution for mass measurement **Example: use existing raw sampling line**	**Simple sampling** – improved mass LOD by a factor of 10	Mass and number no longer measured at similar sampling location. Potentially higher uncertainty on system loss factor for mass.

Optimum concepts for 2): Short sampling systems <8 m

Table 5 Optimised Instrument Solutions for short sampling systems

New method design concept	Simplification	Considerations
Same mass and number kit as current	**Reduce sampling loss**	Minimal benefit as the particle loss in the 25m line is the easiest to predict and validate
		Environment operation concerns
Same current number CPC, single VPR measurement method and single mass measurement method	**Reduce and standardise sampling loss** Same particle loss across number systems **Single VPR type** **Single Mass instrument type**	Specifying a single manufacturer in a measurement standard is difficult on commercial/ competitive/risk grounds
		Environment operation concerns
Real-time electrical mobility particle size distribution with CS Examples: Cambustion DMS-500 or TSI EEPS	**Reduce number of instruments** - replaces CPC by combining particle number and size into a single instrument	Likely higher number measurement uncertainty ~30 % (instrument OEM) vs ~17 % (existing SAE E31 estimation)
		Separate mass analyser
		Environment installation
	Single instrument for mass & number and single size instrument type – replace mass and number instruments	Potentially high uncertainty with unknown size dependent effective density
		Environment installation
Diffusion chargers Examples: Pegasor, Partector2, MPEC+	**Single instrument type for number and size** Robust simple design – some sensors built for harsh environments **Reduced sampling complexity (for some sensors)** - No dilution needed (Linear counting 1.0E03 to 1.5E07 p/cm^3), some sensors can take a hot inlet sample (>350°C) **Simple direct SI calibration** – Amperes, electrometer	Likely higher number uncertainty ~20 to 30 % (instrument OEM) vs ~17 % (existing SAE E31 estimation)
		Separate mass analyser needed
	Single instrument and type for number, size and mass Robust simple design – some sensors built for harsh environments **Reduced sampling complexity (for some sensors)** - No dilution needed, takes a hot inlet sample (potentially no need for CS) Simple direct SI calibration – A, electrometer	Likely higher number uncertainty ~20 to 30 % (from OEM) vs ~17 % existing
		Mass uncertainty potentially high since dependent on size effective density
Portable BC sensors Example: microaetholometer	**Single instrument type for mass**	Mass uncertainty potentially high

Table 6 Optimised Sampling Solutions for short sampling systems:

New method design concept	Simplification	Considerations
Standardise Splitter 1 geometry and flows Example: use Dekati eDiluter & fixed gas line flow	**Reduce particle loss difference between engine types** - Standardise Splitter1 particle losses	Need to ensure probe representativeness at highest power conditions, especially mixed flow sampling
Remove dilution for mass and number measurement – measure hot sample	**Simple sampling** – improved mass LOD by a factor of 10 **Reduced particle loss uncertainty in a complex part** – including temperature gradients	Requires measurement sensors to measure sample 'hot' to prevent water condensation
		Measure sample <350°C requires use of a VPR to meet nvPM definition
		Coagulation impact on number
		Differences between core and mixed flow sampling (theoretically potentially standardise on core sampling only)
Place CS at probe outlet to both number and mass measurements	**Simple sampling –** consistent nvPM definition to mass and number measurements	Overheating of CS at highest engine exhaust temperatures
Standardise probe design Examples: stack measurement, Rake design rules – possible 3D printing, multi-hole probe dilution	**Reduce particle loss difference between engine types**	Stack (as described above this table)
		How to achieve probe representativeness with multi-hole probe tip dilution
		Mixed vs core sampling

Removal of the use of CS would be a further simplification of the above concepts (where mentioned). However, there would need to be a change in nvPM definition unless the sampling system was maintained at 350°C to and in the measurement instruments, which would require a change in accepted measurement technologies.

3.4. Concepts Down select

If particle size dependant effective density is shown to be consistent across many engine technologies, at specific engine power conditions (e.g., a fairly tight range of effective density at each LTO condition) or can be derived from combustor rigs prior to engine test, then utilising PSD or diffusion charger sensors (capable of determining a pseudo average particle size), close to engine exit may be the simplest scientific optimum for both nvPM number and mass measurement concepts. Further still, as some sensors can measure from a hot 350°C sample, no additional volatile particle removal would be needed. This simple scientific optimum concept is shown in Figure 3.

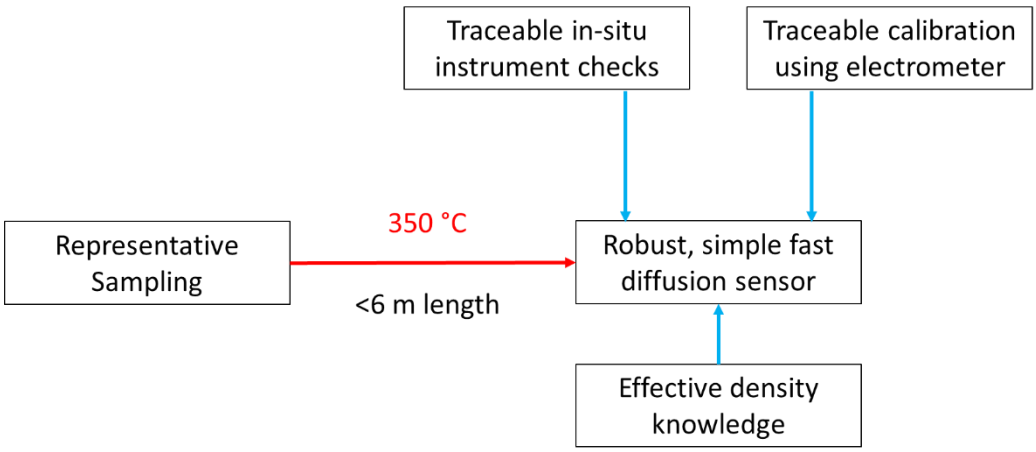

Figure 3: Example of Scientific optimum concept for aircraft engine nvPM number and mass emissions reporting

As a hypothetical system loss example, using the concept shown in Figure 3, with a sample line of 8 mm ID (a suggested average across OEMs rake types) and sample flowrate of 20 sLPM, with 360° total bends (likely worst-case), using the SAE AIR6241 UTRC penetration tool, the diffusion, inertial, bending, and electrostatic losses are shown in Figure 4. It can be observed that at a particle size of 5 nm (lowest size measurement limit of COTS diffusion chargers), the particle transport efficiency is 50 % and at 10 nm it is over 75 %. This would indicate that system loss correction factors would be <2 for number (even including thermophoretic loss) and likely <1.5 for most existing engine types and conditions. This represents a very significant improvement in system loss which, in turn, means potential increases in the measurement analyser uncertainty will be negligible/small in comparison to overall uncertainty.

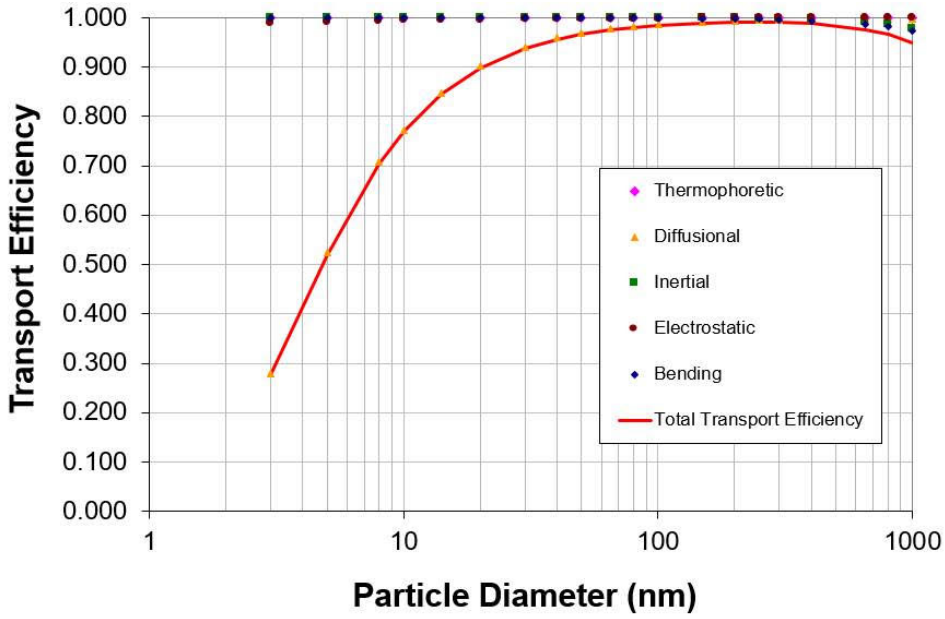

Figure 4: Example of theoretical particle loss in a scientifically optimum nvPM sampling system

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